SOME ASPECTS OF MACHINABILITY
DATA OPTIMISATION

BY

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SUMMARY

Face milling is considered for this work in two main parts. Firstly, the cutting geometry of face milling was examined. As the one independent variable, the author used equivalent chip thickness which is the ratio of the area cut (which is a measure of heat generated) to the cutting edge engaged with the workpiece (which is a measure of heat transferred to the chip, to the cutter and to the workpiece) by each tooth, because cutter wear is a function of cutting temperature.

The machinability data such as cutter life, power required at the cutter, surface finish and vibrations, were obtained using two different face milling cutters (the Walter Cutter and the Sandvik cutter), two different types of tool steel material (B.H.N. 238 and B.H.N. 197 as used by G.K.N. Ltd) in down-cut and up-cut face milling.

The cutter life tests were planned and performed only as a function of cutting speed and of equivalent chip thickness in order to reduce testing time and number of workpieces required. The validity of the equivalent chip thickness was proved. It was found that the equivalent chip thickness gives a guide to the selection of the geometry of teeth commercially available. Cutter life equations were obtained using statistical techniques. The power required at the cutter was expressed only as a function of metal removal rate. The results show both feed and cutting speed affects surface quality and vibration is generally generated by cutting force not by the chatter phenomenon.

With the necessary backlash eliminator down-cut face milling showed better performance (in terms of machinability data, initial contact point at entry conditions) than up-cut face milling. Shorter cutter life was obtained in central milling than in up-cut and down-cut milling, because the width of the workpiece was relatively small according to the cutter diameter used.

Secondly, using the cutter life, metal removal equations and T - MR (T is cutter life; MR is metal removal rate) characteristic function idea, MR was expressed only as a function of T. Then the economics of face milling were examined.

Dedicated to my wife.

The Author

The Author completed his B.Sc and M.Sc. degrees in Mechanical Engineering Faculty of Istanbul Technical University in 1968.

After two years military service he worked for a further two years in industry. After successfully completing his examination, he went abroad for Ph.D studies.

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DECLARATION

No part of this work described in this thesis has been submitted in support of an application for another degree or qualification of this or any other University or other institution of learning.

NOMENCLATURE

W	Width of workpiece (mm)
F	Table speed (m/min)
d	Depth of cut (mm)
φ_e	Engagement angle
φ_z	Angle between any two teeth in cutter
Z	Number of teeth
N	Number of revolution (r/min)
f	Feed per tooth (mm)
h	Underformed radial chip thickness at any instant (mm)
h_m	Mean value of underformed chip thickness (mm)
A_W	Characteristic cross-sectional area of cut for the Walter Cutter (mm^2)
D_W	The nominal diameter of the Walter cutter (mm)
V_W	Cutting speed of the Walter Cutter (m/min)
h_W	Equivalent chip thickness for the Walter Cutter (mm)
A_S	Characteristic cross-sectional area of cut for the Sandvik Cutter (mm^2)
D_S	The nominal diameter of the Sandvik Cutter (mm)
V_S	Cutting speed of the Sandvik Cutter (m/min)
h_S	Equivalent chip thickness for the Sandvik Cutter (mm)
T_W	Cutter life of the Walter Cutter (min)
T_S	Cutter life of the Sandvik Cutter (min)
MR	Metal removal rate
T_p	Total time to produce per piece (min)
Tr	Replacement time for all teeth
C	Total cost to produce per piece
C_o	Operator and overhead cost per unit time.

CONTENTS

CHAPTER I

Introduction

The evaluation of machinability data obtained using the properties of the cutting system (which are known to be: type of machining process, cutter, workpiece being cut, and machine tool) has always been of importance to industry especially from the point of view of economics and utilisation of machine tools.

Machinability data enables the production engineer to select for the process the correct cutter (among those commercially available), the correct process method and the correct machine tool. By using the machinability data obtained, the process selected can be controlled either directly or indirectly.

Face milling, which is one of the cutting processes, removes excess material from the plane surface of given workpieces. It is known as interrupted cutting process and widely used in industry because material can be removed in large amounts in unit time with brazed or throw-away carbide inserts. These inserts or teeth, are subject to impact during their entry into the workpiece being cut, and the chip thickness varies during cutting. Due to the great scarcity of literature available on face milling, in this project, the author analyses the geometry and properties of face milling (down-cut, up-cut and central milling) and determines the variation of the chip thickness. The characteristic feed is defined and the metal removal rate is formulated as a function of cutting speed, characteristic feed and depth of cut.

Cutting tests were planned and performed in order to obtain machinability data within industrially practical ranges. At the same time, the entry condition of each tooth was examined in order to determine the first initial contact of each tooth with the workpiece being cut.

The machinability data (which includes cutter life, power required at the cutter, surface finish produced, acceptable dimensional accuracy and vibrations generated), obtained and evaluated for down-cut, up-cut and central milling in order to compare the results using the Walter cutter and the Sandvik cutter with their different throw-away inserts, and the tool steels (B.H.N. 238 and B.H.N. 197) which were all kindly supplied by G.K.N. Ltd., Birmingham. The results were analysed in graphical and by means of mathematical equations. The equations were obtained in as simple a form as possible using statistical techniques.

Cutter life results were obtained by optical means only as a function of cutting speed and equivalent chip thickness using the mean value of the maximum flank wears. It has been known that wear is related to the cutting temperature in metal cutting. Equivalent chip thickness is calculated by the cutter specification (diameter and number of teeth), the width of the workpiece being cut, the tooth geometry and by cutting variables such as table speed, depth of cut, but excepting cutting speed.

The cutter life equations were obtained using the power transformations method,known as one statistical method,in the semi-logarithmic form. Power is measured in terms of gross and idle power. Power required at the cutter was evaluated only as a function of metal removal rate in order to obtain simple equations. The same slopes were calculated using the Sandvik cutter and the Walter cutter.

Milling processes are generally known as intermittent processes. They are not finishing processes like turning or grinding. C.L.A. (Centre line Average) measurements taken under different cutting conditions give an idea about the kind of surface finish produced. Generally, the vibrations generated by the cutting force were measured on line under different cutting conditions.

Using the machinability data obtained and having due consideration to time and cost,the economics of face milling were investigated from the T - MR characteristic function (T is the cutter life,MR is metal removal rate), optimum cutter life, metal removal rate and cutting variables such as cutting speed, table speed for the preselected depth of cut were obtained bearing in mind the maximum horse power available on the machine tool used.

CHAPTER II

Review of Relevant Literature

As can be seen in Figure (1) and Figure (2) the responses of any machining process can be grouped together into two main groups or indexes, namely: Technological Performance Index, and Economic Performance Index.

Previous investigations, carried out using only one or two of the responses and related to our own research, will be briefly discussed here below:-

2.1. Technological Performance Index and its Measurement.

2.1.1. Temperature

Temperature and its distribution over any local area which is exposed during the cutting process has been the subject of much attention, mostly in turning processes (1), because temperature plays an important role in influencing the rate of wear of cutting tools.

Techniques of temperature measurement in metal cutting are divided into four categories (2).

a) Thermo-electrical methods, b) Calorimetric methods, c) Radiation methods, d) Thermistor methods.

Garter spring pick-up thermocouples positioned at the back of the cutter inserts (which is one of the thermo-electrical methods mentioned above) were used in face milling processes by Wang, Wu and Iwata (3). In order to evaluate the performance of the process, the average cutting temperatures on a multi-tooth cutter were measured and recorded.

Average cutting temperatures were examined for different cutting speeds, feeds and depths of cut, and using different numbers of teeth. It was found that cutting temperatures increased as the number of teeth increased, for the same cutting conditions.

2.1.2. Chipping or Fracture of Tool

When brittle tools like cemented carbide tools and ceramic tools are used either in a continuous or in an interrupted cutting process such as the milling process, chipping can occur in association with a wear zone, because of both mechanical and thermal stresses. Also, chipping which is not associated with any wear zone can occur in a brand new cutting tool as stated by Cook(4).

He theoretically reviewed tool wear mechanisms and tool life criteria, especially in single-tool operations such as turning rather than multi-tooth operations such as milling.

Kronenberg(5) made an analysis of the initial contact of a milling cutter taking face milling as a reference process. Both geometrically and mathematically and with the aid of the graphical method, he showed and explained the location of the inital contact in terms of the geometrical parameters, such as axial and radial rake angles, corner angle, cutter diameter, position of the cutter relative to the workpiece, as well as of the machining variables, such as feed per tooth and depth of cut, but only along the plane of engagement determined by the length of the workpiece. He did not investigate the location of the first plane of engagement determined either by the width of the workpiece as in the case of up-cut face milling or by the length of the workpiece as in the case of down-cut face milling. Taylor(6) showed the necessity of introducing statistical techniques in the field of metal cutting, because of errors especially in the determination of tool life. He also pointed out that the main objective should be to prevent breakage and chipping when applying carbide tools. He tabulated the results of a two-year survey on the condition of brazed tipped carbide tools in terms of percentage worn and chipped tools, for a number of grades of carbides. The mechanism of cracking of carbide tools in face milling, using single tooth cutters, was considered by Shinozaki(7) from the probability point of view. The effect of machining variables on cracking was investigated by plotting the individual variables against the number of cracks on workpieces of constant length. The following criteria are recommended as ideal for cutting with the least probability of cracks:-

a) Minimize the temperature difference at the cutting edge, b) Lower maximum temperature as much as possible. The limitations of the investigation were in using only single-tooth cutters and face milling in central position. Kuljanic (8) showed the tool life to be a function of the number of teeth in the cutter, in face milling. He also proved statistically that the impact of the tooth entering the material does not affect the tool life when two teeth cut simultaneously. He concluded that the tool life tests for predicting the behaviour of the cutter should be carried out with more than one tooth.

The work was limited to one workpiece, one tool material, and face milling for central position of the material. An analysis of thermal strain in peripheral milling processes, using high speed and carbide end-milling cutters was presented by Yellowley and Barrow(9). They briefly pointed out that in the face milling process, workers in Germany have concluded that entry conditions are all-important, whilst Japanese and Russian workers have laid great emphasis on thermal stressing in discontinuous cutting. They found that tooth life in down-cut peripheral milling was higher than in up-cut peripheral milling. Loladze(10) outlined the problem of brittle failure of cutting tools from stress state conditions for different machining processes (turning, Planing, and certain types of milling) using photoelasticity. He theoretically calculated the thermal stresses using temperature gradients for orthogonal cutting.

2.1.3. Tool Wear, Tool-life Criteria and Tool-life Equations

The fundamental reasons behind the wear process mechanism and their applications to machining processes, basically according to time, have been the subject of investigation by many researchers (11), (12). Opitz and Konig (11) showed that different mechanisms operate in tool wear when steel is machined with carbide cutting tools, namely: diffusions reactions, abrasive wear (plastic deformation), adhesive wear (pressure welding), oxidation wear, etc. It was noticed that, at low and medium cutting speeds, tool-life depends on the wear at the flank face. Under high speed conditions, plastic deformation may occur on the rake face which determines the useful life of cutting tools. In recent years, researchers like Konig (12) have been involved with the development of improved cutting tools to obtain longer tool life. Konig (12) claimed that coated carbide tools, like TiN or TiC - coated carbide, might give tool life approximately 100-300% better than traditional carbides.

Cook (4) and Barrow (13) reviewed tool-life criteria especially in single-tool cutting operations. A tool can be used according to any one of the following criteria:-

1. Tool Failure

Tool failure is a most generally accepted criterion for tool-life. Failure can be classified as follows:

a) Chipping

b) Accelerated wear both on flank face and on rake face. Barrow (13) recommended the values discussed below, especially in turning.

1) Flank face wear

1.1) Carbide and ceramic tools can be used until the prescribed value of wear, the mean value $V_B \cong 0,38$ mm or the maximum value $V_B \cong 0,76$ mm, is reached on the flank face (see figure (3)).

1.2) High speed steel tools can be used until the maximum value $V_{B\ max} \cong$ 1.5 mm or complete failure is reached on the flank face.

2) Rake face wear

Carbide and ceramic tools can be used until depth of crater KT = 0.004 + 0.3s (in) is reached on the rake face; s is the feed per revolution in (mm/rev).

Barrow(13) schematically indicated that the relationship between mean value of flank wear V_B and time is in three stages: (a) an initial non-linear rapid wear rate, (b) an approximate constant wear rate, and (c) another zone of non-linear rapid wear rate, with both wear and time on a linear scale. He also pointed out that, provided the correct tool material is used for a machining process, failure by flank wear is usual; in view of this, tool-life equations are usually developed using a flank-wear criterion and, to compare tool-life data, the same criterion should be used. Opitz and Konig(11) showed that in milling the curve of the mean value of flank wear V_B plotted against milling length on a log-log scale, and the curve of the depth of crater KT plotted against cutting time on linear scales, show an approximately linear increase after a first rapid wear rate. Konig(12) obtained curves of V_B against cutting time-in logarithmic scale and KT against cutting time (in linear scale), approximately in linear form, using P25 carbide tool and P25 + TiC - 13Mo - 13Ni Coated carbide tools.

Gilbert, Boston and Siekmann(14) obtained cutter-life data and cutter-life equation for cast iron mostly using carbide brazed single tooth face milling cutters in central milling on a knee-type horizontal milling machine. The parameters and variables (namely: grade of cast iron, tool material, feed per tooth, depth of cut, width of bar, number of teeth) were changed one at a time, using a value of 0.76 mm for the steady flank wear. The limitations were that they used mostly a single tooth cutter, central milling and only one type of tool with a certain geometry.

In process measurements of tool wear obtained by sensors have been given attention, particularly on numerically controlled machine tools rather than conventional machine tools (15), (16), (17). Their investigation is out-side our scope.

2. Change of Surface Finish

Tool wear effects on surface finish. The deterioration of surface finish can determine the end of tool-life.

3. Change of Workpiece Dimensional Tolerance and Accuracy

The cutting edge might have to be replaced if the components produced are out of tolerance, because the degree of tolerance is associated with the wear of the radiused nose of the cutting edge.

4. Change of Cutting Force and Power

Cutting force and power required to cut the workpiece increase as the tool wears. The tool is replaced after a predetermined amount of increase.

5. Economic Considerations

Tools can be replaced before they are completely worn out, on the basis of an estimate of tool-life and of average tool cost. Tool-life data obtained from reliable tests can be evaluated in tabular, graphical, or mathematical form (equation).

An accurate assessment of tool-life data in mathematical form has been necessary, following the development of optimization procedures and numerically-controlled machine tools (13). When considering the validity of tool-life equations, one realizes that they are all emperical.

In the metal-cutting field, many independent parameters and variables contribute many responses as can be seen in Figure (1) and Figure (2). If the number of the independent variables chosen is large, and one of the responses can be selected first, research can be carried out on the evaluation of the effects of each one of the independent variables on the selected response by using the Analyis of Variance, a well known method in the science of Statistics(18). The analysis of Variance can show the significance of the independent parameters and variables influencing a machining process. Generally, when selecting the independent variables from the point of view of tool wear, either of two main different criteria can be adopted:

a) The independent variables such as surface speed, feed, depth of cut etc., are taken into consideration individually.

b) Only two independent variables are taken into consideration individually: surface speed and chip equivalent, or its reciprocal the equivalent chip thickness, which includes feed, depth of cut, tool geometry and some geometric properties.

Using the two main different criteria mentioned above, up-to now three different tool-life equations have been used(13) to predict the behaviour of the cutting process, especially in turning operations.

a) Taylor-type tool-life equations. Firstly, Taylor(19) introduced his best-known tool-life equation $V.T^{n} = K$ (1)

Where n is the slope of the logT-logV plot and K is a constant.

For turning, Kronenberg(20) suggested a method to obtain the following tool-life / cutting-speed relation, by keeping constant the feed, the depth of cut and the tool geometry:

$$(V \pm K_s)\, T^{n_1} = (K \pm K_s) \qquad (2)$$

where K_s is a constant (straightening factor). An extended Taylor-type equation which includes V, S, d, is used especially in turning with one type of tool geometry, as follows:

$$V.T^{\alpha}.\ s^{\beta}.\ d^{\gamma} = K \qquad (3)$$

where the exponents α, β, γ are accepted as reasonably constant.

b) Tool-life equations using the chip-equivalent concept.

Woxen(21) first introduced the idea of chip equivalent q which includes geometrical parameters as well as machining variables of cutting in turning; he expressed the tool-life equation as follows:

$$V = \left(\frac{T_*}{T}\right)^{\alpha}. C. \frac{q + q_o}{1 + cq_o} \qquad (4)$$

where V is the cutting speed, T is the tool-life, T_* is a predetermined tool-life, e.g. 60 mins, α is an exponent, C is a constant determined by work material and tool material referred to the time T_*, q_o is a constant, c is a constant in turning process.

Brewer and Rueda(22) carried out work to demonstrate the validity of the "equivalent chip thickness" h_e which is the reciprocal of q in turning, and pointed out that h_e was unfamiliar parameter in English-speaking countries. Using a high-speed steel tool, they also expressed the tool-life in turning operations using a much simpler relationship involving only two variables, cutting speed V and equivalent chip thickness h_e, instead of five variables, V, S, d, side-cutting edge angle S_c and noise radius r. Colding(23) derived one limited equation and one general hyperbolic tool-life equation involving the variables cutting speed, chip equivalent and tool-life, at first in turning, using a well-known dimensional analysis. The limited tool-life equation was

$$V.T^{\alpha} = Aq^{m} \qquad (5)$$

where α and m are reasonably constant, and A is a constant for the limited tool-life. The general hyperbolic tool-life equation was

$$\emptyset(x,y,x) = -\frac{(X-Xo)^2}{a^2} + \frac{(Y-Yo)^2}{b^2} + \frac{(Z-Zo)^2}{c^2} = H \qquad (6)$$

where $\emptyset(x,y,x)$ is general hyperbolic tool-life function, $X = \ln q$, $Y = \ln V$, $Z = \ln T$, and a, b and c are the semiaxes of the hyperbolic tool-life surface. He also expressed the total cost Q of turning one piece:

$$Q = \frac{Wp.P}{V.s.d} \cdot \frac{T + \delta}{T} + p.T_i \qquad (7)$$

where Wp is the volume of material to be removed per part, p is the cost of machine and operator including overheads, (V.s.d) is the metal volume removed per unit time, T is the tool-life, $\delta = T_d + R/p$, T_d is the tool-replacement time, R is the average cost of regrinding the tool, T_i is the idle time.

He defined f as a productivity function:

$$f = (V.s.d) \cdot \frac{T}{T+\delta} = L \cdot \frac{V}{q} \cdot \frac{T}{T+\delta} \qquad (8)$$

where L is the engaged cutting edge of the tool and q is the chip equivalent. Then he searched to optimize the ratio $\frac{f}{L}$ called productivity.

Later Colding(24), (25) obtained expressions, using the chip equivalent idea, for all types of milling and grinding processes according to his own tool geometry and set-up. Then he used the general tool-life equation in second order polynominal logarithmic form for turning and plain milling processes.

$$k + ax + bx^2 + cy + dy^2 + e z^2 - z + fxy + gyz + hxz = 0 \qquad (9)$$

where k, a, b, c, d, e, f, g, h are constants, $x = \ln q$, $y = \ln V$ and $z = \ln T$.

The equation above is quite complicated and it is not easy to use since lnT also appears in the second order. The effects of cutting angles on tool-life were analysed by Akun(26) using equivalent chip thickness idea in turning. He concluded that if rake angle is increased, tool-life is increased, when the angle (side cutting-edge angle) between the workpiece and the tool is increased, tool-life is decreased in turning.

c) Tool-life Equation in Exponental Form

(Proposed by Konig-Depiereuz)

Konig and Depiereuz (27) derived a tool-life equation for the turning process using T-V and T-S logarithmic curves, obtained during actual cuts, taking non-linearity into account.

They assumed that the slopes K and i of the above curves vary as follows:

$$k = -k_v . V^m \qquad (10)$$

$$i = -i_s . s^n \qquad (11)$$

where k_v, i_s, m, n are constants.

Using actual values of T, v and s, they then obtained their tool-life equation:

$$T = e \left(- \frac{k_v}{m} V^m - \frac{i_s}{n} s^n + C\right) \qquad (12)$$

where C is another constant.

The limitations of this equation are that it is derived for a constant depth of cut in turning, and it does not take into account the experimental errors.

Since all tool-life experimental results include experimental errors, just like any other experimental processes, it is very difficult to obtain the values of five constants (K_V, m, i_s, n, c) by using only five experimental tool-life results (writing five simultaneous equations), especially in a multi-tool cutting process like milling. If the values of T,V and s are not rigidly related to each other, five unknown-constant values cannot be found using five simultaneous equations. This is one of the main reasons why statistical techniques have been so successful in the field of metal cutting as well as in other engineering fields.

The statistical techniques mentioned below have been used to determine the proposed mathematical form of any response of machining processes; They are 1) Response Surface Methodology, 2) Power Transformations, 3) Multiple Regressions, 4) I.C.L Statistical Package XDS.3.

1. Response Surface Methodology

Response surface methodology was first proposed by Prof. G. E. P. Box in 1951 in chemical process engineering. This statistical technique views the response as a surface. Wu$^{(28), (29)}$ first applied this technique to the field of metal cutting using Taylor-type first and second order equations, taking V, s,d individually as independent variables. A composite design was used. After calculating the coefficients by means of the least square method, the confidence intervals were defined. The adequacy of the postulated model was checked by means of Analysis of Variance. Confidence intervals were determined for tool-life results.

2. Power Transformations

Instead of linearizing tool-life equations, Wu, Ermer and Hill$^{(30)}$ used transformations of certain forms of dependent and independent variables to determine directly Taylor-type equations.

The transformations, used in tool-life equations, were in the following forms:

$$T^{\lambda} = \begin{cases} \dfrac{T^{\lambda} - 1}{\lambda (\dot{T})^{\lambda - 1}} & \text{if } \lambda \neq 0 \\ \dot{T} \ln T & \text{if } \lambda = 0 \end{cases} \qquad (13)$$

where T is the tool-life and $\dot{T}$ is the geometric mean value of tool-life observations.

For the independent variables, $U_1, U_2 \ldots\ldots U_p$, the transformations were in the forms below:-

$$U_i = \begin{cases} X_i^{\alpha_i} & \text{if } \alpha_i \neq 0 \\ \ln X_i & \text{if } \alpha_i = 0 \end{cases} \qquad (14)$$

where X_i is any independent variable and α_i is any parameter.

The tool-life equations are generally written as;

$$E(T^{(\lambda)}) = \beta_o + \beta_1 U_1 + \beta_2 U_2 + \beta_3 U_3 \ldots\ldots + \beta_p U_p \qquad (15)$$

where $E(T^{\lambda})$ is the expected value of the transformed tool-life β_o, β_1, $\beta_3 \ldots\ldots \beta_p$ are coefficients and are calculated using the method of least squares. For example if $\lambda \neq 0$ and $\alpha_i \neq 0$, the equation is written as follows:

$$E\left(\frac{T^{\lambda} - 1}{\lambda (\dot{T})^{\lambda-1}}\right) = \beta_o + \beta_1 X_1^{\alpha 1} + \beta_2 X_2^{\alpha 2} + \beta_3 X_3^{\alpha 3} \ldots + \beta_p X_p^{\alpha p} \qquad (16)$$

If $\lambda = 0$ and $\alpha_i = 0$ the equation is written as follows:

$$E(\dot{T}.\ln T) = \beta_o + \beta_1 \ln X_1 + \beta_x \ln X_2 + \beta_3 \ln X_3 \ldots\ldots + \beta_p \ln X_p \qquad (17)$$

This is a logaritmic transformation, which is a special case of the power transformations. The method of the residual sum of squares was used as the numerical criterion to indicate the best fit among the equations. An approximate percent confidence region was determined for tool-life.

3. Multiple Regression and Analysis

Some researchers (31), (32), (33) have already shown that multiple regression, one of the statistical techniques, also plays an important part in finding relationships between any one response of any machining process and a number of independent variables involved in that machining process.

In the past, instead of multiple regression, researchers used linear, curve or surface fitting methods.

Any proposed function which may be converted to linear form can be written as follows:

$$Y = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \dots \beta_p X_p \qquad (18)$$

here Y is the estimated response and $\beta_o, \beta_1, \beta_2, \beta_3 \dots \beta_p$ are coefficients which are determined by the method of least aquares.

Their composite effect is measured by the multiple correlation coefficient.

When the number of independent variables is large, the use of a computer may become necessary. After estimating the coefficients, the analysis of variance can be used to check the adequacy of the proposed model. Certain percentage confidence intervals for the estimated coefficients can be calculated.

4. The I.C.L. Statistical package XDS.3.

The I.C.L. 1900 series statistical mark 2 package (34) defined in the manual gives different facilities.

4.1. Independent and dependent variables are defined at the beginning of the programme. Observations are introduced in a matrix. Using the observation matrix, the package can calculate the mean, the variance and the standard deviation of each of the variables.

A cross-product matrix is calculated from the observation matrix. A covariance matrix is found using the cross-product matrix. Then a correlation matrix is determined by the covariance matrix. All these matrixes are available from the output file.

The regression analysis can be carried out on a covariance which was calculated before the regression analysis. For each analysis, a dependent variable is defined. A significance level of each or of all the independent variables is determined. Two different cases are identified.

a) Significance level $\geqslant$ 99%,using the significance level equal to or greater than 99%, each independent variable, which is written in the regression analysis, is pushed into the regression set.

b) Significance level $\langle$ 99%, using the significance level each independent variable, which is written in the regression analysis, appears when it is significant compared with the standard significance level.

Output of the Programme

Regression coefficients are calculated using the least square method. Standard error of the regression coefficient, confidence interval, student t-statistic, partial correlation coefficient, multiple correlation coefficient, error sum of squares (E.S.S) of each one of the independent variables and also E.S.S. of the dependent variable, are calculated in the analysis.

4.2. Analysis of Variance. As mentioned earlier, the analysis of Variance can be used to break down a measurement variation into additive components. The use of the analysis of Variance is shown in I.C.L. 1900 series statistical mark 2 package.

2.14. Cutting Force and Measurements

In the study of the metal cutting field, measurements and evaluation of the components of cutting force are particularly important especially from the point of view of the mechanism and of the machine tool design, as well as from the point of view of the cutting tool design. For designing of the machine tool structures and the associated mechanisms, only the maximum values of the components of the cutting force are required.

In any metal cutting process the cutting force, which is originated from a point on the interface between the cutting edge of the tool and the workpiece, is a single vector. That vector can be resolved into three mutually perpendicular components called the tangential force F_t the radical force F_r and the axial force F_a. In addition F_t and F_r can be further resolved into two components, one parallel and the other one perpendicular to the direction of feed. One example of force resolution in down face milling process supposing two teeth in engagement with the workpiece is shown in Figure (4).

Traditionally the instantaneous value of each component, especially the tangential force F_t, can be given by a function of the machining parameters, like feed and depth of cut. In face milling, for example, the value of F_t for each tooth is given by Koeningsberger (35) as follows:

$$F_t = P_m . d . f_i^{\,p} \qquad (19)$$

where P_m is the mean value of the specific cutting pressure, d is the depth of cut, f_i is the instantaneous value of the radical chip thickness, and the value of p lies between 0.75 and 0.9.

Especially in milling, measurements of force components F_t, F_r and F_a are difficult because they are oscillating rapidly due to the variation of chip thickness during cutting(36). A dynamometer should record the fluctuations on a time base. For peripheral milling, Figure (5) and Figure (6) show the trend of F_t and F_r in relation to the underformed chip length, both in up-cut and down-cut milling(36). Koenigsberger and Sabberwal(37), Sabberwall(38) measured the horizontal vertical and axial components of the cutting force for different machining variables and different materials, in both up-cut and down-cut peripheral milling, using a three-dimensional dynamometer.

A standard vertical milling machine was used. A hydraulic piston and cylinder arrangement was mounted at the end of the table to eliminate the backlash in the screw and nut assembly in down-cut milling.

He concluded that in down milling the cutting forces are generally higher than in up milling. In down milling the specific and mean cutting pressures are higher than in up milling. In down milling greater power will be required for the rotation of the spindle. Herderson(39) made a theoretical analysis of cutting force components in turning, milling and drilling. He explained each component of the cutting force as a function of the machining parameters and of the tool geometry. Pandley and Shan(40) described and analytical method for evaluating the cutting force components in peripheral and face milling operations using a single tooth cutter. They concluded that the cutting force components can be calculated with sufficent accuracy by describing the cutting action of the tooth by means of a shear plane model. The coefficient of friction largely depends on the tool rake angle and is virtually unaffected by the machining parameters.

2.15. Power Consumption

Because machine tools have limited horse power, the evaluation of the power required during cutting is as important as the evaluation of the cutting force components.

Gilbert, Boston and Siekmann(41) considered the power required in force milling processes using cutters having a single carbide tooth, brazed in position. They examined the unit power (horse power per volume of metal removed in the unit time) required at the cutter in relation to the machining parameters and geometrical variables, using different materials. They also pointed out that the cutting speed has very little effect on the unit horse power at the cutter. The feed per tooth has an appreciable effect on the unit power. Depth of cut has little effect on the unit horse power at the cutter. The width of the surface face-milled effects the thickness of the chip. The Brinell hardness of the material being face-milled also affects the unit horse power.

2.16. Surface Finish

Surface finish is an important parameter especially in finishing processes like turning and grinding. Feed, as a machining parameter, has been known to affect the quality of the surface. Surface roughness, both in the feed direction and in a circumferential direction, and surface waviness, which are known as properties of surface finish, can play an important role to determine the useful life of the tool. Surface roughness in C.L.A index was considered in a regression analysis of feed, noise radius of tool and cutting speed by Bhattacharyya, Gonzalez and Ham(42). In recent years the measurement of surface finish in various processes has been given closer attention, especially using laser beams(43). The discussion of this developement is out-side the scope of our research.

2.2. Economical Performance Index

One of the three machining functions (process cost, process time and profit rate), which together constitute the performance index, can be taken as an objective function. Apart from those three functions, metal removal rate may be proposed as an object function. In machining processes, different types of constraints can arise.

Machining variables can be determined according to a selected objective function, either without constraints or under constraints. The importance of being able to select the economically optimum machining conditions has long been recognized in the metal cutting field. The basic mathematical models which have been used in the analysis of the economics of machining are: Unit-time model, unit-cost model, and profit-rate model.

1. Unit-time model

The total time per piece T_p can be divided into elements as follows:

a) Non-productive time T_1.T_1 includes loading, unloading and set-up time; it is independent of machining variables.

b) Machining or feed engagement time $T_2 = T_c + T_o$, where T_c is the actual time for cutting and T_o is the time for approach and overtravel. In practice, $T_2 \cong T_c$.

c) Tool replacement time $T_3 = \frac{T_r . T_c .}{T}$

where T_r is the replacement time (time for replacing the cutting edge or edges) and T is the tool or cutter life.

Thus: $$T_p = T_1 + T_c + T_r \cdot \frac{T_c}{T} \qquad (20)$$

The reciprocal of T_p is the production rate P_p which indicates the number of pieces produced per unit time.

$$P_p = \frac{1}{T_p} \tag{21}$$

2. Unit-cost model

If C_o is the cost rate (which includes operator costs and overheads), and Y is the cost per cutting edge or edges of the tool, we have:

$C_1 = C_oT_1$ = non-productive cost.

$C_2 = C_oT_2 \cong C_oT_c$ = machining cost.

$C_3 = C_oT_3 = C_oT_r \cdot \frac{T_c}{T}$ = tool replacement cost.

$C_4 = Y \cdot \frac{T_c}{T}$ = tool cost.

The total cost per piece, C, will then be given by:

$$C = C_1 + C_2 + C_3 + C_4 = C_oT_1 + C_oT_c + C_oT_r \cdot \frac{T_c}{T} + Y \cdot \frac{T_c}{T} \tag{22}$$

3. Profit rate

The profit per unit time, Pr, can be written as follows:

$$P_r = \frac{S-C}{T_p} \tag{23}$$

where S is the selling price per piece and may be assumed to be a function of T_p, C is the total cost per piece, and T_p is the total time per piece.

It is essential that cost, time and tool-life data should be available to evaluate economic cutting conditions. But it is not always essential to express tool-life data in a mathematical form; Optimum cutting conditions can be obtained using tool-life data curves drawn using points obtained in actual tests.

As mentioned earlier, Brewer and Rueda$^{(22)}$ used a number of nomograms to determine the economic cutting speed in turning. The cutting speed was determined for a selected maximum feed under cutting force and horsepower restrictions using the equivalent chip thickness variable for different tool materials (High speed steel, carbide, ceramic) and work piece materials (cast irons, steels).

Ravignani(44) suggested graphical methods for determinining the optimum machining conditions from tool-life curves obtained from actual tests, using the relationships between the basic unit-time, the unit-cost and the profit-rate models. He extended his studies to the case of different operations successively carried out on the same workpiece. He also derived a method for determining the optimum ranges of the cutting conditions. He showed some examples in turning. Generally, his studies, need a rather high degree of simplication for practical use. Jakobsson(45) suggested a method to obtain optimum cutting conditions, based on actual tests and using T-V and V-q curves drawn on a logarithmic graph, where q is the chip equivalent. The productivity, $P = \frac{V}{q} \cdot \frac{T}{T+T_V}$, is calculated as an economic criterion to obtain values. In the above equation T_V is tool replacement time + tool cost per replacement expressed in machining time Tool-life data are more convenient(13) if expressed in mathematical form.

Brown(46) considered the selection of machining parameters when turning with a single-point tool in one pass and in two passes, using a unit-cost model. When turning in one pass with constant feed and constant depth of cut, using Taylor's well known tool-life relationship $VT^n = K$ he derived an expression for the minimum-cost tool-life.

$$T_{vm} = \frac{C_o T_3 + Y}{C_o} \cdot \left(\frac{1}{n} - 1\right) \qquad (24)$$

and for the corresponding speed V_{vm}

$$V_{vm} = \frac{K}{\left(T_e \cdot \left(\frac{1}{n} - 1\right)\right)^n} \qquad (25)$$

where $T_e = \frac{C_o T_3 + Y}{C_o}$

Similarly, with constant speed and depth of cut, using $s.T^{n_1} = K_1$ Taylor's tool-life equation for feed s, he obtained an expression for the minimum-cost tool-life.

$$T_{sm} = \frac{C_o T_3 + Y}{C_o} \cdot \left(\frac{1}{n_1} - 1 \right) \qquad (26)$$

and for the corresponding feed:

$$s_{sm} = \frac{K_1}{T_{sm}^{\ n_1}} \qquad (27)$$

He also derived the expressions for the cost of the two passes, which is the sum of the cost of each pass plus the cost of time required to change conditions from one pass to the next, at each pass using different cutting speeds, feeds and depths of cut. The derivations are rather complex and needs simplifying before they can be used in practice.

Taylor$^{(6)}$ showed the effect of speed on the unit cost model at constant feed using the relationship $VT^n = K$ in turning. He also examined the effect residual variance in the determination of the equation linking the tool-life T to the cutting speed V. In the absence of any quantitave statement regarding residual variance, he applied 95% confidence limits which produced a variation of ± 30% on the individual determinations of tool-life value, thus indicating that the work and tool material are the main sources of variability. He showed graphically the probable range of unit cost models with 95% limits. He pointed out that EN970 specification allows hardness the vary from 248 to 302 Brinell. Variations of this magnitude can cause tool-life to alter by 50%.

Ermer and Wu (47) investigated statistically the effect of experimental errors in tool-life tests on the determination of the minimum unit cost model using $VT^n = K$ (Taylor's tool-life equation) in turning. They determined a probable range of cutting speeds for minimum-cost because of uncertainty in the tool-life equation. A decision rule based on the minimum principle was used for the selection of a particular cutting speed for minimum-cost confidence interval. Ermer and Morris (48) used a different approach, a correction factor for the selection of the cutting speed for minimum cost, which takes into account the effect of experimental errors in tool-life tests. French, Milner and Weston (49) presented a computer programme for selecting the cutting parameters using only the known properties of machine tool, cutter and workpiece in turning.

They pointed out that for the numerical control of machine tool,it is necessary to determine the four facts listed below in order to obtain maximum utilization, because of high initial investment cost of machine tool: a) tool motions, b) cutting variables, c) tools required, d) sequence of operations.Throughout their investigations, the workpiece material used was steel because any research and development programme concerned with machining should include a high proportion of ferrous matals as stated by PERA reports No. 142 (50). Okushima and Hitomi (51) analysed theoretically the profit per piece in turning, using a linear break-even chart and employing Taylor's tool-life equation $VT^n = K$. Wu and Ermer (52) showed the application of economic principle to the profit-rate criterion for the selection of the optimum machining conditions in turning, using Taylor's tool-life equation $VT^n = K$. Amergeo and Russell (53) analysed theoretically the selection of machining conditions based on profit-rate for a single pass turning process, using Taylor's tool-life equation

$VT^{\alpha} . s^{\beta} = K_1$. It was found that the largest possible feeds should be used when selecting cutting conditions, in order to obtain minimum-cost or maximum production-rate; in general the maximum profit-rate is not achieved under conditions affording minimum-cost or maximum production rate.

Armarego and Russell(54) also showed theoretically the use of the profit-rate criterion in single pass shaping and peripheral milling. They applied Taylor's tool-life equation to peripheral milling with a single-tooth cutter, as follows:

$$T = \frac{A}{V^{\frac{1}{n}} . (teg)^{\frac{1}{n_1}}} \qquad (28)$$

where T was the tool-life, expressed as actual cutting time of the one tooth of the cutter, V was the cutting speed, teg. was the average chip thickness (because of variations in chip thickness), and A, n, n_1 are constants. They determined the machining time from the ratio $\frac{l}{F}$, where l was the length of workpiece and F was the table speed and obtained the tool replacement time from the formula

$$T_d . \frac{T_{cs}}{T}$$

where T_d was the time required to replace the tooth of the single-tooth cutter, T_{cs} was the cutting time for the one tooth to cut workpieces, and T was described by equation (28). Wu and Tee(55) determined the optimum cutting conditions using maximum profit-rate and the cutting speed at maximum feed to meet the fixed demand. The effect of the variation of selling price per piece and operator cost on the profit rate was examined.

In single-pass turning operations with fixed feed and depth of cut, using Taylor's tool-life equation $T = \dfrac{K}{\left(V\,\frac{1}{n}\right).S\,\frac{1}{n_1}}$, Kizhanatham and Brian(56) analysed a cost model, including the in-process inventory cost which is determined as the cost due to the waiting of the semi-finished jobs in the workshop for processing by some machine, and the penalty cost which is a cost for violating a due date clause.

Ermer(57) showed the application of geometric programming to turning operations, to obtain optimum cutting conditions for minimum unit cost under constraints such as available speeds, feeds, horsepower, surface finish. The optimum cutting conditions obtained by his method are subject to uncertainty because some coefficients of the unit cost model, such as non-productive time and coefficients of constraint, are subject to variations.

Iwata, Muratsu, Iwatsubo and Fujii(58) showed an analytical method to determine optimum cutting conditions by considering the probabilistic nature of coefficients in some constraints such as cutting force, horse power and surface finish.

Friedmann and Tipnis(59) introduced a new concept which explained the existence of a characteristic relation between metal removal rate MR and tool-life T for a given metal process. They showed that the optimum point, which determines optimum cutting conditions, must lie on the MR-T characteristic curve. Tipnis and Friedmann(60) showed the application of the above concept to circular sawing and peripheral end milling processes they obtained a MR-T curve, using the cutting speed V and the feed per tooth f as the two variables.

They also theoretically explained the use of the MR-T characteristic curve for the selection of economic cutting conditions under limited cost data, the economical development of tool-life data, the comparison of machining responses such as tool-life, surface finish, the determination of an objective function for adaptive control, and the maximisation of Metal removal rate at the desired level of surface integrity.

As can be followed from the literature survey, in the field of face milling processes little research has been done covering all aspects, especially in order to obtain mechinability data such as cutter life, power required, surface finish produced, and vibration of workpiece. The chip equivalent, which is the reciprocal of the equivalent chip thickness, was proved and used by Woxen (21) in turning. Colding (24),(25) only derived mathematical formulas for the chip equivalent in all aspects of milling processes using his own tool geometry and grinding processes. He did not use it in face milling processes. Cutter life tests have not been conducted using only two independent variables namely cutting speed and equivalent chip thickness, and no equation has been obtained using the two independent variables mentioned above. The power required at the cutter has not be obtained in terms of metal removal rate. The surface finish obtained has not been expressed in term of any machining variable. The vibration of workpiece in three directions, namely tangential, feed and axial directions, has not been measured. Surprisingly, there are few available machinability data in face milling processes. Milner (61) pointed out a similar conclusion.

CHAPTER III

Theoretical Analysis of the Technological Performance Index, the Relationship of each of its Machining Responses and Economic Index in Face Milling Processes

Face milling was chosen as a typical process in order to evaluate the performance indexes of face milling processes themselves as well as other metal cutting processes. It removes metal from a given plain surface more efficiently than the shaping process, it is widely used in industry especially with brazed or throw-away carbide inserts. For this research we were fortunate to obtain the co-operation of the GKN Ltd., Smethwick, Birmingham, a Company producing nuts, bolts and fasteners.

Surprisingly there is litte available machinability data for face milling processes. The following considerations on face milling will be limited to those cases which are of particular importance in establishing relationships such as cutter life, cutting force, power required, surface finish, and vibration produced.

3.1. On the Mechanics of Face Milling

Face milling, which is considered as interrupted cutting process and treated to be a type of milling process such as the others peripheral (slab), end, side etc., milling, is essentially similar to continuous single-point tool cutting except variation of the chip thickness and impact upon the first engagement of each tooth of the cutter with the workpiece material being machined. Three types of face milling, which are described according to set-ups and machining directions, are named as central, down-cut (climb) and up-cut (conventional) milling as shown in Figure (7).

In up-cut and down-cut milling, the eccentricity, e, determines the distance between two planes of symetry: One plane passes through the centre of the cutter, the other passes through the longitudinal axis of the workpiece. In up-cut milling, the cutter rotates against the direction of the table movement, in other words, the workpiece advances towards the cutter on the side where the teeth move against it. In down-cut milling, the cutter rotates in the direction of the table movement, in other words, the workpiece advances towards the cutter on the side where the teeth move away from it. In central milling, the centre of the cutter is on the longitudinal axis of the workpiece being machined.

In Figure (8) one typical down-cut face milling is shown, in which the width of the workpiece is W, the table speed F, the depth of cut d, the engagement angle φ_e, the angle φ_z between any two teeth. The cutter, which has diameter D and number of teeth z, rotates a number of revolutions per unit time N and a cutting speed V. In face milling, the thickness of the unde formed chip varies continuously while each tooth of the cutter cuts the workpiece. In up-cut milling, the unde formed radial chip thickness increases from a small value f_s to the maximum value f. In down-cut milling f occurs almost at the beginning of the cut and the unde formed radial chip thickness will then decrease. In central milling, the unde formed radial thickness increases to f from f_s then decreases again to f_s. The path of each tooth of the cutter relative to the workpiece is a trochoid. For the sake of simplicity it is assumed that the path generated by each tooth is circular (65).

In any face milling process, each tooth cuts a certain volume of metal (W.d.f). All teeth will cut a total volume of metal removed in the unit time, MR, will then be (W.d.f.z.N). The characteristics of MR are as follows:

a) The equation is the same for all face milling processes.

b) Time is not related to the tooth engagement time T_z which is a function of φ_e.

In face milling processes the expressions below are well known;

$$V = \pi.D.N. \tag{29}$$

$$F = f.z.N. \tag{30}$$

$$MR = W.d.f.z.N = W.d.F \tag{31}$$

If the teeth are equally spaced along the periphery of the cutter the angle φ_z between any two teeth is written by:

$$\varphi_z = \frac{2\pi}{z} \tag{32}$$

It may not be necessary to space teeth equally, in fact it might be desirable. Doolan, Phadke, Wu$^{(66)}$ proposed a method to design a face milling cutter with unequal tooth spacing which has a higher stability against relative vibration between the cutter and workpiece.

In up-cut milling, the unde formed radial chip thickness h at any instant can be expressed approximately according to the set-up used as shown in Figure (9) in the following:

$$h = f.\operatorname{Sin}\varphi \tag{33}$$

The mean value of the unde formed chip thickness h_m can be written as follows:

$$h_m = \frac{1}{\varphi_e}\int_{\varphi_o}^{\varphi_t} f.\operatorname{Sin}\varphi.d\varphi \tag{34}$$

$$h_m = \frac{f}{\varphi_e}\;(\operatorname{Cos}\varphi_o - \operatorname{Cos}\varphi_t) \tag{35}$$

In down milling, the unde formed radial chip thickness h_1 at any instant can be written approximately as shown in Figure (10) in the following provided the same value f is used;

$$h_1 = f.\cos \varphi_1 \qquad (36)$$

The mean value of the unde formed chip thickness h_{1m} can be written as follows:

$$h_{1m} = \frac{1}{\varphi_{e1}} \int_{\varphi_{o1}}^{\varphi_{t1}} f.\ \cos \varphi_1 . d\varphi_1 \qquad (37)$$

$$h_{1m} = \frac{f}{\varphi_{e1}} \quad (\sin \varphi_{t1} - \sin \varphi_{o1}) \qquad (38)$$

It can be seen that for the same f value and angles, up-cut and down-cut face milling produce chips with the same mean chip thickness value:

$$h_m = h_{1m} \qquad (39)$$

From now on, therefore only h_m will be used in notation.

Either of the two situations below can occur face milling processes

a) $\varphi_e \leq \varphi_z$ (40)

Either one or non tooth is engaged with the workpiece at any time.

b) $\varphi_e > \varphi_z$ (41)

One or more than one tooth could be engaged with the workpiece at any time. The number of teeth engaged with the workpiece, z_e, depends both upon φ_e and z. The value of φ_e also depends upon the relative position of the cutter with respect to the workpiece. φ_e increases, when the workpiece is displayed from the centre-line position towards the down-cut or the up-cut position, that is to increase the value of φ_e. The value of z_e is written as follows:

$$z_e = \frac{\varphi_e}{\varphi_z} \tag{42}$$

or

$$z_e = \varphi_e . z/2\pi \tag{43}$$

For example, if $z_e = 1.6$, it will indicate that for 40% of the time only one tooth cuts and for the remaining 60% two teeth cut. The author proposes that for any set-up regardless of type of face milling, the metal removal rate, MR, may be also expressed in the other way apart from the equation(31) using the mean value of unde formed chip thickness h_m and the engagement angle φ_e ideas as follows:

$$MR = h_m . d . \frac{D}{2} . \varphi_e . z . N \tag{44}$$

or

$$MR = h_m . d . V . \frac{\varphi_e}{\varphi_z} \tag{45}$$

The value of MR depends upon h_m, which is a function of f and the geometry of set-up, d, V, φ_e and φ_z. In MR, the term which in this research the author called the "characteristic feed" f_c is defined as follows:

$$f_c = \frac{\varphi_e}{\varphi_z} . h_m \tag{46}$$

When φ_e is smaller than φ_z it shows only one or non tooth is engaged with the workpiece at a time and non-cutting time exist between any two teeth, the ratio $\frac{\tau_e}{\tau_z}$, is smaller than 1, determines non-cutting time, hence f_c becomes smaller than h_m. If τ_e is equal to τ_z it also showns only one tooth is engaged with the workpiece at any time but non-cutting time does not exist between any two teeth, the ratio $\frac{\tau_e}{\tau_z}$ is equal to 1, hence f_c becomes equal to h_m. When τ_e is bigger than τ_z, it shows one or more than one tooth is engaged with the workpiece at any time, the ratio $\frac{\tau_e}{\tau_z}$ is bigger than 1, hence f_c, which becomes bigger h_m, determines the complete motion of one tooth plus the partial motions of one or more teeth, which will engage the workpiece while the first tooth completes cutting.

Metal removal rate, MR can be calculated by using one of the formulas given below:

$$MR = W.d.F = f_c.d.V \qquad (47)$$

The product $f_c.d$ determines the area A_c which will be called "the characteristic cross-sectional area of cut";

$$A_c = f_c.d \qquad (48)$$

For example when τ_e is bigger than τ_z, A_c is the total area cut by one tooth while passing across W.

f_c and A_c are related to the mean value of chip thickness. They can give better understnading than f itself in order to evaluate responses of face milling. Because f is varied during cutting.

3.2. Equivalent Chip Thickness Idea and its Derivation in Face Milling

All energy, which is required to remove excess metal from a given surface, is converted into heat, mostly in frictional heat and in shear plane (67). The sum of energy in a metal cutting process is expanded in several forms listed below:

a) Shear energy alone the shear plane.

b) Friction energy among chip, tool and workpiece.

c) Surface energy due to the formation of a new surface area.

d) Momentum energy.

The temperature at a specific point on the tool can be determined in terms of the quantity of heat generated during cutting and the quantity of heat taken out of the specific point. Every temperature can be related to a particular value of wear on the tool. Referring to face milling, Kuljanic (8) stated that the heat generated rate Q_z can be determined as follows:

$$Q_z = K_s.A.V.z \qquad (49)$$

where K_s is specific cutting pressure, A is chip cross-sectional area, V is speed of face milling cutter and z is number of teeth in face milling cutter.

The heat generated is transfered to chips removed, the tool, the workpiece, the surrounding air by radiation, convection and to cooling fluid if it is used. Woxen (21) assumed that the heat is chiefly carried to the workpiece because of a low heat conducting coefficient and the cross-section of the tool being relatively small, the difference in mean temperature between the nose of the tool and the workpiece greater than between the nose of the tool and chip, the surrounding air and cooling fluid which carry off heat indirectly chiefly from the workpiece and a large volume of the workpiece in relation to chip. Woxen (21) stated that the contact surface between the tool and the workpiece is a measure of the heat carried off. He first proposed the engaged cutting-edge of tool to constitute a measure for the contact surface and in doing so for the heat transport in turning. Woxen showed that in turning actual area of cut $A = s.d.$ (where s is feed and d is depth of cut) is a measure of the heat quantity generated with cutting speed and the engaged cutting-edge length of the tool L is a measure of the heat quantity carried off by chip, tool and workpiece. The relation which is called the chip equivalent q was first used by Woxen(21) and it was expressed by the ratio of the engaged cutting-edge length of the tool L to the area of cut A in turning as seen in Figure (11).

$$q = \frac{L}{A} \qquad (50)$$

The reciprocal of q, which is called equivalent chip thickness h_e, was used by Barrow(13), Brewer and Rueda(22) in turning.

$$h_e = \frac{1}{q} \qquad (51)$$

In this research the idea of equivalent chip thickness and its application, which have not been searched yet in face milling, will be used in order to investigate face milling processes.

Because dimensionally equivalent chip thickness is easier to understand and it can play a useful part in helping researchers to a deeper appreciation of face milling rather than feed f itself, because of the variation of f during cutting. Two different face milling cutter, the Walter cutter and Sandvik cutter (with their indexable right hand P25 grade throwaway inserts) which are widely used in industry, were used throughout this project. The angles for both Walter cutter and Sandvik cutter are shown in Figure (12), Figure (13) respectively.

By using the idea of equivalent chip thickness, in face milling two quantities are considered; area, which is a measure of the heat quantity generated with cutting speed, is calculated as characteristic cross-section area of cut Because the heat is generated while one tooth or more teeth pass across the width of workpiece W depending upon the set-up. Therefore characteristic cross-section area of cut is taken into account as a measure of the heat generated with cutting speed. Length, which is a measure of the heat generated carried out by chip, tool and workpiece, is calculated as cutting-edge of one tooth of the cutter engaged with the workpiece. Because cutting-edge of each tooth of the cutter engaged with the workpiece has the same value while the cutter pass across the width of workpiece W.

Equivalent chip thickness is the ratio of these two quantities mentioned above.

Two situations are developed; one is for Walter cutter, the other is for Sandvik cutter.

3.2.1. Derivation of an Equivalent Chip Thickness Expression for the Walter Cutter in Face Milling.

Characteristic cross-section area of cut A_W for Walter cutter is calculated from the ratio of metal removal rate MR to cutting speed as follows:

$$A_W = \frac{MR}{V_W} \qquad (52)$$

Metal removal rate is also calculated from either the equation (31) or the equation (47) obtained in section 3.1. For the simplicity the equation (31) is used. Hence A_W is written as follows:

$$A_W = \frac{W.d.F.}{V_W} \qquad (53)$$

or
$$A_w = \frac{W.d.f.z}{D_w} \qquad (54)$$

Where W is the width of the workpiece, d is the depth of cut, f is feed per tooth, z is the number of teeth and D_w is nominal diameter of the cutter as shown in Figure (12). The cutting edge of tooth engaged with the workpiece L_w is written using the tool geometry parameters as shown in Figure (12), in the following:

$$L_w = l_w + \frac{d}{\text{Sin } \theta_w . \text{ Cos } \delta_w} \qquad (55)$$

where l_w is the horizontal length of insert, θ_w is the approach angle, δ_w is the positive axial rake angle, d is the depth of cut. The values are: l_w = 1mm, $\theta_w = 42^\circ$, $\delta_w = +8^\circ$. These values were taken from one of Walter Current Technical Informations (68) and were checked under the Nikon Shadow projector in the Metrology Laboratory of the Production Engineering Department of the University of Aston.

Hence in face milling the equivalent chip thickness h_w for the Walter Cutter can be written as follows:

$$h_w = \frac{A_w}{L_w} \qquad (56)$$

$$h_w = \frac{W.d.f.z/\pi D_w}{l_w + \frac{d}{\text{Sin}\theta_w . \text{ Cos } \delta_w}} \qquad (57)$$

As can be seen from equation (57) the effects of seven geometrical parameters and machining variables, W, f, z, D_w , l_w , θ_w , and δ_w on h_w are significant. If the values of W, f, z and θ_w are increased, h_w will be increased. If D_w , l_w , δ_w are increased, h_w will be decreased. The effect of d on h_w is not very significant. Only big variations in d will affect on h_w. The equation (56) is valid for all types of face milling. The value of h_w is not related to cutting speed.

3.2.2. Derivation of an Equivalent Chip Thickness Expression for the Sandvik Cutter in Face Milling

Characteristic cross-section area of cut A_s for Sandvik Cutter is calculated from the ratio of metal removal rate MR to cutting speed as follows:

$$A_s = \frac{MR}{V_s} \qquad (58)$$

$$A_s = \frac{W.d.f.z}{\pi .D_s} \qquad (59)$$

D_s is the nominal diameter of the cutter as shown in Figure (13). These two formulas are not the same (formulas (54) and (59)), because diameters of cutters are not the same value.

Two situations can arise according to cutting-edge of tooth engaging the workpiece as seen in Figure (13).

a) $$d < l_a \qquad (60)$$

where d is depth of cut, l_a is vertical length as seen in Figure (13). In this situation engaged cutting-edge of tooth L_{s1} can be expressed by:

$$L_{s1} = l_s + \frac{\left(l_\theta + \frac{d}{\text{Sin}\phi} - l_\theta \cdot \frac{\text{Sin}\,\theta_s}{\text{Sin}\,\phi}\right)}{\text{Cos}\,\delta_s} \qquad (61)$$

where l_s and l_θ are the length of tooth, θ_s and ϕ are the angles of corners, δ_s is the negative axial rake angle. These values were taken from the Sandvik Catalogue$^{(69)}$ and also were checked under the Nikon Shadow Projector in the Metrology laboratory of the Production Engineering Department.

The values are: $l_s = 1.4$ mm, $l_\theta = 1$ mm, $\theta_s = 30^\circ$, $\phi = 60^\circ$, $\delta_s = -7^\circ$

b) $$d > l_a \tag{62}$$

In this situation engaged cutting-edge of tooth can be written as;

$$L_{s2} = l_s + \frac{\left[l_\theta + l_\phi + \frac{d}{\mathrm{Sin}\lambda_s} - (l_\phi . \frac{\mathrm{Sin}\theta_s}{\mathrm{Sin}\ \phi}) \frac{\mathrm{Sin}\phi}{\mathrm{Sin}\lambda_s} \right]}{\mathrm{Cos}\ \delta_s}, \tag{63}$$

where l_ϕ is another length of tooth, λ_s is the approach angle as seen in Figure (13). The other values are $l_\phi = 1.4$ mm, $\lambda_s = 75^\circ$.

Hence the equivalent chip thickness h_{s1} for situation (a) can be written as:

$$h_{s1} = \frac{W.d.f.z/\pi.D_s}{l_s + \frac{\left(l_\theta + \frac{d}{\mathrm{Sin}\phi} - l_\theta . \frac{\mathrm{Sin}\ \theta_s}{\mathrm{Sin}\ \phi} \right)}{\mathrm{Cos}\ \delta_s}} \tag{64}$$

The equivalent chip thickness h_{s2} for situation (b) can be written as:

$$h_{s2} = \frac{W.d.f.z/\pi.D_s}{l_s + \frac{\left[l_\theta + l_\phi + \frac{d}{\mathrm{Sin}\lambda_s} - (l_\phi + l_\theta . \frac{\mathrm{Sin}\theta_s}{\mathrm{Sin}\phi}) \frac{\mathrm{Sin}\phi}{\mathrm{Sin}\lambda_s} \right]}{\mathrm{Cos}\ \delta_s}} \tag{65}$$

As can be seen from equation (64) and equation (65), the effects of eleven geometrical parameters and machining variables, W, f, z, D_s, l_s, l_θ, l_ϕ, θ_s, ϕ, λ_s, δ_s, on h_{s1} and h_{s2} are significant. If the values of W, f, z are increased h_w will be increased. When the values of l_s, l_θ, l_ϕ, δ_s are increased, h_{s1} and h_{s2} will be decreased. δ_s has a negative value but it does not effect on the result. The effect of d on h_{s1} and h_{s2} are not very significant. Only big variations in d will affect on h_{s1} and h_{s2}. The equations for h_{s1} and h_{s2} are valid for all types of face milling. The value of h_{s1} and h_{s2} are not related to cutting speed. The equivalent chip thickness formula takes into account all lengths of one insert engaged with the workpiece during cutting and cutting angles of inserts, machining variables (feed per tooth f and depth of cut d but not cutting speed V), cutter specifications (diameter, number of teeth z, and axial rake angle), and width of workpiece W. By using the equivalent chip thickness, the many independent variables, which determine the cutter life, are reduced to only two independent variables, namely, cutting speed and equivalent chip thicknesses. Feed per tooth itself, due to variation during face milling, cannot be one of the independent variables. It is obvious that in metal cutting tests when the number of independent variables is reduced big savings can be achieved both in the time consumed and in the number of workpieces required.

The equivalent chip thickness can also give useful information about the selection of inserts geometry, cutters and machining variables except cutting speed, which selection is among the duties of the Production Engineer.

3.3. Chipping Mechanism in Face Milling

Generally the chipping mechanism, which limits the use of brittle cutting tools like carbide and ceramic tools especially in interrupted cutting processes such as face milling, can easily occur because of the two reasons below: These two reasons can act either together or separetely.

a) Chipping, which can be the consequence of mechanical stresses produced by cutting force, can be related to entry conditions, when the contact point between the tool and the workpiece occur along the cutting edge of the tool even as soon as the cutting process starts. Cook (4) pointed out that chipping is not associated with any wear zone and can occur in brand new cutting tool.

b) Chipping can be the consequence of both mechanical and thermal stresses, after a certain cutting time, not only under severe cutting conditions but also under medium cutting conditions.

As it was mentioned in Chapter II, Kronenberg (5) made an analysis from the geometrical point of view of the initial contact point only along the length of the workpiece between the face milling cutter and the workpiece. Shinozaki (7) examined cracks, which are caused by both mechanical and thermal stresses, almost perpendicular to the cutting edge on both the rake face and the flank face from probabilistic point of view. The analysis of this part is mainly related to entry conditions. The equations derived by Kronenberg (5) used here are given below:

The intersection angly i' between rake face of tool and plan of engagement is given as follows:

$$tg\, i' = \frac{tg\,\delta \,.\, \text{Cos}\ r}{\text{Sin}\ (r-\varepsilon)} \qquad (66)$$

where δ is the axial rake angle, r is the radial angle and ε is the engagement angle which changes continuously according to set-up.

Slope of transient surface of metal being machined produced by approach angle of tool is given below:

$$\text{Slope of transient surface} = \frac{tg\ (\text{approach angle})}{\text{Cos}\,\varepsilon} \qquad (67)$$

Using the value of i' and the value of slope of transient surface, the location of initial contact point can be determined, according to the engagement plane described, cutter angles and machining variables. When initial contact point is not on the cutting edge or edges of the tool used, chipping cannot occur, but if initial contact point is on the cutting edge or edges, chipping can occur.

3.4. Definition of Face Milling Cutter life

Face milling cutter life is defined as the time between two replacement operations or two regrinding operations of all teeth in the cutter.

This is the total time, which is obtained by adding the cutting times that are spent to cut the individual workpieces until the below-mentioned criterion occurs. In this research two different criteria are used, namely i) chipping of some of the teeth and ii) 0.635 mm (0.025in) arithmetic mean value of maximum widths of wears measured on the flank faces of all teeth. Which ever occurs first, it determines the end of cutter life. Chipping on cutting edges may occur first, especially when using carbide tools. When chipping on cutting edges of some teeth occur, the cutter may still cut the workpiece for a very short time; afterwards the number of cutting edges chipped increases rapidly and all teeth are replaced.

In this investigation, chipping takes place under different conditions especially up-cut face milling. According to the second criterion, when the aritmetic mean of the maximum widths of wears measured on the flank faces reaches the value 0.635 mm (0.025 in), all teeth are replaced. Only the aritmetic mean value can determine the concept of cutter wear, because the maximum width of flank wear varies from one tooth to another since all teeth are not in the same position even if they are checked by dial gauge before cutting begins. It is also assumed that each tooth of a cutter cuts an equal chip, a condition unlikely to occur in practice.

The cutting time of one pass, t, is given by the ratio of the length to cut the given material, to the feed rate or table speed F, as seen in Figure (14):

$$t = \frac{1}{F} \tag{68}$$

3.4.1. Cutter Life Relationship in Face Milling

Cutter life is only expressed as a function of the cutting speed and of the equivalent chip thickness in this research.

After experimental results, cutter life as the dependent variable, cutting speed and equivalent chip thickness as the independent variables are taken, and the relationship among these variables is established to obtain the proposed equation. In this research two different types of cutter life equations are predicted, the coefficients of the independent variables are calculated, the adequacy of the predicted model is checked and the confidence intervals, within the certain percentage, are determined.

3.4.1a) The first proposed model of cutter life is the logaritmic form of the Konig-Depiereux type equation$^{(27)}$:

$$\hat{y} = \dot{T}\ln T = b_o + b_1 V^{\alpha_1} + b_2 h_f^{\alpha_2} \tag{69}$$

where $\hat{y}$ is the predicted value of cutter life on a logaritmic scale, V is the cutting speed, h_f is the equivalent chip thickness (for the Walter Cutter and Sandvik Cutter, h_f is taken into account as h_w and h_s respectively), α_1 and α_2 are the power parameters, and b_o, b_1 and b_2 are the least-squares estimates. The uncertainty of the least-squares estimates b_o, b_1 and b_2 as indicated by certain percent confidence intervals.

The coefficients b_o, b_1, b_2 in the equation (69) are estimated by the method of least squares as:

$$B = (XT.X)^{-1}XT.y \tag{70}$$

where B is the vector of the values of b_o, b_1 and b_2, X is the matrix of independent variables, XT is the transpose of X, $(XT.X)^{-1}$ is the inverse of (XT.X), y is the vector of observed cutter life, i.e., $y = \dot{T}.\ell nT$,

where $\dot{T}$ is the geometric mean value of the observed cutter lives. The residual sum of squares (R.S.S.) is calculated as the numerical criterion to determine the best fit of the cutter life model:

$$R.S.S. = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{71}$$

where y_i is the i^{th} observed value of cutter life, $\hat{y}_i$ is the i^{th} predicted value of cutter life, n_o is the number of observations.

The experimental error is estimated by the error variance S^2;

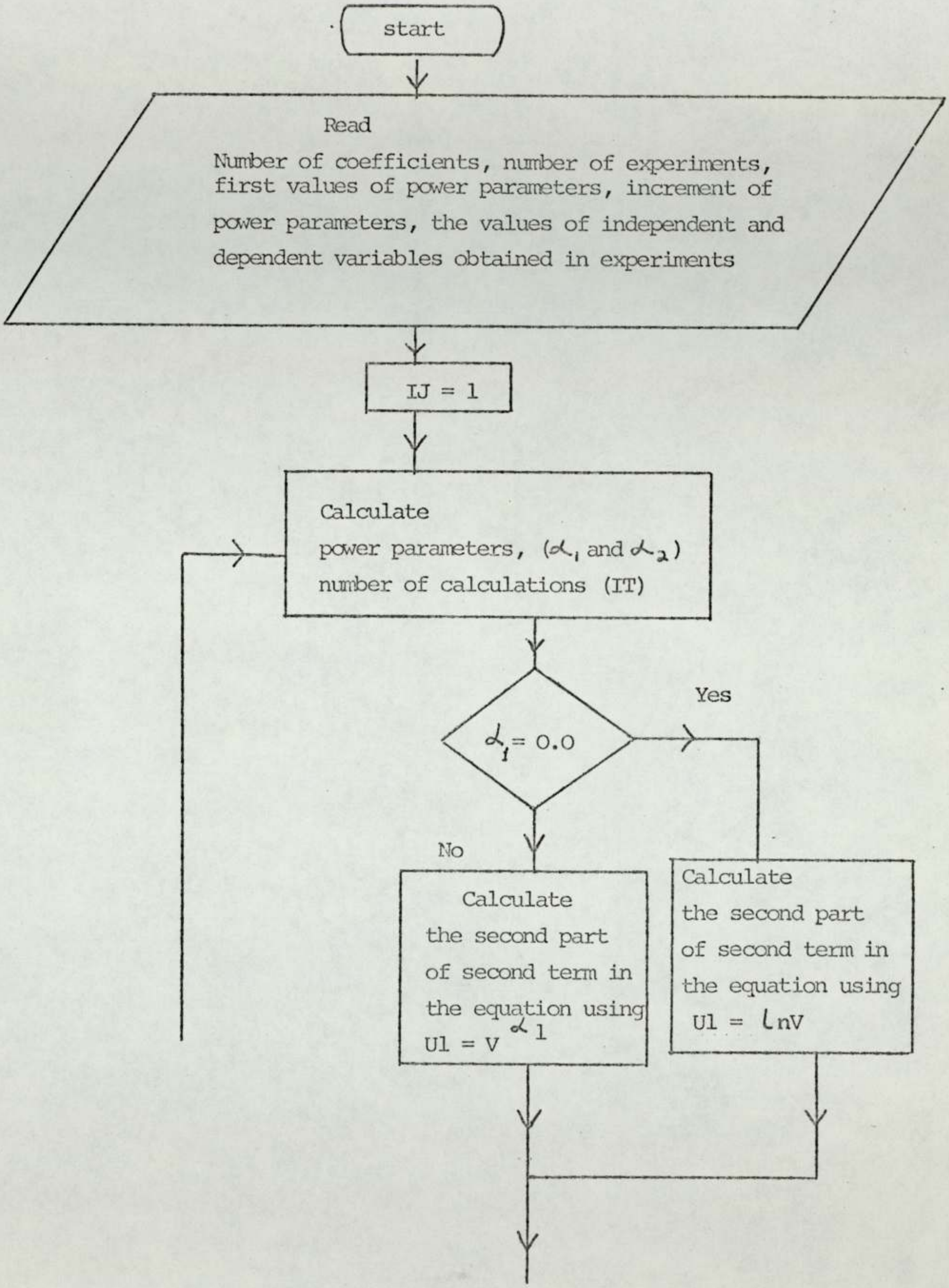
$$S^2 = \frac{R.S.S.}{n_o - p} \tag{72}$$

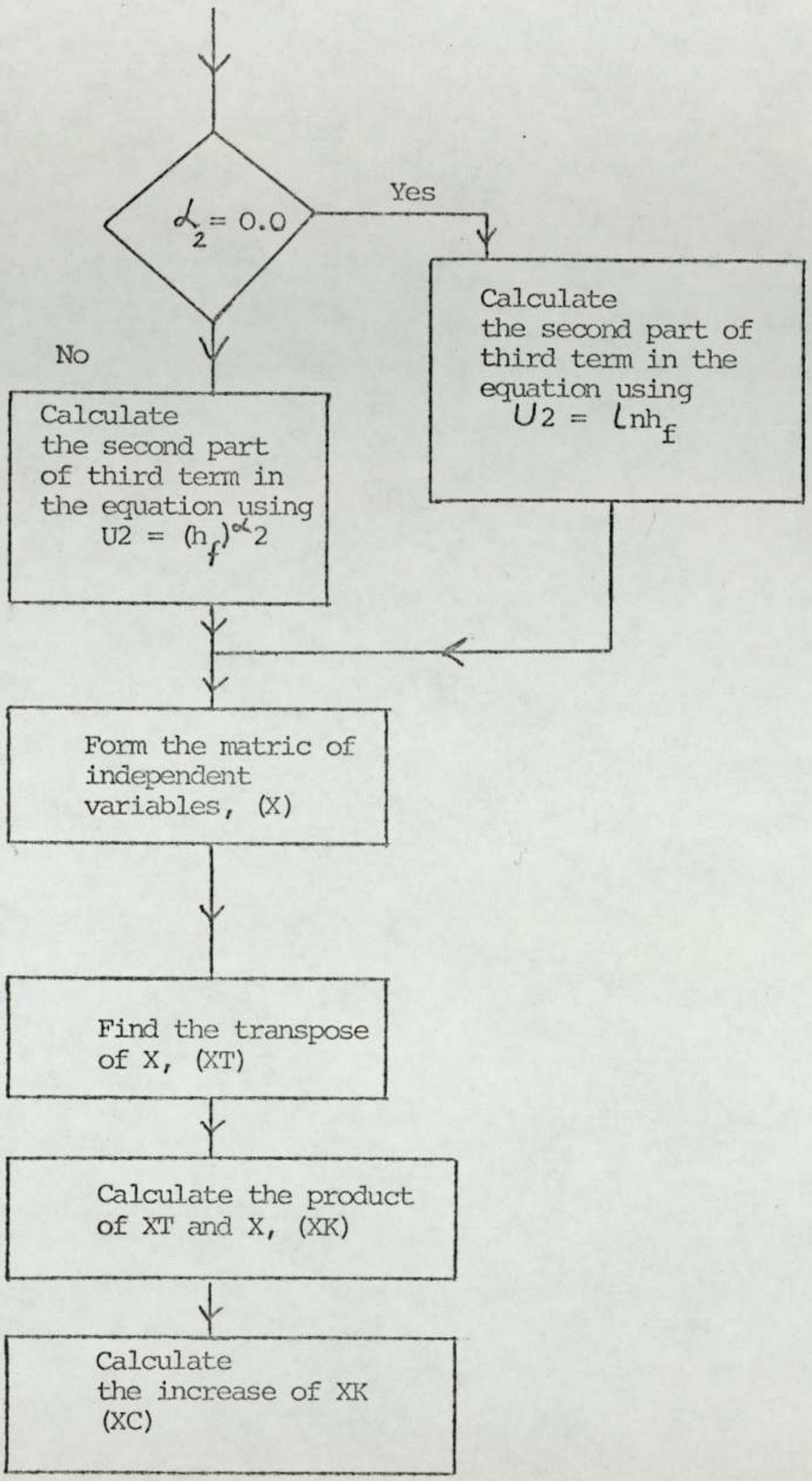
where p is the number of coefficients. The confidence interval (CI) for any coefficients b_i, under the assumption of spherical normality, is given by;

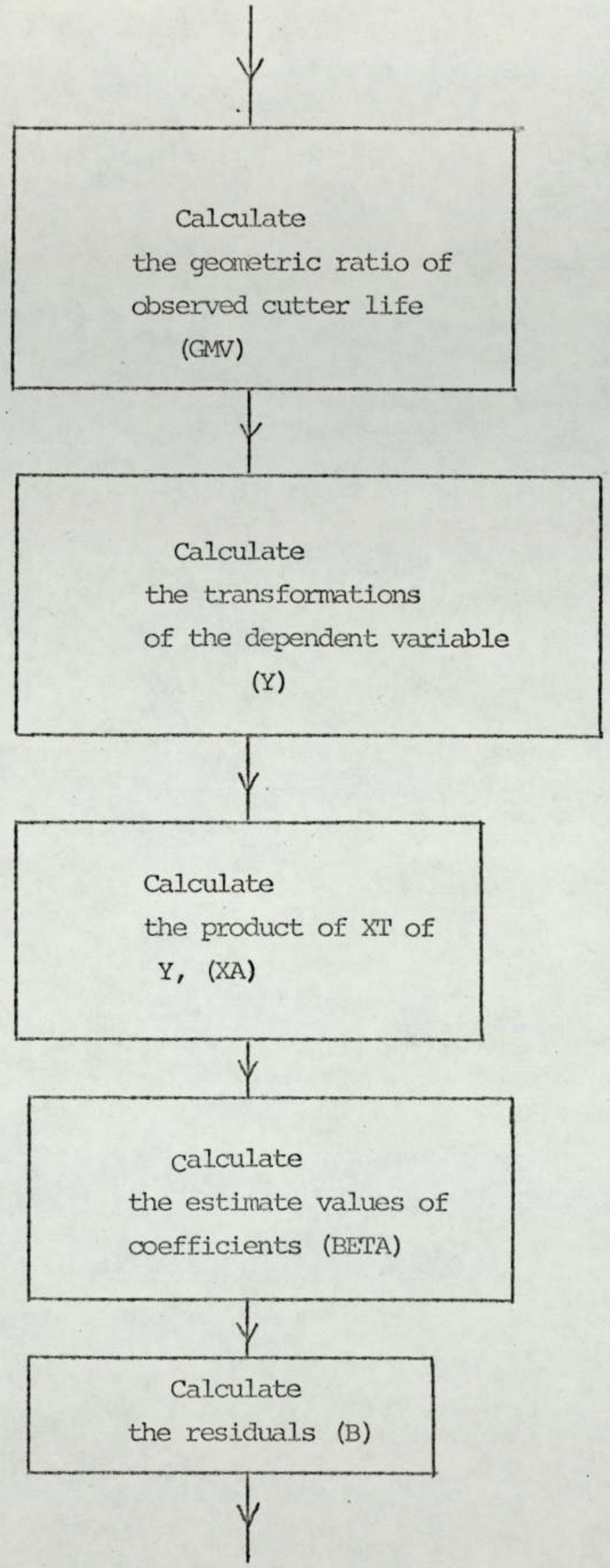
$$CI(b_i) = b_i \pm t_{v;\xi/2} \cdot \sqrt{S^2 . d_{ii}} \tag{73}$$

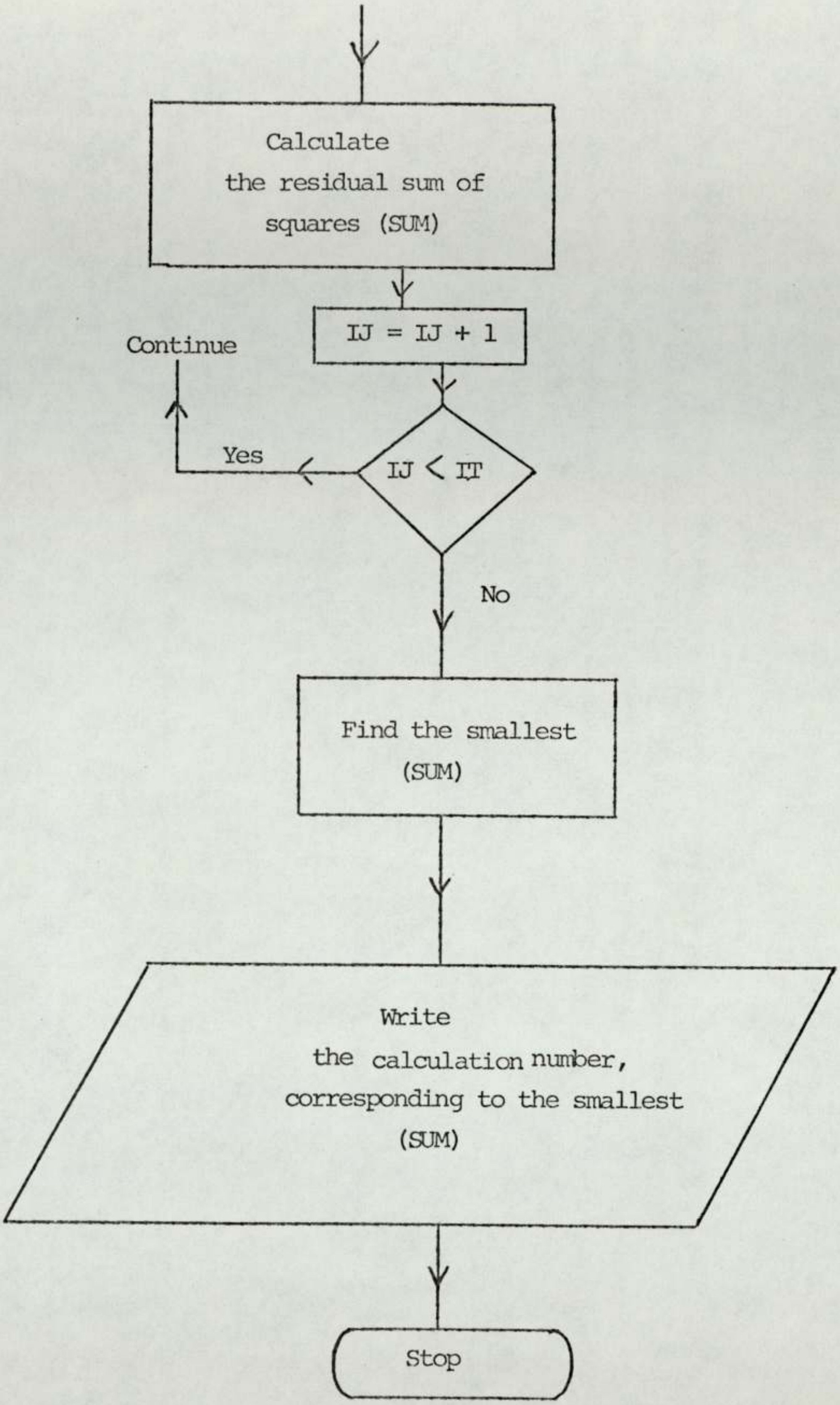
where $t_{v;\xi/2}$ is the Student's t-distribution (with v the degree of freedom and ξ the level of significance), and d_{ii} is the element of the i^{th} row and i^{th} column of the inverse of (XT.X).

The computer program was written to calculate the coefficients of the first proposed cutter life equation (69). The flow chart of the program is given below:


start
Read
Number of coefficients, number of experiments, first values of power parameters, increment of power parameters, the values of independent and dependent variables obtained in experiments
IJ = 1
Calculate
power parameters, (α_1 and α_2)
number of calculations (IT)
$\alpha_1 = 0.0$
Yes
No
Calculate
the second part of second term in the equation using
$U1 = V^{\alpha 1}$
Calculate
the second part of second term in the equation using
$U1 = \ln V$


$\alpha_2 = 0.0$
Yes
No
Calculate the second part of third term in the equation using $U2 = \ln h_f$
Calculate the second part of third term in the equation using $U2 = (h_f)^{\alpha_2}$
Form the matric of independent variables, (X)
Find the transpose of X, (XT)
Calculate the product of XT and X, (XK)
Calculate the increase of XK (XC)


Calculate the geometric ratio of observed cutter life (GMV)
Calculate the transformations of the dependent variable (Y)
Calculate the product of XT of Y, (XA)
Calculate the estimate values of coefficients (BETA)
Calculate the residuals (B)


Calculate the residual sum of squares (SUM)
IJ = IJ + 1
Continue
Yes
IJ < IT
No
Find the smallest (SUM)
Write the calculation number, corresponding to the smallest (SUM)
Stop

When $\alpha_1 = 0$ and $\alpha_2 = 0$, the equation is written;

$$\dot{T}\,\ell nT = b_o + b_1\,\ell nV = B_2\,\ell nh_f \qquad (74)$$

This is a logaritmic transformation which is similar to Taylor's type of tool-life equation.

The computer programme can also give the comparison between the linear logaritmic transformation and any other transformation in term of R.S.S.

3.4.1b) The Second proposed model of cutter life is the second-order equation in a logarithmic form;

$$\ln T = b_o + b_1 \ln V + b_2 \ln h_f + b_3\,(\ln V)^2 + b_4\,(\ln h_f)^2 + b_5\,\ln V.\ln h_f \qquad (75)$$

where T is the predicted value of cutter life on a logarithmic scale, V is the cutting speed on a logarithmic scale, h_f is the equivalent chip thickness on a logarithmic scale (for the Walter Cutter, $h_f = h_w$, for the Sandvik Cutter, $h_f = h_s$) and b_o, b_1, b_2, b_3, b_4 and b_5 are the least-squares estimated coefficients. To calculate the coefficients, statistical package (34) was used.

3.5. Power Relationships in Face Milling

In face milling, the power required (in H.P) at the cutter can be given, when one or more than one tooth is engaged with the workpiece, by the expression:

$$H.P = \frac{\sum F_t.V}{4500} \qquad (76)$$

where $\sum F_t$ is the total tangential force (in kg) and V is the cutting speed (in $\frac{m}{min}$).

When only one tooth is engaged with the workpiece, the value of F_t is given by Koeningsberger$^{(35)}$ as:

$$F_t = k_s.d.h^p \tag{77}$$

where k_s is the specific cutting pressure, d is the depth of cut, h is the instantaneous value of the radial chip thickness, and the value of p lies between 0.75 and 0.9. For instance, in up-cut milling, h can be given by equation (33) as;

$$h = f.\ \mathrm{Sin}\,\phi$$

Hence $F_t = k_s.d.(f.\mathrm{Sin}\,\phi)^p$ (78)

The maximum value of F_t, $F_{t\ max}$, occurs when $\phi = 90^o$.

$$F_{t\ max} = k_s.d.f^p \tag{79}$$

The ratio of $\frac{F_t}{F_{t\ max}}$ is written as;

$$\frac{F_t}{F_{t\ max}} = (\mathrm{Sin}\,\phi)^p \tag{80}$$

Power, P, may be written as;

$$P = k_s.d.(f.\mathrm{Sin}\,\phi)^p.V \tag{81}$$

The value of P is changed according to the value of ϕ under one cutting condition.

In this research, average total tangential force ΣF_t is proposed as follows:

$$Ft = K_s.d.h_m.\frac{\varphi_e}{\varphi_z} \qquad (82)$$

or

$$Ft = K_s.d.f_c \qquad (83)$$

where h_m is the mean value of the undeformed chip thickness as calculated equation (35), φ_e is the engagement angle, and φ_z is the angle between any two teeth as calculated equation (32).

Hence power required at the cutter can be given as

$$P = k_s.A_c.V \qquad (84)$$

or

$$P = k_s.MR \qquad (85)$$

k_s can be changed with the equivalent chip thickness.

3.6. Surface Finish Relationship in Face Milling

Surface finish obtained can be expressed in terms of different measurements taken. In this research,(C.L.A.) index is taken as a measurement of surface finish in order to compare surface profiles obtained in different cutting tests. In any machining process, it is known that feed is an important independent variable on surface finish. In some situations, cutting speed may be the other independent variable like in face milling, because surface finish is produced when the cutter across all over workpiece. Surface finish model is proposed as:

$$S.F = K_1.V^{k_2}.f^{k_3} \qquad (86)$$

or when logarithms of both sides are taken, the following expression is written;

$$\ln S.F = \ln K_1 + K_2 . \ln V + K_3 . \ln F \qquad (87)$$

$\ln K_1$, K_2 and K_3 are calculated using the method of least squares.

3.7. Vibrations Relationships in Face Milling

Vibrations, in milling process, may occur due to a number of causes (70). Mainly two reasons can be recognized.

a) Vibrations due to the geometry of milling process,

b) Self excited vibrations. Vibrations due to the geometry of process are known as forced vibrations. Those may come out from two main reasons in face milling.

ai) Variation of the chip thickness, because cutting force F_t is changed with the chip thickness as given in equation (78).

aii) Impact due to interrupted cutting.

b) Self-excited vibrations.

Chip removing machine tools belong to a group of dynamical systems in which a slight disturbance of the steady-state motion may generate internal forces which depend on the velocity of the disturbance. Cutter and workpiece perform a relative motion, then the cutting system becomes dynamically unstable (70). That is called Chatter which can be detected either by its noise or surface finish marks.

In this research, vibrations generated are considered as forced vibrations. Chatter marks on any surface finish produced that have not been observed. Peak-to-peak amplitude of vibrations in feed and axial directions in down-cut milling, in feed and tangential directions in up-cut milling are taken into account rather than frequencies of vibrations.

The maximum peak-to-peak vibration amplitude model is proposed by the following expression.

$$\mathrm{VIB.AMP} = D_1 . V^{D_2} . (s_{max})^{D_3} \qquad (88)$$

where S max is the maximum area being cut, S max = d.f.

When logarithms of both sides are taken, the following expression is written;

$$\ln \mathrm{VIB.AMP} = \ln D_1 + D_2 . \ln V + D_3 . \ln s_{max} \qquad (89)$$

Ln, D_1, D_2 and D_3 are estimated using the least-squares method.

3.8. Economics of Face Milling

Generally in metal cutting field, producing a batch of components to the acceptable dimensional accuracy and surface finish is to make decisions the right choice of machine tool among available machine tools, cutting tools, method of the process, the use of cutting fluid, machining conditions such as cutting speed, feed and depth of cut. The approaches, to make such decisions have been known as economics of machining, can be achieved in two ways. One is a mathematical solution, the other is a graphical solution. In some cases mathematical solution can be much more suitable when cost, time information as well as sufficiently accurate tool-life data are available about the process. In some cases graphical and mathematical solutions together can give a reliable answer in machine shop practice.

The concept of T-MR characteristic functions can give another application to machining economics (59), (60). At any given constant tool-life value, it is possible to obtain several different metal removal rates, depending on the combination of its variables and vice versa.

In this research, more or less the same cutter life results were obtained in the validity tests of equivalent chip thicknesses both using Sandvik cutter and Walter cutter. But metal removal rates were different (Test No. 6 and 7 - using Walter cutter in down-cut milling. Test No. 5 and 6 - using Sandvik cutter in down-cut milling). It was proved that the T -MR characteristic function could give the best possible combinations of metal removal rates and tool life$^{(59)}$.

3.8.1. Unit-time model

In face milling, the total time to produce per piece, Tp, can be written as;

$$T_p = T_{LU} + T_{set\text{-}up} + T_{ar} + K.\frac{MV}{MR} + K.\frac{MV}{MR}\cdot\frac{T_r}{T} \qquad (90)$$

where T_{LU} is loading and unloading time, $T_{set\text{-}up}$ is set-up time, T_{ar} is approach and returning time of the cutter. These three times are independents from machining variables. It is also very difficult to give their exact values in machine shop practice. Their values partially depend upon the behaviour of the operator which uses the machine tool. Their controls can be possible either in bonus production system or using the robot. The total of $(T_{LU} + T_{set\text{-}up} + T_{ar})$ is simplified as T_1. MV is the volume of the metal to be removed, MR is the metal removal rate, K is the constant coefficient which is determined by the position of the cutter relative to the workpiece as seen in Figure (14).

$$K = \frac{l}{l_p} \qquad (91)$$

where l is the length which can be calculated using the geometry of cutting, l_p is the length of the workpiece being cut.

By introducing K, MR is considered as unique variable during cutting. T_r is the replacement time for all teeth. T is the cutter life.

$$T_p = T_1 = K.MV \quad (\frac{T + T_r}{MR.T}) \qquad (92)$$

T_1, K, MV and Tr are independent values from machining variables. To obtain extreme values of T_p in terms of machining variables, $F_1 = \frac{MR.T}{T+T_r}$ function, which is the reciprocal of the part of the second term in equation (92), should be searched. For the minimum value of T_p, the function F_1 should reach the maximum value. F_1 is a function of MR and T.

$$F_1 = F_1(MR, T) \qquad (93)$$

It may be possible to obtain the characteristic function, T = T(MR), which is the best combination of metal removal rates and cutter life values (59).

For the existence of T-MR characteristic function, in the other words, to obtain the function T = T(MR), their Jacobian should vanish (71) as follows:

$$J = \frac{\partial (MR,T)}{\partial (V,h_f)} = \begin{vmatrix} \frac{\partial MR}{\partial V} & \frac{\partial MR}{\partial h_f} \\ \frac{\partial T}{\partial V} & \frac{\partial T}{h_f} \end{vmatrix} = 0 \qquad (94)$$

MR can be expressed by a function of d, h_f and V as seen in equations (57), (64) and (65).

$$MR = MR(d, V, h_f) \qquad (95)$$

In this expression d can be taken into account as one chosen parameter depending upon the maximum available cutting force, horsepower and test results obtained. Therefore, MR can be written as;

$$MR = MR(V, h_f) \qquad (96)$$

Cutter life T can also be expressed in a function of V and h_f;

$$T = T(V, h_f) \qquad (97)$$

Using equation (94), T = T(MR) can be obtained. For the maximum value of F_1, the first derivation of F_1, $\frac{dF_1}{dMR}$ should vanish.

$$\frac{dF_1}{dMR} = \frac{T}{T+T_r} + MR \frac{T_r}{(T+T_r)^2} \cdot \frac{dT}{dMR} = 0 \qquad (98)$$

or

$$T(T + T_r) + MR.T_r. \frac{dT}{dMR} = 0 \qquad (99)$$

Hence optimum cutter life T and metal removal rate MR can be obtained.

3.8.2. Unit-cost model.

In face milling, the total cost to produce per piece C can be written as follows;

$$C = Co.T_1 + Co.K. \frac{MV}{MR} + Co.K. \frac{MV}{MR}. \frac{T_r}{T} + Y.K. \frac{MV}{MR} \cdot \frac{1}{T} \qquad (100)$$

where Co is the operator and overhead cost per unit time, Y is the total cost of cutting edges of the cutter

or $$C = Co.T_1 + Co.K. \frac{MV}{MR} \left(1 + \frac{T_r + Y/Co}{T}\right) \qquad (101)$$

Co, T_1, K, MV, Tr and Y are independent values from machining variables. To obtain the extreme values of C, the function $F_2 = \frac{MR.T}{T + Tr + Y/Co}$ should be searched. For the minimum value of C, the function F_2 should reach the maximum value. The functions F_1 and F_2 are similar functions except the term (Y/Co). By following the similar procedure as unit-time model the first derivation of F_2 to MR should be zero.

$$\frac{dF_2}{dMR} = \frac{T}{T + Tr + Y/Co} + MR \frac{(Tr + Y/Co)}{(T + Tr + Y/Co)^2} \cdot \frac{dT}{dMR} = 0$$

or

$$T(T + Tr + Y/Co) + MR(Tr + Y/Co) . \frac{dT}{dMR} = 0 \qquad (102)$$

The optimum cutter life T and metal removal rate for the minimum value of C can be determined.

3.8.3. Profit-Rate.

The profit per unit time, Pr, can be written in face milling as;

$$Pr = \frac{S - C}{T_p} \qquad (103)$$

where S is the selling price per piece, C is the cost per piece, T_p is the time to produce the piece. The equation (103) is also a function of C and T_p, therefore only of MR and T. But the value of S is not always the fixed value.

In this research C and T_p will be considered in order to obtain optimum machining variables.

CHAPTER IV

Experimental Equipment, Workpiece Materials, plan of Experimental Work Technique and Procedure

4.1. Experimental Equipment

4.1.1. The Machine Tool

The conventional horizontal Knee-type milling machine manufactured by Cincinnati, which has been used for teaching purposes and research work for some years in the Production Department, was used in this project in such a manner to achieve face milling processes. It was coupled with 15 H.P electric motor. Additional balancing or flywheel mass was constructed on the milling spindle in order to reduce torsional vibrations. The machine tool was attached to the calibrated meter which reads directly horsepower consumption up to 20 H.P. and the tachometer which shows a number of revolution of the spindle per minute up to 2000 r/min. Before the research was started, the tachometer readings were checked with another tachometer during cutting. It was noticed that the actual readings were not corresponding to the numbers written on the machine tool. The table speeds or feed rates were calculated using three methods : Firstly X-Y plotter; secondly stopwatch; and finally time counter in order to measure times for the fixed distances during cutting. It was also found that actual table speeds or feed rates calculated did not correspond with the numbers written on the machine tool.

Actual number of revolutions per minute N used in the research, followed a very close geometric progression. They are given below (in r/min);

198, 238, 300, 378, 460, 580, 680, 860

Actual table speeds or feed rates F used in the research also followed a very close geometric progression. They are given below (in m/min):

0.356, 0.447, 0.559, 0.686, 0.864, 1.092, 1.354, 1.666

The machine tool was stopped from time to to time to obtain necessary measurements. According to up-cut or down-cut face milling backlash eliminator was adjusted at each time to eliminate the backlash in the screw and nut assembly of the table. General view of the machine tool with the equipment are shown in Figure (15).

4.1.2. The set-up

Each workpiece being machined was mounted on the big plain block and clamped using screws in such a manner to simulate a vice and to ensure enough rigidity. The view of the set-up is seen in Figure (16).

4.1.3. The Cutters

Throughout the research two different cutters with their indexable throwaway inserts were used. Both were medium grades P25, and recommended for light and rough machining of steels. They were mounted on the horizontal plain knee-type milline machine by means of arbors.

i) The Walter milling cutter, type Wendelnovex F244, nominal diameter D_W = 101.6 mm, with 8 indexable inserts, grade P25, axial rake angle $\delta_W = +8^o$, the approach angle $\theta_W = 42^o$, radial rake angle = -16^o, face relief angle = 5^o.

The geometry of the cutter and one of the inserts is shown in Figure (12). General view of this cutter with one workpiece and the top view of one of the inserts are shown in Figure (17) and in Figure (18) respectively.

ii) The Sandvik milling cutter, type T-Max 265.1 , nominal diameter D_s = 100 mm, with 8 indexable inserts, grade P25, axial rake angle $\delta_s = -7^{\circ}$, the approach angle $\lambda_s = 75^{\circ}$, radial rake angle = -5°, face relief angle = 5°, the geometry of the cutter and one of the inserts is shown in Figure (13) General view of this cutter, one workpiece and the top view of one of the inserts are seen in Figure (19) and in Figure (20) respectively.

4.1.4. Wear Measurements

The travelling microscope, which has a magnification of times 5, was mounted and adjusted on the table of the milling machine in order to measure maximum flank wear $V_{B\ max}$ on the flank face of each tooth of a cutter. The microscope is seen in Figure (16). From time to time cutting process was stopped. When the clear wear picture of each tooth was observed through the microscope with the aid of electric light, the measurement of $V_{B\ max}$ was taken. For each situation, eight measurements were recorded, because of eight teeth on a cutter used. Then arithmetic mean value of eight measurements was obtained with the corresponding cutting time in order to determine wear-cutting time progress. The cutter life criterion, which was used in this investigation, was either 0.635 mm (0.025 in) arithmetic mean value of maximum flank wears or chipping of some teeth and which ever occurs first, it takes into account.

4.1.5. Power Measurements

The calibrated meter was already attached to the milling machine in order to measure directly idle power and power consumed during cutting in unit of horse power. According to wear progress with cutting time, horse power readings were taken and recorded when two teeth were engaged with the workpiece. The meter is seen in Figure (16).

4.1.6. Surface Finish Measurements

Talysurf device was used to measure average surface roughness (C.L.A) of the surface finish produced. A pointed stylus detected the surface for a fixed distance, then centre line average meter indicated (C.L.A) readings according to cutting conditions. It is shown in Figure (21).

From time to time the graph of the surface was obtained from the graph recorder. The Talylin device was also used to measure the waviness of the surface.

4.1.7. Vibration Measurements

Two identical vibration analysers with their magnetic pick-ups were used in order to measure peak-to-peak vibration amplitutes and frequencies in two different directions when two teeth were engaged with the workpiece under cutting conditions. By using the storage oscilloscope, vibration photographs were taken. The positions of vibration pick-ups is shown in Figure (16).

4.1.8. Workpiece Materials

Two different types of tool steel, which were provided by GKN Ltd., were tested. The company uses these types of materials in its production. Their compositions are given below:

i) Tool steel (B.H.N. 238)

C	1.69%
Si	0.29%

Mn	0.12%
Cr	11.82%
V	0.14%
Mo	0.65%

The mean value of Brinnel hardness number is 238. Materials were annealed. Widths of workpieces were varied according to cutting conditions between 25.4 mm and 46 mm, lengths were between 150 mm and 200 mm and heights were between 40 mm and 90 mm.

ii) Tool Steel (B.H.N.197)

C	1.53%
Si	0.35%
Mn	0.25%
Cr	11.91%
V	0.17%
Mo	0.75%

The mean value of Brinnel hardness number (B.H.N.) is 197. Materials were annealed. Widths of workpieces were varied according to cutting conditions between 37 mm and 44 mm, lengths were between 150 mm and 200 mm and heights were 90 mm.

4.2. Plan of Experimental Works

As it was mentioned before there is little published machinability data available on face milling processes. Limited knowledge in the range of cutting speed V, feed per tooth f, depth of cut d exists.

Using carbide tools in face milling, the range of cutter life T, horse-power required, surface finish produced, vibration, which are normally dependent variables, did not exist. There was also lack of knowledge in literature about equivalent chip thickness,which is a function of geometrical parameters of one of the inserts and machining variables, f, d except V, is used as one independent variable in this investigation in order to obtain machinability data. Also the range of equivalent chip thicknesses used was unknown. In this research in investigation of each machining response and its mathematical form as less as possible, the number of independent variables are used. That achievement reduces experimental time consumed as well as a number of workpieces required in order to obtain machinability data.

4.2.1. Planning Cutter Life Tests

In the research, cutter life tests were planned and performanced using the Walter Cutter and the Sandvik Cutter, annealed Tool Steel materials B.H.N. 238 and B.H.N. 197 types in down-cut and up-cut face milling. Before planning cutter life tests, the working region, which can be thought around optimum cutting conditions, may be determined for cutter life, cutting speed and equivalent chip thickness. In this research a typical domain for cutter life was considered between 10 and 70 minutes. This procedure identifies the working region in the cutter life domain but it doesn't determine the ranges in the cutting conditions domain (as cutting speed and equivalent chip thickness). A convenient criterion, which can be used for identification of cutting conditions domain in face milling, can be metal removal rate MR, provided W is constant. High level MR is always desirable until power limitation is taken into account.

Because there is a relationship between MR to be cut and power required at the cutter. In this research two types of face milling were planned and tested namely down-cut and up-cut milling. All tests were conducted dry. Central face milling was performed under cutting speed of 182.21 m/min and equivalent chip thickness of 0.133 mm. Two teeth of the cutter were chipped at the 0.412 mm average maximum flank wear which was lower than the chosen cutter life criterion of 0.635 mm. In this research the linear distance between any two teeth for both cutters was bigger than the width of the workpiece being machined in most cases. At least one tooth was always engaged with the workpiece in any type of milling. Generally carbide tools are particularly weak under thermal stress. The characteristic repetitions of heating and cooling of one tooth during one rotation of the cutter are important. These repetitions should be balanced, especially the width of workpieces is small like width of workpieces used in this research. When down-cut or up-cut milling were positioned, the contact time of any tooth with the workpiece was increased.

Therefore down-cut or up-cut milling can give longer cutter life when width of workpieces are small. Kronenberg(5) approached the problem from impact problem of view. He also tested five different face milling using the narrow workpiece (19 mm) in order to reduce tool wear due to cutting, in comparison with the wear due to impact. He found that both in up-cut and down-cut face milling, tool wear due to impact were smaller than tool wear in central milling.

4.2.1a. Planning of Cutter Life Tests for Annealed Tool Steel (mean B.H.N. 238) using Walter Cutter in down-cut milling

As it was mentioned before due to lack of knowledge in literature, two pilot tests were peformed at the beginning in order to plan cutting tests. Cutting conditions of first pilot test were chosen as follows, a number of revolution per minute N available on the machine tool was selected to be 198 r/min, it gave a cutting speed of 63.19 m/min. Feed rate or table speed F available on the machine tool was selected to be 0.356 m/min, the width of each workpiece W, which was sent by the company, was 25.4 mm (1 in), depth of cut d was chosen 2.54 mm (0.100in). Using the specification of Walter Cutter the value of equivalent chip thickness h_w was obtained to be 0.075 mm from the equation (57).

Cutter life was obtained to be 143.2 mins. That value was out of typical domain of cutter life and the value of MR was 22.968 cm^3/min. The cutting conditions of second pilot test was chosen as follows; a number of revolution per minute N available on the machine tool was selected to be 238 r/min which was higher than previous N. It gave a cutting speed of 75.96 m/min.

Feed rate F available on the machine tool was selected to be o.447 m/min which was higher than previous F. Depth of cut d was selected to be 1.52 mm which was lower than previous d. This time the value of equivalent chip thickness h_w was selected to be 0.116 mm which was as twice as previous h_w. Using the equation (57) the width of each workpiece was calculated to be 42.7 mm.

Cutter life for these cutting conditions was obtained to be 120.8 mins. That value was still out of typical domain of cutter life and the value of MR was 29.012 cm^3/min. It was decided to increase cutting speed V which meant to increase a number of revolutions N. The next value of N available on the machine tool was 300 r/min. It gave a cutting speed of 95.75 m/min.

According to the value of N, F was increased to the value of 0.559 m/min in order to keep the value of f at the same level as previous f.

This time the value of h_w was kept constant that was the value of 0.116 mm as the previous value. The value of W was selected to be 45.7 mm (1.8in) and depth of cut d was calculated to be 1.26 mm (0.050 in) from the equation (57). Using these cutting conditions, the cutter life was obtained to be 61.8mins which was in the typical domain of cutter life. Hence the lower limits of cutting speed and equivalent chip thicknesses were determined according to available material, machining variables and the cutter specifications. Under these cutting conditions the value of MR was calculated to be 32.188 cm^3/min.

Three more levels of cutting speeds were selected, according to the values of N available on the machine tool. One more level of h_w was chosen to be 0.143 mm, this being different to 0.116 mm the previous one.

After determining of the levels of both cutting speeds and equivalent chip thicknesses, two tests were conducted to prove the validity of equivalent chip thickness. For both tests the same low cutting speed and the same low equivalent chip thickness, which were 120.65 m/min and 0.116 mm respectively, were used provided W, f and d values were changed. On the first test W was chosen to be 38.1 mm, $d=2.79$ mm and $F=0.685$ m/min respectively.

On the second tests W was increased to 45.72 mm by 17% and d was decreased to 0.77 mm by 72% F was increased to 0.863 m/min by 21%. Metal removal rates were 72.81 cm^3/min and 30.38 cm^3/min respectively. Planning of cutting tests and cutter life results are shown in Table (1).

4.2.1b. Planning of Cutter Life Tests for Annealed Tool Steel (mean B.H.N. 238) Using the Sandvik Cutter in down-cut milling

At this time, planning of cutting tests became easier than previous planning of cutting tests because of experience obtained. Three levels of cutting speed V_s=118.75, 144.51 and 182.21 m/min and three levels of equivalent chip thicknesses h_s=0.083, 0.122 and 0.133 mm were selected according to available width of material and machining variables. Specially two values of equivalent chip thickness were chosen close to each other in order to compare cutter life test results which can also give idea about the validity of equivalent chip thickness. First cutting conditions were chosen as follows; a number of revolution per minute N available on the machine tool was selected to be 378 r/min, it gave a cutting speed of 118.75 m/min. Feed rate or table speed available on the machine tool was chosen to be 0.559 m/min, and d was selected to be 1.65 mm and available W was taken to be 40 mm. All these variables gave the value of 0.083 mm of the equivalent chip thickness using the equation (64). Cutter life value was obtained to be 51.6 min. This value was in the typical domain of cutter life.

Two tests were conducted to prove the validity of equivalent chip thicknesses at the same cutting speed of 144.51 m/min. and at the same equivalent chip thickness of 1.122 mm. To obtain this value of equivalent chip thickness from the equation (65), first cutting conditions were chosen as follows; W = 43.2 mm; F = 0.864 m/min; and d = 1.905 mm.

In order to obtain the 0.122 mm value of equivalent chip thickness, F was increased to 1.092 m/min, d was reduced to 1.27 mm. Then using the first equation (64) the value of W was calculated to be 42 mm.

Metal removal rates were 58.25 and 71.03 cm^3/min. Another test under the conditions of V_s of 182.21 m/min and h_s of 0.133 was repeated twice to compare cutter life results. Planning of cutting tests and results are shown in table (2).

In addition to these tests two more tests were performed. The first test was in up-cut milling in order to compare the cutter life results with the cutter life obtained in down-cut milling under the conditions of V_s of 182.21 m/min, and h_s of 0.133 mm. Cutter life result was obtained to be 7.8 mins which was smaller than the cutter life obtained in down-cut milling. Second test was tried under the conditions of V_s of 182.21 m/min, and h_s of 0.133 mm in central milling.

Two of the inserts were chipped at 0.412 mm flank wear. Hence the test was not completed. Another test was planned under the conditions of cutting speed of 182.21 m/min, feed rate of 1.666 m/min, depth of cut of 2.03 mm, W of 57 mm, MR of 192.772 cm^3/min. The test was a failure, some cutting edges were broken, because of power required was exceeded maximum available power on the machine. Chips obtained in these tests are seen in Figure (22).

4.2.1c. Planning of Cutter Life Tests for Annealed Tool Steel (mean B.H.N. 197) Using Sandvik Cutter in Up-cut milling.

B.H.N. of second type of tool steel materials, which were sent by the company, were lower than first type of materials received.

Obviously in order to compare dependent variable (s) some independent parameters and variables should be kept constant. At the beginning, one of the major aims of the project, was to compare cutter life results both in down-cut and in up-cut milling. Unfortunatley, the same type of materials were not obtained from the company. The values of cutting speeds and equivalent chip thicknesses were kept the same as down-cut milling using available widths of materials. At the beginning $(3)^2$ experiments were planned and carried out. Three tests under low-speed conditions and two tests in medium-speed conditions were not completed.

Because two or three cutting edges of the cutter were chipping simultaneously, then three more tests were planned and carried out using a higher cutting speed until power available on the machine tool reached to the limit in order to obtain the cutter life equation. One test under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm was repeated twice.

The reasons for chipping will be investigated and explained in Chapter V. Another test was carried out in down-cut milling to compare the cutter life result with the cutter-life result obtained in up-cut milling.

Planning of cutting tests and results are shown in table (3).

4.2.1d. Planning of Cutter Life Tests for Annealed Tool Steel (mean B.H.N.197) Using Walter Cutter in Up-cut Milling.

In order to compare tests results three levels of cutting speeds and three levels of equivalent chip thicknesses were planned. Planning of tests are shown in table (4). This time, eight of nine tests were failures. These were like those of Sandvik Cutter life tests in up-cut milling, that is, cutting edges were chipping on the first or second cut pass. Obviously cutter wear was not associated with any wear zone. The reasons for chipping will be investigated and explained in chapter V.

4.3. Planning of Power Tests

Tests of power were not planned, because planning of cutter life tests also gave an opportunity to obtain different values of metal removal rate, MR, and power measurements. In this research during every cutter life test under planned cutting conditions three measurements of power were taken, when any two teeth were engaged with workpiece. First, measurements were taken around average maximum flank wear of 0.2 mm, the second measurement around 0.4 mm and the final one around 0.6 mm.

4.4. Planning of Surface Finish Tests.

Special tests of surface finish were not planned, because milling process is generally recognized as intermittent process and many cases milling is not final process like turning or grinding. Only surface roughnesses in C.L.A. index were measured while cutter life tests were being performed. Surface waviness measurements were taken, but in each case over a fixed distance at different positions, different wavinesses of the surface profile were obtained.

4.5. Planning of Vibration Tests

Vibration measurements in two directions were taken according to a type of milling. Vibration in the third direction was also taken in order to compare measurements. It is known that tool wear is affected by vibrations. In order to avoid the point mentioned above all vibration measurements were recorded and photographed, as shown in Figure (16), when cutter wear had the same level in all set-ups. These were taken when two teeth of the cutter were engaged with the workpiece.

Vibrations under each cutting conditions were stored to the osciloscope in order to take their photographs. Horizontal scale which represent the frequency of vibration, was 5 m sec per division. Vertical line which represent amplitude of vibration, was 0.1 m volt per division.

4.6. Technique and Procedure of Tests.

At the beginning of each cutting test, the positions of all new brand teeth of each cutter were measured in the axial direction using a dial gauge to make sure that all teeth were the same position. Maximum allowable height was ± 0.0127 mm. Each workpiece was held rigidly. Cutting variables such as a number of revolution, table speed or feed rate, depth of cut etc., were fixed according to the cutting test condition. From time to time cutting was stopped and maximum flank wear of each tooth was measured and recorded where ever it occured. Typical crater wear for both Sandvik Cutter and Walter Cutter are shown in Figure (23) and Figure (24) respectively. Typical flank wear for both the Sandvik Cutter and the Walter Cutter are also seen in Figure (25) and Figure (26) respectively. The arithmetic mean value of eight maximum wears was calculated. The total cutting time was also calculated as the product of the number of passes and the cutting time per pass calculated by equation (68). Normally four times the above mentioned procedure was repeated in order to observe a wear-cutting time progress. The points obtained were joined with each other by straight lines. When either some cutting edges were chipped or the 0.635 mm arithmetic mean value of flank wears was reached roughly, machining was stopped. Then the end of the cutter life was obtained from wear-cutting time progress under each cutting condition chosen. The first point on wear-cutting time graph was determined after short cutting time. From time to time the 0.635 mm arithmetic mean value was exceeded to trace the progress of wear. That was noticed after a certain time some cutting edges were chipped. One of the cutter life criteria, which was the 0.635 mm arithmetic mean value, determined correctly the end of each cutter life test. All tests were conducted dry, because cutting fluid cools cutting edges when they are free, after cutting they are healed. These cooling and heating repetitions make worse effect on cutter life than cutting is conducted to be dry.

Typical examples of chips obtained during cutter life tests using the Sandvik cutter, annealed tool steel (B.H.N. 238) and the Walter Cutter in down-cut milling are seen in Figure (27) and Figure (28) respectively.

Three gross power measurements were recorded when any two teeth were engaged with the workpiece being cut. It was noticed that power was increased due to wear progress. To obtain power required at the cutter, idle horse power plus power required to drive the table were substracted from each gross power value. The arithmetic mean value of three calculated power was obtained as power required at the cutter.

Surface finish roughnes (in C.L.A. index) measurements were recorded around 0.4 mm flank wear. When the teeth were brand new, rough surface finish was produced. Due to wear progress surface finish produced was better, toward the end of each cutter life test surface finish was rough. These were observed for both the Sandvik Cutter and the Walter Cutter. When the cutter acrossed the workpiece completely, ten measurements (in C.L.A. index) were taken in direction of table movement. Then the arithmetic mean value of ten readings was calculated under each cutting test condition.

Vibration measurements were obtained in two different directions in each case. In the other direction vibration amplitude and frequency were not high values. In down-cut milling, measurements were taken in feed and axial direction and in up-cut milling in feed and tangential direction.

Typical examples of vibrations taken for both the Sandvik cutter and the Walter cutter are seen in Figure (29) and Figure (30) respectively. All reading were obtained around 0.4 mm flank wear.

CHAPTER V

Experimental Results, Discussion of Results and Relevant Relationships

5.1. Experimental Results and Discussion of Results

One of the aims of this research was to prove the validity of equivalent chip thickness in face milling. That was achieved in two ways; first proof was to use the same cutting speed and the same equivalent chip thickness but to change the relevant variables of equivalent chip thickness. In down-cut milling, using the Walter cutter under the conditions of the cutting speed of 120.65 m/min and the equivalent chip thickness of 0.116 mm, the values of cutter life were obtained to be 39.0 mins and 38.2 mins. Their wear-cutting time progresses are seen in Figure (31). Also using the Sandvik cutter under the conditions of the cutting speed of 144.51 m/min and the equivalent chip thickness of 0.122 mm, the values of cutter life were obtained to be 20.4 mins and 18.9 mins. Their wear-cutting time progresses are drawn in Figure (32).

The results obtained were acceptable, because in any machining test, ± 10% variation is always allowable. Second proof was to choose two close values of equivalent chip thickness and to trace cutter life results in different cutting speeds. These were achieved selecting equivalent chip thickness values of 0.122 mm and 0.133 mm using the Sandvik cutter and two different workpiece materials in both down-cut and up-cut milling. The wear-cutting time progresses obtained using the Walter cutter, tool steel (B.H.N. 238) in down-cut milling are shown in Figure (33), Figure (34), Figure (35), Figure (36) and Figure (37).

The wear-cutting progresses obtained using the Sandvik cutter, tool steel (B.H.N. 238) in down-cut milling are seen in Figure (38), Figure (39) and Figure (40). Cutter life results, which were obtained using the Walter cutter and the Sandvik cutter in down-cut milling, versus cutting speeds are seen in semilog. scale Figure (41) and Figure (42) respectively.

Some cutting tests were repeated twice under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm using the Sandvik cutter and two different workpiece materials (namely tool steel B.H.N. 238 and 197) in both down-cut and up-cut milling. Cutter life results were obtained to be 9.10, 8.20, 11.49 and 11.17 mins respectively. Their wear progresses are shown in Figure (43) and Figure (44).

In central milling, one test was planned using the Sandvik cutter under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm, but the test was not completed, because two teeth were chipped around the 0.412 mm flank wear. W was 46.4 mm which was bigger than the linear distance between any two teeth in the Sandvik cutter. The wear progress is shown in Figure (45). Under the same cutting conditions, up-cut and down-cut milling were performed successfully. When width of workpiece is small, down-cut or up-cut milling can give longer cutter life because of better partial balance of heating and cooling repetitions of each tooth. One up-cut milling was tested under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm using tool steel (B.H.N. 238) and the Sandvik cutter to compare the cutter life result with the cutter life result obtained in down-cut milling under the same conditions. The cutter life was obtained to be 7.8 mins which was lower than the cutter life results of 9.10 and 8.20 mins obtained in down-cut milling. The wear-cutting time progress is seen in Figure (45).

One down-cut milling test was also performed under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm using tool steel (B.H.N. 197) and the Sandvik cutter. The cutter life was obtained to be 13.9 mins which was bigger than the cutter life results of 11.49 and 11.17 mins obtained in up-cut milling. The wear-cutting time progress is shown in Figure (46).

Using the Sandvik cutter and tool steel (B.H.N. 197), up-cut milling tests were a failure at very short time or 0.3 mm flank wear under low and medium cutting speed conditions. The other tests under high speed conditions were performed until around 0.5 mm flank wear. Their wear-cutting time progresses are shown in Figure (47), Figure (48) and Figure (49). Using the Walter cutter and tool steel (B.H.N. 197) only one test was performed until around 0.5 mm flank wear which was smaller than the cutter life criterion used in down-cut milling tests. The wear-cutting time progress is seen in Figure (50).

By examining cutter life results it was noticed that cutting speed was one of the significant independent variable in cutter life results especially under high-speed conditions. Generally when cutting speed was increased cutter life decreased. Equivalent chip thickness played a significant role under low-speed conditions. When equivalent chip thickness was increased by means of W, f and d, cutter life decreased.

Equivalent chip thickness values of the cutters being commercially available gives ideas about which cutter can provide longer cutting time. Under the same cutting variables (at the same cutting speeds, table speeds or feed rates, depth of cuts, widths of workpieces, number of teeth) the smaller equivalent chip thickness values were calculated, when the Sandvik cutter was used. Hence the longer cutter life results were obtained,because under the same cutting variables in each test the same amount of heat was generated but bigger value of each cutting edge engaged with the workpiece being cut (due to bigger lengths values of each cutting edge),which is a measure of the contact surface, was obtained,when the Sandvik cutter was used. In the other words heat generated was transfered in bigger value to chips, the cutter and the workpiece being cut by using the Sandvik cutter in each test.

Longer cutter life results were obtained in down-cut milling with comparing cutter life results of down-cut milling to up-cut milling. Under the same cutting conditions, cutter workpiece material.

5.2. Chipping Mechanism

The reasons for failure, which was occured by chipping of some cutting edges, at very short cutting time for both the Sandvik cutter and the Walter cutter in up-cut milling tests were thought to be related to cutting force and mechanical stresses caused by entry conditions along the width of the workpiece being cut, AB, for both the Sandvik cutter and the Walter cutter as seen in Figure (51) and Figure (52) respectively. Because the initial contact point between AB and each tooth always occurs along the cutting edge of each tooth. Some examples are seen in Figure (51) and Figure (52). It is known that failure caused by both mechanical and thermal stresses normally occurs after certain cutting time; not very short cutting time. Shinozaki(7) pointed out thermal cracks after certain cutting time in face milling.

The location of the initial point can be determined applying equations (66) and (67) derived by Kronenberg(5) to both the Sandvik cutter and the Walter cutter. The intersection angle i' between rake face of one tooth and plane of engagement can be calculated as follows:

a) For the Sandvik cutter; the angle of the engagement plane ε changes continuously according to progress of cutting. If for example $\varepsilon = -47^{\circ}$, thus the values of i', θ'_s, $\emptyset'$ and λ_s can be calculated using the formulas (66) and (67);

$$\mathrm{tg}\, i' = \frac{\mathrm{tg}\,\delta_s . \mathrm{Cos}\, r}{\mathrm{Sin}(r - \varepsilon)}$$

$$\mathrm{tg}\, i' = \frac{\mathrm{tg}\,(-7) . \mathrm{Cos}\,(-5)}{\mathrm{Sin}\left[-5-(-47)\right]} \qquad (104)$$

Hence the angle, $i' = -10^{\circ}$

The cutting edge angles, θ'_s, $\emptyset'$ and λ'_s

$$\mathrm{tg}\,\theta'_s = \frac{\mathrm{tg}\,\theta_s}{\mathrm{Cos}\,\varepsilon}$$

$$\mathrm{tg}\,\theta'_s = \frac{\mathrm{tg}\,30}{\mathrm{Cos}\,(-47)} \qquad (105)$$

$$\theta'_s = 40^{\circ}$$

and

$$\mathrm{tg}\,\emptyset' = \frac{\mathrm{tg}\,\emptyset}{\mathrm{Cos}\,\varepsilon}$$

$$\mathrm{tg}\,\emptyset' = \frac{\mathrm{tg}\,60}{\mathrm{Cos}\,(-47)} \qquad (106)$$

$$\emptyset' = 68^{\circ}.5$$

and

$$\mathrm{tg}\,\lambda'_s = \frac{\mathrm{tg}\,\lambda_s}{\mathrm{Cos}\,\varepsilon}$$

$$\mathrm{tg}\,\lambda'_s = \frac{\mathrm{tg}\,75}{\mathrm{Cos}\,(-47)} \qquad (107)$$

$$\lambda'_s = 80^{\circ}$$

b) For the Walter cutter;the angle of the engagement plane ε again changes continuously according to the progress of cutting.

$$tg\, i' = \frac{tg\, \delta_W . \text{Cos } r}{\text{Sin}(r - \varepsilon)}$$

If for example $\varepsilon = -\ 47^{\circ}$

$$tg\, i' = \frac{tg\ (8).\ \text{Cos}(-16)}{\text{Sin}\ [-5-(-47)]}$$

$$i' = 11^{\circ}.4$$

The cutting edge angle, θ'_W

$$tg\, \theta'_W = \frac{tg\, \theta_W}{\text{Cos } \varepsilon}$$

$$tg\, \theta'_W = \frac{tg\ 42}{\text{Cos}(-47)} \tag{108}$$

$$\theta'_W = 53^{\circ}$$

Initial contact points in both cases are along the cutting edges as seen in Figure (53) and Figure (54). Surface finish was also examined over a certain area after cutting. On surface finish the traces of the broken cutting edges were seen.

However in down-cut milling, the initial contact points for both the Sandvik cutter and the Walter cutter were away from the cutting edges and toward the inside of the edges. Plan of engagement was always occured along the length of the workpiece, l, in down-cut milling.

5.3. Cutter life Relationships

The computer programme was written to calculate the coefficients of the proposed cutter life model given by the equation (69) for both the Walter cutter life data and the Sandvik cutter life data given in Table (1) and Table (2). The flow chart of the Computer programme written is given in Chapter III. The programme and the results for both the Walter cutter life data and the Sandvik cutter life data are seen in Appendix I. Their R.S.S. contour diagrams in $\alpha_1 - \alpha_2$ plane are also shown in Figure (55) and Figure (56). An example of a R.S.S. value, coefficients and confidence interval of coefficients are given in Appendix II.

The cutter life equation, using the Walter cutter life data, was obtained as;

$$31.836 \ln T_w = 226.568 - 2.066 V_w^{0.8} - 857.419\ 10^2 h_w^{4.0}$$

or

$$\ln T_w = 7.177 - 0.065 V_w^{0.8} - 2693.237 h_w^{4.0} \qquad (109)$$

R.S.S., which was the minimum value, was calculated to be 0.411. The error variance S^2 was obtained to be 0.046 using the equation (72). The 95 percent confidence interval for b_o, $CI(b_o)$ is given as;

$$CI(b_o) = b_o \pm t_{v;\,\xi/2} \cdot \sqrt{S^2 \cdot d_{ii}}$$

$t_{v;\,\xi/2}$ was taken to be 2.262 from a statistic table

$$CI(b_o) = 7.117 \pm 2.262 \cdot \sqrt{(0.046)(1.525)}$$

$$CI(b_o) = \begin{cases} 7.716 \\ 6.518 \end{cases}$$

for b_1 ;

$$CI(b_1) = -0.065 \pm 2.262 \cdot \sqrt{(0.046)(0.00076)}$$

$$CI(b_1) = \begin{cases} -0.052 \\ -0.078 \end{cases}$$

for b_2 ;

$$CI(b_2) = -2693.237 \pm 2.262 \sqrt{(0.046)(467.57\ 10^4)}$$

$$CI(b_2) = \begin{cases} -1644.190 \\ -3742.284 \end{cases}$$

Two more cutter life equations can be written using the upper and lower limits of coefficients calculated above. If the upper limit of $CI(b_o)$ is used for b_o, the lower limits of $CI(b_1)$ and $CI(b_2)$ are chosen for b_1 and b_2 and vice versa.

$$\ln T_w = 7.716 - 0.078V_w^{0.8} - 3742.284h_w^{4.0} \qquad (110)$$

and

$$\ln T_w = 6.518 - 0.052V_w^{0.8} - 1644.190h_w^{4.0} \qquad (111)$$

Logarithmic transformations of both sides, which is similar to Taylor type tool-life equations, were also obtained in the results.

$$31.835 \ln T_w = 420.399 - 79.199 \ln V_w - 30.512 \ln h_w$$

or

$$\ln T_w = 13.206 - 2.488 \ln V_w - 0.958 \ln h_w \qquad (112)$$

R.S.S was calculated to be 0.885 which is bigger than the value of R.S.S. obtained in the equation (109).

The second proposed cutter life equation which is in the second order model, was obtained using the statistical package Mark 2(34). The computer programme and results are seen in Appendix III. The multiple correlation coefficient was calculated to be 0.990

$$\ln T_w = 45.391 - 12.994 \ln V_w + 6.846 \ln h_w$$

$$+ 0.346 (\ln V_w)^2 - 1.6 (\ln h_w)^2 - 3.354 \ln V_w . \ln h_w \qquad (113)$$

R.S.S. was calculated to be 0.228.

The first proposed cutter life equation, using the Sandvik cutter life results, was obtained as;

$$18.195 \ln T_s = -220.96 + 757.52 V_s^{-0.2} - 645.871 \, 10^3 h_s^{5.6}$$

or

$$\ln T_s = -12.14 + 41.63 V_s^{-0.2} - 35 \, 10^3 h_s^{5.6} \qquad (114)$$

R.S.S., which was the minimum value, was calculated to be 0.041. The error variance S^2 was obtained to be 0.005 using the equation (72). The 95 percent confidence interval for b_o, $CI(b_o)$ is calculated as;

$$CI(b_o) = -12.14 \pm 2.306 \sqrt{(0.005)(80.674)}$$

$$CI(b_o) = \begin{cases} -10.68 \\ -13.60 \end{cases}$$

for b_1

$$CI(b_1) = 41.63 \pm 2.306 \sqrt{(0.005)(585.580)}$$

$$CI(b_1) = \begin{cases} 45.58 \\ 37.68 \end{cases}$$

for b_2

$$CI(b_2) = -35\ 10^3 \pm 2.306 \sqrt{(0.005)(44.64\ 10^8)}$$

$$CI(b_2) = \begin{cases} -24.1\ 10^3 \\ -45.9\ 10^3 \end{cases}$$

Hence two more cutter life equations can be written using the upper and lower limits of coefficients calculated above.

$$\ln T_s = -10.68 + 37.68\ V_s^{-0.2} - 45.9\ 10^3 h_s^{5.6} \qquad (115)$$

and

$$\ln T_s = -13.60 + 45.58\ V_s^{-0.2} - 24.1\ 10^3 h_s^{5.6} \qquad (116)$$

Logarithmic transformations of both sides, which is similar to Taylor type tool-life equation, were also obtained in the results;

$$18.195 \ln T_s = 303.143 - 56.354 \ln T_s - 14.534 \ln h_s$$

or

$$\ln T_s = 16.661 - 3.097 \ln V_s - 0.799 \ln h_s \qquad (117)$$

R.S.S. was calculated to be 0.060 which is bigger than the value of R.S.S. obtained in the equation (114).

The second proposed cutter life equation, which is in the second order logarithmic model, was also obtained. The coefficients of the proposed equation and the miltiple correlation coefficient were calculated using the Statistical package Mark 2 (34). The computer programme written and the coefficients obtained are seen in Appendix IV. The multiple correlation coefficient was calculated to be 0.930

The cutter life relationship is given;

$$\ln T_s = -\,122.597 + 62.440\ \ln V_s + 19.933\ \ln h_s - 6.387\ (\ln V_s)^2 + 5.437\ (\ln h_s)^2 + 0.857\ \ln V_s . \ln h_s \qquad (118)$$

5.4. Power Relationships

Powers required at any cutter in different cutting conditions were measured and evaluated in a function of metal removal rate, because metal removal rate can be easily calculated. The results in each test were obtained subtracting idle horse power and power required to move the table from the gross horse power. The results are given in Table (5) and Table (6),(7),Figure (57) and Figure (58) for both the Walter cutter and the Sandvik cutter using tool steel (B.H.N. 238 and 197), in down-cut milling and up-cut milling respectively.

As can be seen by examining the results, there is not much difference between power required at the Walter cutter and power required at the Sandvik cutter in down-cut milling under different cutting conditions. For the Sandvik cutter less power is required at the spindle in up-cut milling than down-cut milling.

The power relation equations, which are in the first order logarithmic models, were obtained. The coefficients were calculated the least square method using the Statistical package. One example of the computer programmes written and results are seen in Appendix V.

The equation using the Walter cutter, tool steel (B.H.N. 238) and and in down-cut milling was obtained.

$$H.P._W = 0.0816 + 0.0738\ MR \qquad (119)$$

The correlation coefficient was calculated to be 0.995

It is known that when MR is 0.0, horse power consumption is zero. Hence the equation above can be written as;

$$H.P._W \cong 0.075\ MR \qquad (120)$$

The equation using the Sandvik cutter, tool steel (B.H.N. 238) in down-cut milling was obtained;

$$H.P._S = 0.178 + 0.0738\ MR \qquad (121)$$

The correlation coefficient was calculated to be 0.982 For the same reason the equation can be written as;

$$H.P._S \cong 0.075\ MR \qquad (122)$$

Both equations have the same slopes.

5.5. Surface Finish Relationships

Surface finish results are given in Table (8), Table (9) and Table (10) . Cutting speed plays a significant role on surface finish. Better surface finish results were obtained using the Sandvik cutter in down-cut milling and rough surface finish were produced in up-cut milling.

The coefficients of the surface finish equations were calculated by the least square method using the Statistical package Mark 2(34) in first order logarithmic models.

The equation , using the Walter cutter in down-cut milling is written as;

$$\ln S.F_W = 4.326 - 1.013 \ln V_W + 0.064 \ln h_W \qquad (123)$$

The multiple correlation coefficient was calculated to be 0.660, the equation, using the Sandvik cutter in down-cut milling, is written as;

$$\ln S.F_s = 1.27 - 0.741 \ln V_s - 0.853 \ln h_s \qquad (124)$$

The multiple correlation coefficient was calculated to be 0.733.

5.6. Vibration Relationship

Vibration amplitutes results from peak to peak (P.T.P.) are given under different cutting conditions in Table (11), Table (12) and Table (13). It was found that cutting speed and maximum area being cut were significant variables on vibration amplitude produced. The results obtained also show that vibrations are generated by cutting force components applied to the cutting system. There is not much difference between vibration amplitutes produced by the Walter cutter and the Sandvik cutter in down-cut milling, but less vibrations were produced during the up-cut milling.

The relevant vibration equations were obtained. The coefficients of the equations were calculated by the least square method using the Statistical package Mark 2[(34)] in the first order logarithmic model.

The equation using the Walter cutter in down-cut milling is written as;

$$\ln VIB.AMP_W = 4.636 - 0.174 \ln V_W + 0.537 (s_{max_W}) \qquad (125)$$

where (s_{max_W}) is the maximum area being cut which is equal to d.f. The multiple correlation coefficient was calculated to be 0.848.

The equation using the Sandvik cutter in down-cut milling is written as;

$$\ln VIB.AMP_S = 7.426 - 0.682 \ln V_S + 0.898 (s_{max_W}) \qquad (126)$$

where (s_{max_W}) is the maximum area. The multiple correlation coefficient was calculated to be 0.895.

CHAPTER VI

Economics of Face Milling and Applications

Basically two models are considered, namely unit-time model and unit-cost model in this research. The use of profit-rate can be difficult, because selling price of each piece is not normally fixed at the beginning of the process in practice.

1) Unit-time model.

The total time to produce one piece T_p was written in Chapter III as;

$$T_p = T_1 + K.\ MV. \left(\frac{T + T_r}{MR.T} \right) \tag{127}$$

where T_1 is the total, K is the constant, MV is the volume of metal to be removed, T_r is the replacement time of teeth, T is the cutter life, MR is the metal removal rate.

To obtain the minimum values of T_p, which is the aim of industry, the reciprocal of the second term of the equation above $F_1 = \frac{MR.T}{T + T_r}$, which is called time function in this research, should be maximum. Then the equation, which will give the optimum cutter life value, was obtained in Chapter III as;

$$T(T + T_r) + MR.\ T_r . \frac{dT}{dMR} = 0 \tag{128}$$

The first derivation of T to MR can be obtained using the T - MR characteristic function.

a) Determination of optimum cutting conditions using the Walter cutter, tool steel material (B.H.N. 238) in down-cut milling.

The cutter life equation was obtained using power transformations in the form as;

$$\ln T_w = b_o + b_1 . \frac{V_w^{\alpha_1}}{1000^{\alpha_1}} + b_2 \, h_w^{\alpha_2} \qquad (129)$$

where $b_o = 7.117$, $b_1 = -0.065$, $\alpha_1 = 0.8$, $b_2 = -2693.23$, $\alpha_2 = 4.0$, V_w in $\frac{mm}{min}$ and h_w in mm.

Metal removal rate, MR, was written in Chapter III as follows;

$$h_w = \frac{MR/V_w}{l_w + \frac{d}{\sin \theta_w . \cos \delta_w}}$$

or

$$MR = \left(l_w + \frac{d}{\sin \theta_w . \cos \delta_w} \right) . h_w . V_w \qquad (130)$$

where V_w in $\frac{mm}{min}$, h_w in mm, and l_w in mm.

In this research, depth of cut d is taken into account as any parameter, not a variable. In calculation, any value is given to depth of cut bearing in mind horse power limitation of the machine tool used. Therefore the first term of the equation above

$$l_w + \frac{d}{\sin \theta_w . \cos \delta_w}$$ is calculated as any

parameter. Hence MR is expressed only as a function of h_w and V_w. For the existence of the MR - T characteristic function, their Jacobian should vanish as follows:

$$J = \begin{vmatrix} \frac{\partial MR}{\partial h_w} & \frac{\partial MR}{\partial V_w} \\ \frac{\partial T_w}{\partial h_w} & \frac{\partial T_w}{\partial V_w} \end{vmatrix} = 0 \qquad (131)$$

The partial differentiations, $\frac{\partial MR}{\partial V_w}$, $\frac{\partial MR}{\partial h_w}$, $\frac{\partial T_w}{\partial V_w}$ and $\frac{\partial T_w}{\partial h_w}$ can be obtained using the equations (129) and (130) respectively.

$$\frac{\partial MR}{\partial V_w} = a_1.h_w, \frac{\partial MR}{\partial h_w} = a_1.V_w$$

$$\frac{\partial T_w}{\partial V_w} = b_1.\alpha_1.\frac{V_w^{\alpha_1 - 1}}{1000^{\alpha_1}} . T$$

$$\frac{\partial T_w}{\partial V_w} = b_2.\alpha_2. h_w^{\alpha_2 - 1} . T$$

where $a_1 = l_w + \frac{d}{\text{Sin } \theta_w . \text{ Cos} \delta_w}$

By using the formulas above in equation (131) the following expression is obtained ;

$$\frac{b_1 \alpha_1}{1000^{\alpha_1}} . V_w^{\alpha_1} = b_2 . \alpha_2 . h_w^{\alpha_2} \qquad (132)$$

The equation above gives the relationship between V_w and h_w. This is also the T - MR curve in V_w - h_w plane and an exponential form. Using the equations (130) and (132) we obtain;

$$h_w^{\alpha_2} = \frac{b_1 . \alpha_1 . V_w^{\alpha_1}}{b_2 . \alpha_2 . 1000^{\alpha_1}} \qquad (133)$$

and

$$h_w^{\alpha_2} = \left(\frac{MR}{a_1}\right)^{\alpha_2} \frac{1}{V_w^{\alpha_2}} \qquad (134)$$

The relationship between V_w and MR can be obtained as;

$$\frac{b_1}{b_2} \cdot \frac{\alpha_1}{\alpha_2} \cdot \frac{V_w^{\alpha_1}}{1000^{\alpha_1}} = \left(\frac{MR}{a_1}\right)^{\alpha_2} \cdot \frac{1}{V_w^{\alpha_2}}$$

or

$$\left(\frac{1}{1000^{\alpha_1}} \cdot \frac{b_1}{b_2} \cdot \frac{\alpha_1}{\alpha_2}\right)^{\frac{\alpha_1}{\alpha_1+\alpha_2}} \cdot V_w^{\alpha_1} = \left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 . \alpha_2}{\alpha_1+\alpha_2}}$$

Using the cutter life equation (129) T_w can be written only as a function of V_w

$$\ln T_w = b_o + \frac{b_1}{1000^{\alpha_1}} \left(1 + \frac{\alpha_1}{\alpha_2}\right) V_w^{\alpha_1} \qquad (135)$$

Hence the relationship between T_w and MR can be obtained as follows;

$$\ln T_w = b_o + \frac{b_1}{1000^{\alpha_1}} \cdot \left(1 + \frac{\alpha_1}{\alpha_2}\right)\left(\frac{1000^{\alpha_1} . b_2 \alpha_2}{b_1 \alpha_1}\right)^{\frac{1}{\alpha_1+\alpha_2}} . \left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 \alpha_2}{\alpha_1+\alpha_2}}$$

This is the MR - T_w characteristic equation. By using the values of parameters, the equation can be written as follows;

$$\ln T_w = 7.117 - 0.006 \left(\frac{MR}{a_1}\right)^{0.667} \qquad (136)$$

That is the unique equation, because the ratio $\frac{MR}{a_1}$ is equal to $h_w . V_w$, the value of the equation is not related to the value of d. The curve of the equation above is given in Figure (59).

To obtain equation(128), the first derivation of T_w to MR is calculated

$$\frac{d\,T_w}{d\,MR} = \frac{b_1}{1000^{\alpha_1}} \quad (1 + \frac{\alpha_1}{\alpha_2})\left(1000^{\alpha_1} . \frac{b_2 - \alpha_2}{b_1 \cdot \alpha_1}\right)^{\frac{\alpha_1}{\alpha_1 + \alpha_2}} . \frac{\alpha_1 . \alpha_2}{\alpha_1 + \alpha_2} .$$

$$\left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 . \alpha_2}{\alpha_1 + \alpha_2}} . \frac{T}{MR} \qquad (137)$$

Using equation (137) obtained, the equation, which will give the optimum value of the cutter life, is written as follows:

$$(T_w + T_r) + T_r \; (\ln T_w - b_o) \frac{\alpha_1 . \alpha_2}{\alpha_1 + \alpha_2} = 0 \qquad (138)$$

The solution of the equation above depends on the values of T_r, b_o, α_1 and α_2.

Two different values of the replacement time of teeth, T_r, are considered as 15 and 30 mins, which are acceptable values in industry.

i) $T_r = 15$ mins

The equation (138) is written as:

$$T_w + 15 + 15 \; (\ln T_w - 7.117) \; 0.667 = 0$$

T_w was calculated to be 24 mins which is the optimum cutter life value in this situation. The value of MR was obtained to be 65217.02 $\frac{mm^3}{min}$ using T_w of 24 mins and considering the value of d to be 1.905 mm (o.075 in).

The optimum values of cutting speed V_w and equivalent chip thickness h_w were calculated to be 134.62 m/min and 0.125 mm respectively. Table speed F can be calculated according to the value W of the workpiece being cut.

ii) $T_r = 30$ mins.

$$T_W + 30 + 30\ (\ln T_W - 7.117)\ 0.667 = 0$$

T_W was calculated to be 39 mins which is the optimum cutter life value in this situation.

As can be seen when T_r is increased cutter life should be used longer.

The value of MR was calculated to be 53538.77 $\frac{mm^3}{min}$, provided d was considered to be 1.905 mm. The optimum values of V_W and h_W were obtained to be 114.19 m/min and 0.121 mm respectively. Table speed F can be calculated according to the value of W being used.

As can be observed when cutter life is used longer, the value of MR should be decreased.

b) Determination of optimum cutting conditions using the Sandvik cutter, tool steel material (B.H.N.238) in down-cut milling.

The cutter life equation was obtained using the power transformations method as:

$$\ln T_s = b_o + b_1 \frac{V_s^{\alpha_1}}{1000^{\alpha_1}} + b_2\, h_s^{\alpha_2} \qquad (139)$$

where $b_o = -12.144$, $b_1 = 41.634$, $b_2 = -35497.19$

$\alpha_1 = -0.2$, $\alpha_2 = 5.6$, V_s in $\frac{mm}{min}$ and h_s in mm

Metal removal rate, MR was written in Chapter III as follows:

$$h_s = \frac{MR/V_s}{a_2}$$

$$\text{where } a_2 = \begin{cases} l_s + \dfrac{l_\theta + \frac{d}{\sin\phi} - l_\theta \cdot \frac{\sin\theta_s}{\sin\phi}}{\cos\delta_s}, & \text{if } d < la \\[2ex] l_s + \dfrac{\left[l_\theta + l_\phi + \frac{d}{\sin\lambda_s} - (l_\phi + l_\theta \frac{\sin\theta_s}{\sin\phi}) \cdot \frac{\sin\phi}{\sin\lambda_s}\right]}{\cos\delta_s} \\[2ex] \text{if } d > la \end{cases}$$

Depth of cut d is taken as any parameter, in calculation any value is given to d according to horse power available on the machine tool used. The same formulas, which were obtained and used to determine optimum cutting conditions using the Walter cutter in down-cut milling, can be also used in this section.

MR is only a function of h_s and V_s

$$MR = MR(h_s, V_s)$$

For the existence of MR - T characteristic function, their Jacobian should vanish. By doing the procedure, the following expression is obtained:

$$\frac{b_1 . \alpha_1}{1000^{\alpha_1}} V_s^{\alpha_1} = b_2 . \alpha_2 . h_s^{\alpha_2}$$

The equation above is the MR - T curve in V_s - h_s plane.

The MR - T relationship is also obtained as;

$$\ln T_s = b_o + \frac{b_1}{1000^{\alpha_1}} \left(1 + \frac{\alpha_1}{\alpha_2}\right) \left(1000^{\alpha_1} . \frac{b_2 . \alpha_2}{b_1 . \alpha_1}\right)^{\frac{\alpha_1}{\alpha_1 + \alpha_2}} \left(\frac{MR}{a_2}\right)^{\frac{\alpha_1 . \alpha_2}{\alpha_1 + \alpha_2}}$$

By using the values of parameters the MR - T_s curve is written as:

$$\ln T_s = -12.144 + 115.96 \left(\frac{MR}{a_2}\right)^{-0.207} \qquad (140)$$

The Curve of the equation is given in Figure (60).

The equation, which will give the optimum cutting conditions, can be written as;

$$T_s + T_r + T_r \left(\ln T_s - b_o\right) \frac{\alpha_1 . \alpha_2}{\alpha_1 + \alpha_2} = 0 \qquad (141)$$

Two different values of the tool replacement time T_r are considered as 15 and 30 mins.

i) T_r = 15 mins

$$T_s + 15 + 15\ (\ln T_s + 12.144) - 0.207 = 0$$

T_s was calculated to be 33 mins which is the optimum cutter life value in this situation. The value of MR was obtained to be 64036.16 mm^3/min using T_s of 27 mins provided d was considered to be 1.905 mm (0.075 in).

The optimum values of cutting speed V_s and equivalent chip thickness h_s were calculated to be 111.43 m/min and 0.139 mm respectively. Table speed F can be calculated according to the value of W being used.

ii) T_r = 30 mins.

$$T_s + 30 + 30\ (\ln T_s + 12.144) - 0.207 = 0$$

T_w was calculated to be 72 mins which is the optimum cutter life value in this situation. When T_r is increased, cutter life should be used longer.

The value of MR was calculated to be 50622.06 mm^3/min. The optimum values of V_s and h_s were calculated to be 87.36 m/min and 0.140 mm. Table speed F can be calculated according to the value of W being used

2. Unit-cost model

The total cost to produce one piece C was written in Chapter III as;

$$C = C_o.T_1 + C_o.K.\ \frac{MV}{MR}\ (1 + \frac{T_r + Y/C_o}{T})$$

where C_o is the operator and overhead cost per unit time, T_1 is the total idle time including set-up time, K is the constant which is calculated by $\frac{1}{1_p}$ as seen in Figure (14), MV is the metal volume to be removed, MR is the metal removal rate, T_r is the replacement time of teeth, Y is the total cost of cutting edges of the cutter.

To obtain the minimum values of C, the reciprocal of the second term of the equation above $F_2 = \frac{MR.T}{(T + T_r + \frac{Y}{C_o})}$ which is called cost function in this research, should be maximum. Then the equation, which will give the optimum cutter life value was obtained in Chapter III as;

$$T(T + T_r + \frac{Y}{C_o}) + MR(T_r + \frac{Y}{C_o}) \frac{dT}{dMR} = 0$$

where the first derivation of T to MR can be obtained using the T - MR characteristic equation as done in the previous section.

a) Determination of optimum cutting conditions using the Walter cutter, tool steel (B.H.N. 238) in down-cut milling. In the previous section (unit-time model) the relationship between T and MR was obtained as below:

$$\ln T_w = b_o + \frac{b_1}{1000^{\alpha_1}} \left(1 + \frac{\alpha_1}{\alpha_2}\right)\left(1000^{\alpha_1} . \frac{b_2 . \alpha_2}{b_1 . \alpha_1}\right)^{\frac{\alpha_1}{\alpha_1+\alpha_2}} \left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 . \alpha_2}{\alpha_1+\alpha_2}}$$

The first derivation of T_w to MR was calculated as;

$$\frac{dT_w}{dMR} = \frac{b_1}{1000^{\alpha_1}} \left(1 + \frac{\alpha_1}{\alpha_2}\right)\left(1000^{\alpha_1} . \frac{b_2 . \alpha_2}{b_1 . \alpha_1}\right)^{\frac{\alpha_1}{\alpha_1+\alpha_2}} \left(\frac{\alpha_1 . \alpha_2}{\alpha_1+\alpha_2}\right) . \left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 . \alpha_2}{\alpha_1+\alpha_2}} .$$

$$. \frac{T}{MR} \qquad (142)$$

Using equation (142), to obtain the optimum cutter life value, the equation below should be solved.

$$\left(T_w + T_r + \frac{Y}{C_o}\right) + \left(T_r + \frac{Y}{C_o}\right) \quad (\ln T_w - b_o)\frac{\alpha_1 \cdot \alpha_2}{\alpha_1 + \alpha_2} = 0, \quad (143)$$

The solution of the equation above is related to the values of C_o, T_r, Y, b_o, α_1 and α_2

The following information was obtained from G.K.N. Ltd.

$$C_o = £4.20/\text{hour} = 7 \text{ pence/min}$$

$$Y = 176 \text{ pence}$$

By using the values of the parameters, the equation (143) is written as;

$$(T_w + T_r + 25) + (T_r + 25)(\ln T_w - 7.117).\ 0.667 = 0$$

Two different values of T_r are considered as 15 mins and 30 mins.

i) $T_r = 15$ mins

$$(T_w + 15 + 25) + (15 + 25)(\ln T_w - 7.117).\ 0.667 = 0$$

T_w was calculated to be 47 mins which is the optimum cutter life value in this situation. This result shows that the optimum tool life for minimum unit cost is larger than for minimum unit time. The optimum tool life for minimum unit time was already calculated to be 21 mins. in the previous section. The MR value for the 47 mins optimum cutter life value was obtained to be 50220.08 mm^3/min, d was considered to be 1.905 mm (0.075 in). The optimum cutting speed V_w and equivalent chip thickness h_w were calculated to be 106.55 m/min and 0.119 mm respectively. Table speed F can be calculated corresponding to the value of W being used.

ii) $T_r = 30$ mins

$$(T_w + 30 + 25) + (30 + 25)(\ln T_w - 7.117)0.667 = 0$$

T_W was calculated to be 58 mins which is the optimum cutter life value in this situation. The value of MR for the 58 mins optimum cutter life value was calculated to be 45449.79 mm^3/min and d was considered to be 1.905 mm (0.075 in). Corresponding optimum V_s and h_s were calculated to be 98.04 m/min, 0.117 mm respectively. Table speed F can be calculated according to the value of W being

b) Determination of optimum cutting conditions using the Sandvik cutter, tool steel material (B.H.N. 238) in down-cut milling. The same formulas obtained in the previous sections will be used in this section in order to calculate optimum cutting conditions. The values of C_o and Y are taken to be 7 pence/min and 176 pence respectively as previous values.

The equation, which will determine optimum tool life, is written below by using the parameters of the Sandvik cutter life equation. Two different values of T_r are considered as 15 mins and 30 mins.

i) $T_r = 15$ mins

$$(T_s + 15 + 25) + (15 + 25)(\ln T_s + 12.14) - 0.207 = 0$$

T_s was calculated to be 98 mins which is the optimum cutter life value in this situation. The value of MR for this 98 mins optimum cutter life value was calculated to be 46139.99 mm^3/min, d was considered to be 1.905 mm (0.075 in). The optimum values of V_s and h_s were calculated to be 79.77 m/min and 0.141 mm respectively. Table speed F can be calculated according to the value of W being cut.

ii) $T_r = 30$ min.

$$(T_s + 30 + 25) + (30 + 25)(\ln T_s + 12.14) - 0.207 = 0$$

T_s was calculated to be 140 mins which is the optimum cutter life value in this situation. The value of MR for the 140 mins optimum cutter life was calculated to be 41669.06 mm^3/min and d was considered to be 1.905 mm (0.075 in). The optimum values of V_s and h_s were calculated to be 71.65 m/min and 0.142 mm respectively. Table speed F can be calculated according to the value of W being cut.

T_r on optimum cutting conditions is significant. When T_r takes longer time, the cutter should be used longer time. Longer cutter life leads smaller metal removal rate, hence cutting speed and the other variables should be decreased and vice versa. The effect of Y on optimum cutting conditions is also significant. When the cost of teeth used is high, the cutter should be used in production for longer time. C_o is also another significant parameter. When C_o is increased, the cutter should be used for shorter time. The Sandvik cutter in both unit time and unit-cost gives the higher optimum cutter life than the Walter cutter because of the effect of the coefficients. The optimum cutter life value for minimum cost is higher than for minimum time.

Generally low cutting speed, high table speed and high depth of cut should be selected to obtain optimum cutting conditions in face milling bearing in mind maximum power available on the machine tool.

Optimum cutting speed for minimum time and minimum cost under the situation of the Sandvik cutter is selected to be smaller value than under the situation of the Walter cutter.

Under the situation of the Sandvik cutter, optimum equivalent chip thickness and using the result of equivalent chip thickness, table speed is selected higher value than under the situation of the Walter cutter for minimum time and minimum cost.

CHAPTER VII

Conclusions and Future Work

7.1. Conclusions

7.1.1. The selection of the cutter diameter should be related to the width of the workpiece being cut.

A maximum of 1.5 times the workpiece width is rather a good choice because in order to balance cooling and heating repetations of each tool and reduce impact effect of each tooth entering the workpiece, the number of teeth, which will be contacting the workpiece, should be as high as possible at any time. When the width of workpiece is relatively small, the down-cut or up-cut milling position* increases the number of teeth compared with central milling.

7.1.2. Metal removal rate was found to be a function of cutting speed, characteristic feed (which is determined by average chip thickness and the engagement angle), depth of cut, and also from the product of width of workpiece, table speed and depth of cut. Then equivalent chip thickness was formulated in each situation.

7.1.3. In order to evaluate machinability data, and at the same time to save tests and amount of workpiece material required, the number of independent variables was selected as small as possible.

7.1.4. The cutter wear hardly affects horse power consumption, surface finish produced, and vibration generated. Generally, mean value of measurements was taken to determine dependent variables above.

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* i.e. Offset of workpiece to left and right side of cutter centre line

7.1.5. In the life evaluation of a multi-tooth cutter, the number of wear measurements should be on at least half the number of teeth used, because each tooth does not remove the same amount of material from the workpiece being cut.

7.1.6. The maximum width of wear land on each flank face is a better measurement than the mean value of the width of flank wear, in order to determine the useful life of the cutter. This is because after a certain cutting time, the maximum flank wear leads to the complete failure of the cutting edge. Measuring the maximum wear on each tooth takes a shorter time than measuring the mean value.

7.1.7. In down-cut milling,0.625 mm (0.025 in) for the arithmetic mean value of maximum widths of flank wears was found a more acceptable value than 0.762 mm (0.030 in). This is because of widespread variation amoung the wear values of different teeth on the cutter. But in up-cut milling, only the 0.5 mm arithmetic mean value of maximum widths of flank wears was reached.

7.1.8. Down-cut milling gives a better performance than up-cut or central milling, especially when the width of the workpiece is relatively small. When the cost of each tooth is considered, down-cut milling can be prefered because it gives longer cutter life, provided a backlash eliminator is used. The first initial contact point of each tooth with the workpiece is always away from the cutting edge in down-cut milling, but occurs on the cutting edge in up-cut milling. Hence when a brittle cutting edge like a carbide cutting edge is used, chipping can easily occur in up-cut milling.

In this situation the cutter which has negative axial rake gives more strength than the cutter which has positive axial rake. In up-cut milling, more overall power is required, because more power is required in the direction of feed to produce the movement of the workpiece, but less power is required at the cutter itself.

Down-cut milling also produces better surface finish than up-cut milling. With the backlash eliminator, the same level of amplitude of vibration is generated on the workpiece being cut in down-cut milling when using different face milling cutters.

Less amplitude of vibration is generated on the workpiece being cut in up-cut milling.

7.1.9. In planning of cutting tests, firstly the selection of levels of cutting variables such as number of revolution table speed etc., is made.

A typical range of cutter life which can be selected is from 10 to 70 mins, and metal removal rate can give some indication to the production engineer to enable him to choose the levels of cutting variables.

7.2.0. Equivalent chip thickness can also give some guidance in the selection of tooth shape amoung commercially available tooth shapes. The cutting edge which gives the longer engaged cutting edge with the workpiece should be prefered from the cutter life point of view. This is because the heat generated during cutting is easily transfered to the chips, to the cutter and to the workpiece being cut, through the engaged cutting edges. In such a situation, a smaller equivalent chip thickness value is obtained.

7.2.1. In up-cut milling, cutting edges of inserts, which have negative axial rake values, in the Sandvik Cutter showed greater strength than cutting edges of inserts, which have positive axial rake values, in the Walter Cutter.

7.2.2. The exponential form of cutter life equation gives a better fit than the first-degree logarithmic polynominal equation.

7.2.3. By using the T - MR characteristic function, the optimum cutting conditions were obtained. Different optimum values were calculated when using unit-time and unit-cost equations. Generally, one should select low values for the cutting speed, and high values for table speed, and depth of cut, always bearing in mind the horse power limitations of the machine tool and the grade of teeth selected. The replacement time of teeth, the cost of each tooth, operator and overhead cost are significant parameters like the coefficients of the cutter life determined by workpiece material, tooth material, cutting variables etc., in the selection of cutter life, metal removal rate, and cutting variables.

7.2. Future Work

7.2.1. Cutting Tests.

Further cutting tests should be performed taking different values of the equivalent chip thickness as an independent variable with different values of the cutting speeds in the typical domain of cutter life and metal removal rate to be made better appreciation of equivalent chip thickness idea.

7.2.2. Different workpiece materials.

Different types of workpiece materials which are used in industry, mostly ferrous metals with different hardness and geometrical properties, should be tested.

7.2.3. Different cutters.

Different cutters and inserts which are commercially available with different diameters and numbers of teeth should be used on various milling machine tools having different dynamic characteristics.

7.2.4. Cutting force and measurements of cutting force components.

Three dimensional dynamometers, also capable of recording fluctuations on a time basis, should be used in order to complete the machinability data. The relationship between the tangential force and the characteristic feed, which is determined by the average chip thickness and the engagement angle between the cutter and the workpiece being cut, will be obtained in much more simple mathematical form.

APPENDIX I

```
      TRACE 2
      END
```

```
      TRACE 1
      TRACE 2
      MASTER TOMRIS
C     *********************************
C    POVER TRANSFORMATIONS FOR WALTER CUTTER
C     *********************************
C
      DIMENSION VC(50),ECT(50),CT(50),X(15,15),XT(15,15),XC(20,20),
     1A1(2000),A2(2000),BL(2000),XA(20,20),XI(20,20),
     2Y(100),BETA(10,10),U1(100),U(10),B(2000),A(100),SUM(2000),U2(100),
     3ALF1(150),ALF2(150),WKSPACE(10),XK(20,20)
C     *******     INPUT DATA    *********
      READ(1,1) N
      READ(1,1) NOB
      READ(1,2) A1L,A1I,A2L,A2I
      READ(1,3) NCA1,NCA2
      DO  10  I=1,NOB
      READ(1,4) VC(I),ECT(I),CT(I)
 10   CONTINUE
      READ(1,160)(WKSPACE(I),I=1,10)
 160  FORMAT(10A8)
C     *******     FORMATS FOR INPUTS     *********
  1   FORMAT(I0)
 2    FORMAT(4F0.0)
  3   FORMAT(2I0)
  4   FORMAT(3F0.0)
C    ******  ******   ***********
      WRITE(2,198)
 198  FORMAT(//,40X,24H NUMBER OF CALCULATIONS /)
      IT=NCA1*NCA2
      WRITE(2,199) IT
 199  FORMAT(I50)
      DO 15 N5=1,IT
      SUM(N5)=0.0
  15  CONTINUE
      DO 16 M1=1,N
      DO 16 M2=1,N
      XC(M1,M2)=0.0
 16   CONTINUE
      DO 17 N1=1,N
      XA(N1,1)=0.0
  17  CONTINUE
      DO 18 N3=1,N
      BETA(N3,1)=0.0
  18  CONTINUE
      DO 19 N4=1,NOB
      A(N4)=0.0
 19   CONTINUE
      DO 80 I=1,N
      DO 80 J=1,N
      XK(I,J)=0.0
 80   CONTINUE
C    ******      ******      ********
      IJ=1
      VN1=0.0
      DO  21  I1=1,NCA1
```

```
      VN1=VN1+A1I
      ALF1(I1)=A1L+VN1
      VN2=0.0
      DO  20  I2=1,NCA2
      VN2=VN2+A2I
      ALF2(I2)=A2L+VN2
      WRITE(2,500)
  500 FORMAT(//,36X,27H ESTIMATE VALUES OF POWERS /)
      WRITE(2,51) ALF1(I1),ALF2(I2)
   51 FORMAT(F40.5,F15.5)
      WRITE(2,190)
  190 FORMAT(///,30X,37H THE MATRIX OF INDEPENDENT VARIABLES /)
      IF(ALF1(I1).EQ.0.0)  GO TO 700
      DO 650 I=1,NOB
      U1(I)=VC(I)**ALF1(I1)
  650 CONTINUE
      GO TO 660
  700 DO 652 I=1,NOB
      U1(I)=ALOG(VC(I))
  652 CONTINUE
  660 IF(ALF2(I2).EQ.0.0) GO TO 701
      DO 654 I=1,NOB
      U2(I)=ECT(I)**ALF2(I2)
  654 CONTINUE
      GO TO 670
  701 DO 671 I=1,NOB
      U2(I)=ALOG(ECT(I))
  671 CONTINUE
  670 DO 23 I=1,NOB
      X(I,1)=1.0
      X(I,2)=U1(I)
      X(I,3)=U2(I)
      WRITE(2,191) X(I,1),X(I,2),X(I,3)
  191 FORMAT(F35.1,2F14.4)
   23 CONTINUE
      WRITE(2,192)
  192 FORMAT(//,30X,29H THE TRANSPOSE OF THE MATRIX /)
      DO 24 J=1,N
      DO 24 I=1,NOB
      XT(J,I)=X(I,J)
   24 CONTINUE
      WRITE(2,193)((XT(J,I),I=1,NOB),J=1,N)
  193 FORMAT(F15.3,11F9.3)
      WRITE(2,188)
  188 FORMAT(//,30X,31H MULTIPLICATION OF TWO MATRIXS /)
      DO 25 I=1,N
      DO 25 J=1,N
      XK(I,J)=0.0
      DO 25 K=1,NOB
      XK(I,J)=XK(I,J)+XT(I,K)*X(K,J)
   25 CONTINUE
      WRITE(2,189) ((XK(I,J),J=1,N),I=1,N)
  189 FORMAT(F30.5,2F25.5)
C     *******    *******    ******
      WRITE(2,165)
  165 FORMAT(//,35X,18H INVERSE OF MATRIX/)
      IFAIL=0
      CALL F01AAF(XK,20,N,XC,20,WKSPACE,IFAIL)
      IF(IFAIL.EQ.0) GO TO 170
      WRITE(2,150)
  150 FORMAT(1H0,18H FAILURE IN F01AAF)
      STOP
```

```
  170 DO 155 I=1,N
      WRITE(2,156)(XC(I,J),J=1,N)
  156 FORMAT(F30.5,2F25.5)
  155 CONTINUE
C     *****      *****      *****      *****
      WRITE(2,194)
  194 FORMAT(//,30X,41H GEOMETRIC RATIO OF OBSERVED CUTTER LIFE /)
      CAR=1.0
      DO  50  I=1,NOB
      CAR=CAR*CT(I)
   50 CONTINUE
      AN=1.0/NOB
      GMV=CAR**AN
      WRITE(2,195) GMV
  195 FORMAT(F55.4)
      WRITE(2,205)
  205 FORMAT(//,30X,43H TRANSFORMATIONS OF THE DEPENDENT VARIABLE /)
      DO 33 M=1,NOB
      Y(M)=GMV*ALOG(CT(M))
      WRITE(2,206) Y(M)
  206 FORMAT(F55,5)
   33 CONTINUE
      WRITE(2,300)
  300 FORMAT(//,40X,21H SECOND PART OF BETA /)
      DO 34 I=1,N
      XA(I,1)=0.0
      DO 34 J=1,NOB
      XA(I,1)=XA(I,1)+XT(I,J)*Y(J)
   34 CONTINUE
      WRITE(2,301) (XA(I,1),I=1,N)
  301 FORMAT(F55.5)
      WRITE(2,207)
  207 FORMAT(//,30X,34H ESTIMATE VALUES OF COEFFICIENCIES /)
      DO 35 I=1,N
      II=0
      BETA(I,1)=0.0
      DO 35 J=1,N
      II=II+1
      BETA(I,1)=BETA(I,1)+XC(I,J)*XA(II,1)
   35 CONTINUE
      WRITE(2,208) (BETA(I,1),I=1,N)
  208 FORMAT(F55.5)
      IF(ALF1(I1).EQ.0.0) GO TO 800
      DO 750  K1=1,NOB
      U1(K1)=VC(K1)**ALF1(I1)
  750 CONTINUE
      GO TO 760
  800 DO 752  K1=1,NOB
      U1(K1)=ALOG(VC(K1))
  752 CONTINUE
  760 IF(ALF2(I2).EQ.0.0) GO TO 801
      DO 754 K1=1,NOB
      U2(K1)=ECT(K1)**ALF2(I2)
  754 CONTINUE
      GO TO 770
  801 DO 771 K1=1,NOB
      U2(K1)=ALOG(ECT(K1))
  771 CONTINUE
  770 WRITE(2,209)
  209 FORMAT(//,40X,15H THE RESIDUALS /)
      DO 40 L=1,NOB
      U(1)=1.0
```

```
      U(2)=U1(L)
      U(3)=U2(L)
      A(L)=0.0
      DO 41 I=1,N
      A(L)=A(L)+U(I)*BETA(I,1)
 41   CONTINUE
  40  CONTINUE
      DO 45 L=1,NOB
      B(L)=Y(L)-A(L)
      WRITE(2,210) B(L)
 210  FORMAT(F55.5)
  45  CONTINUE
      WRITE(2,211)
 211  FORMAT(//,30X,26H RESIDUALS SUM OF SQUARES /)
      SUM(IJ)=0.0
      DO  42  M=1,NOB
      SUM(IJ)=SUM(IJ)+B(M)*B(M)
  42  CONTINUE
      WRITE(2,212) SUM(IJ)
 212  FORMAT(F50.5)
      WRITE(2,225)
 225  FORMAT(/,30X,26H *****      *****      *****/)
      IJ=IJ+1
      IF(IJ.GT.IT) GO TO 501
   20 CONTINUE
  21  CONTINUE
C    ******      ******      ********
  501 WRITE(2,213)
 213  FORMAT(//,40X,18H THE SMALLEST SUM /)
      COMP=3000000.0
      DO 72 MC=1,IT
      IF(SUM(MC).GT.COMP) GO TO 72
      COMP=SUM(MC)
      IP=MC
  72  CONTINUE
      WRITE(2,214) IP,SUM(IP)
 214  FORMAT(I30,F25.5)
      STOP
      END
```

```
                1.0          46.2617          0.0000
                1.0          46.2617          0,0002
                1.0          46.2617          0,0002
                1.0          46.2617          0,0004
                1,0          54.1288          0,0002
                1,0          54.1288          0,0004
                1,0          65.1572          0,0002
                1,0          65.1572          0,0004

                THE TRANSPOSE OF THE MATRIX

  1,000   1.000   1,000   1.000   1,000   1,000   1,000   1,000   1.000   1.000   1,000   1.000
 27,575  31.950  38,451  38,451  46,262  46,262  46,262  46,262  54,129  54,129  65,157  65,157
  0,000   0.000   0.000   0,000   0,000   0,000   0,000   0.000   0,000   0.000   0.000   0.000

                MULTIPLICATION OF TWO MATRIXS

        12.00000             560,04653             0,00279
       560.04653           27649,55556             0,13743
         0.00279               0.13743             0.00000

                INVERSE OF MATRIX

         1.52518              -0,03053           -73,77131
        -0.03053               0,00076           -21,74650
       -73,77131             -21,74650      46756Y3.65613

                GEOMETRIC RATIO OF OBSERVED CUTTER LIFE

                        31,8555

                TRANSFORMATIONS OF THE DEPENDENT VARIABLE

                       158.03904
                       152,62564
                       131,26645
                       118,83855
                       136,52610
                       116,63125
                       115,97142
                        89,45869
                        96,00101
                        68,67043
                        75,15892
                        62,84562

                SECOND PART OF BETA

                      1322,03133
                     57975,05057
                         0,27215

                ESTIMATE VALUES OF COEFFICIENCIES

                       226,56768
                        -2,06628
                    -65741,68409
```

```
                    THE RESIDUALS

                           -8,85775
                            7,59776
                           -0,30549
                            7,57581
                            5,64105
                            1,17760
                            0,51798
                           -5,68556
                           -3,19696
                           -9,99854
                           -1,25119
                            6,76490

       RESIDUALS SUM OF SQUARES

                 416,63728

       *****      *****      *****


              ESTIMATE VALUES OF POWERS

          0,80000          4,20000


       THE MATRIX OF INDEPENDENT VARIABLES

         1.0        27.5752         0.0000
         1,0        31.9498         0.0001
         1,0        38.4513         0.0001
         1,0        38.4513         0.0003
         1,0        46.2617         0.0000
         1,0        46.2617         0.0001
         1,0        46.2617         0.0001
         1,0        46.2617         0.0003
         1,0        54.1288         0.0001
         1,0        54.1288         0.0003
         1,0        65.1572         0.0001
         1,0        65.1572         0.0003

       THE TRANSPOSE OF THE MATRIX

  1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000   1.000
 27.575  31.950  38.451  38.451  46.262  46.262  46.262  46.262  54.129  54.129  65.157  65.157
  0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000

       MULTIPLICATION OF TWO MATRIXS

      12.00000             560.04655                 0.00186
     560.04655           27649.55536                 0.09163
       0.00186               0.09163                 0.00000

             INVERSE OF MATRIX

       1.52446              -0.03066               -66.54159
      -0.03066               0.00076               -31.45084
     -66.54159             -31.45084           9896955.89148
```

```
TRANSFORMATIONS OF THE DEPENDENT VARIABLE

                    158,03904
                    152,62364
                    131,28645
                    118,83855
                    136,32610
                    116,63125
                    115,97142
                     89,43869
                     96,00101
                     68,87043
                     75,15892
                     62,84582


                SECOND PART OF BETA

                   1322,03155
                  57975,05057
                      0,41061


ESTIMATE VALUES OF COEFFICIENCIES

                    227,14126
                     -2,06433
                 -58953,33894


                THE RESIDUALS

                     -9,04638
                      7,86026
                     -0,05563
                      7,44713
                      5,06266
                      1,41250
                      0,75267
                     -5,82940
                     -2,97754
                    -10,15746
                     -1,05319
                      6,58437


RESIDUALS SUM OF SQUARES

          417,76046

*****      *****      *****



      ESTIMATE VALUES OF POWERS

  0,80000          4,00000



THE MATRIX OF INDEPENDENT VARIABLES

  1,0         27.5752          0.0000
  1,0         31.9498          0.0002
  1,0         38.4513          0.0002
  1,0         38.4513          0.0004
```

```
                    0,36914
                    12,04165

   RESIDUALS SUM OF SQUARES

             592.74297

   *****     *****     *****


             THE SMALLEST SUM

77                416,65728
```

```
                         THE RESIDUALS

                               1.87118
                              -0.04770
                              -1.81470
                              -0.25659
                               0.64009
                              -0.74952
                               0.32947
                              -1.68162
                               0.27344
                               1.65539
                              -0.25945

                RESIDUALS SUM OF SQUARES

                         13.65302

                *****      *****      *****


                     ESTIMATE VALUES OF POWERS

                 -0.20000          5.60000


                THE MATRIX OF INDEPENDENT VARIABLES

                 1.0          0.3847         0.0000
                 1.0          0.3847         0.0000
                 1.0          0.3847         0.0000
                 1.0          0.3698         0.0000
                 1.0          0.3698         0.0000
                 1.0          0.3698         0.0000
                 1.0          0.3698         0.0000
                 1.0          0.3531         0.0000
                 1.0          0.3531         0.0000
                 1.0          0.3531         0.0000
                 1.0          0.3531         0.0000

                THE TRANSPOSE OF THE MATRIX

1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
0.3847   0.3847   0.3847   0.3698   0.3698   0.3698   0.3698   0.3531   0.3531   0.3531   0.3531
0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

                MULTIPLICATION OF TWO MATRIXS

          11.000000              4.045713              0.000085
           4.045713              1.489716              0.000030
           0.000083              0.000030              0.000000

                     INVERSE OF MATRIX

          80.674022           -216.891422          -107808.273121
        -216.891422            585.580850           201691.023125
     -107808.273059         201691.022957       4463814190.936687
```

```
GEOMETRIC RATIO OF OBSERVED CUTTER LIFE

              18,1950


TRANSFORMATIONS OF THE DEPENDENT VARIABLE

              71,75256
              65,40355
              60,62962
              58,42145
              54,86780
              53,47819
              51,55045
              44,27971
              41,80444
              40,17966
              38,28482


          SECOND PART OF BETA

             580,65203
             214,92392
               0,00417


ESTIMATE VALUES OF COEFFICIENCIES

            -220,95961
             757,52331
         -643871,45654


          THE RESIDUALS

               1,89646
              -0,08382
              -1,78641
              -0,21486
               0,60042
              -0,78919
               0,35421
              -1,66392
               0,22974
               1,67610
              -0,21874


RESIDUALS SUM OF SQUARES

          13,62838

*****       *****       *****


          ESTIMATE VALUES OF POWERS

 -0,20000         5,80000


THE MATRIX OF INDEPENDENT VARIABLES
```

```
        GEOMETRIC RATIO OF OBSERVED CUTTER LIFE

                       18,1950

        TRANSFORMATIONS OF THE DEPENDENT VARIABLE

                      71,75256
                      65,40555
                      60,62962
                      58,42145
                      54,86780
                      53,47819
                      51,55045
                      44,27971
                      41,80444
                      40,17966
                      38,28482

                 SECOND PART OF BETA

                     580,65203
                   51289,25508
                       0,00023

       ESTIMATE VALUES OF COEFFICIENCIES

                     127,04155
                      -1,26423
               -10345948,85546

                 THE RESIDUALS

                       2,75910
                       0.27026
                      -1.04993
                      -0,77098
                      -0,44426
                      -1,85587
                      -0,50806
                      -1.14507
                       0,26004
                       2,08880
                       0.19596

      RESIDUALS SUM OF SQUARES

                 18,70728

      *****      *****      *****


                 THE SMALLEST SUM

23                    15,62858
```

APPENDIX II

APPENDIX II

A Calculation of R.S.S. Value using the Walter Milling Cutter Life Results in Down-Cut Milling

The proposed cutter life model was as follows:

$$\dot{T}\ln T = b_o + b_1 V^{\alpha_1} + b_2 h_f^{\alpha_2}$$

For the Walter cutter h_f is taken into account as h_w, Hence;

$$\dot{T}\ln T_w = b_o + b_1 V_w^{\alpha_1} + b_2 h_w^{\alpha_2}$$

The coefficients b_o, b_1 and b_2 are estimated by the method of least squares in the matrix form as;

$$B = (X'X)^{-1}X'y$$

where x is the matrix of independent variables

X' is the transpose of X

$(X'X)^{-1}$ is the inverse of (X'X)

y is the vector of cutter life observations,

i.e., $y = \dot{T}.\ln T$

The matrix of independent variables X is formed using the values of V, h_w, α_1 and α_2. For example, if $\alpha_1 = 0.4$, $\alpha_2 = 0.6$, V and h_w are taken from the table (1), and X is written as follows:

$$X = \begin{vmatrix} 1.0 & 5.251 & 0.211 \\ 1.0 & 5.652 & 0.275 \\ 1.0 & 6.201 & 0.275 \\ 1.0 & 6.201 & 0.311 \\ 1.0 & 6.802 & 0.151 \\ 1.0 & 6.802 & 0.275 \\ 1.0 & 6.802 & 0.275 \\ 1.0 & 6.802 & 0.311 \\ 1.0 & 7.357 & 0.275 \\ 1.0 & 7.357 & 0.311 \\ 1.0 & 8.072 & 0.275 \\ 1.0 & 8.072 & 0.311 \end{vmatrix}$$

The inverse of the product of X and X' is obtained from the computer programme as follows:

$$(X'X)^{-1} = \begin{vmatrix} 6.72329 & -0.69750 & -7.04160 \\ -0.69750 & 0.13407 & -0.78002 \\ -7.04160 & -0.78002 & 45.45204 \end{vmatrix}$$

The geometric mean value of observed cutter life values T is calculated as follows:

$$\dot{T} = (T_1 \cdot T_2 \cdot T_3 \quad \ldots\ldots T_n)^{\frac{1}{n}}$$

$$\dot{T} = 31.835$$

$$y = \dot{T} \ln T_w = \begin{vmatrix} 158.039 \\ 152.623 \\ 131.286 \\ 118.838 \\ 136.326 \\ 116.631 \\ 115.971 \\ 89.438 \\ 96.001 \\ 68.870 \\ 75.158 \\ 62.845 \end{vmatrix}$$

Hence the matrix of the independent variables B is obtained as

$$B = \begin{vmatrix} 372.939 \\ -29.286 \\ -236.582 \end{vmatrix}$$

The value of the residual sum of squares (R.S.S.) is calculated to be 730.382 for this example.

Hence the predicted cutter life equation is written;

$$31.382.\ \ln T_w = 372.939 - 29.286 V_w^{0.4} - 236.582 h_w^{0.6}$$

or

$$\ln T_w = 11.714 - 0.920 V_w^{0.4} - 7.432 h_w^{0.6}$$

The 95 percent confidence interval (CI) for the coefficients under the assumption of spherical normality, is given by;

$$CI(b_i) = b_i \pm t_{v;\,\xi/2}\sqrt{(S^2 . d_{ii})}$$

where $t_{v;\,\xi/2}$ is Student's t - distribution with v degree of freedom which is equal to $(n_o - p)$, ξ the level of significance and d_{ii} is the element of i^{th} row and i^{th} column of the inverse of (X'X). The estimate of the error variance S^2 is calculated;

$$S^2 = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n_o - p}$$

where y_i is the i^{th} observed cutter life and $\hat{y}_i$ predicted cutter life, n_o is the number of observations, and p is the number of coefficients.

For this example S^2 is calculated as;

$$S^2 = \frac{730.382/(31.835)^2}{(12 - 3)}$$

$$S^2 = 0.08$$

For the statistical tables at $v = 9$ and $\xi = 0.05$, t ; 0.025, is obtained to be 2.262. Hence the 95% confidence interval for b_o is

$$CI(b_o) = 11.714 \pm (2.262) \sqrt{(0.08)(6.723)}$$

$$= 11.714 \pm 1.659$$

$$CI(b_o) = \begin{cases} 13.373 \\ 10.055 \end{cases}$$

for b_1 is

$$CI(b_1) = -0.920 \pm (2.262) \sqrt{(0.08)(0.134)}$$

$$= -0.920 \pm 0.234$$

$$CI(b_1) = \begin{cases} -1.154 \\ -0.686 \end{cases}$$

for b_2 is

$$CI(b_2) = -7.432 \pm (2.262) \sqrt{(0.08)(45.452)}$$

$$= -7432 \pm 4.313$$

$$CI(b_2) = \begin{cases} -11.745 \\ -3.119 \end{cases}$$

Two more cutter life equations can be written using lower and upper limits of coefficients obtained as follows;

$$\ln T_w = 10.55 - 1.154 V_w^{0.4} - 11.745 h_w^{0.6}$$

and

$$\ln T_w = 13.373 - 0.686 V_w^{0.4} - 3.119 h_w^{0.6}$$

APPENDIX III

DEPARTMENT

FORTRAN STATEMENT

```
JØB▽:EPP8057,REGWAL,JD(JT▽100,MZ▽20K)
UASTATSXDS3▽▽PAGE,LINES▽1000
WALLIFLP
ØBSERVATION▽MATRIX        MATRX1
CØL▽NAMES                 MATRX1
▽▽VARILVVARECTVASQLVVASQLEVAMLVELNCULI
MATRIX                    MATRX1
  RØW001 4.146  -2.590  17.189  6.708  -10.738  4.964
  RØW002 4.330  -2.154  18.749  4.640   -9.327  4.794
  RØW003 4.562  -2.154  20.812  4.640   -9.827  4.124
  RØW004 4.562  -1.945  20.812  3.783   -8.873  3.733
  RØW005 4.793  -3.147  22.973  9.904  -15.084  4.282
  RØW006 4.793  -2.154  22.973  4.640  -10.324  3.664
  RØW007 4.793  -2.154  22.973  4.640  -10.324  3.643
  RØW008 4.793  -1.945  22.973  3.783   -9.322  2.809
  RØW009 4.989  -2.154  24.890  4.640  -10.746  3.016
  RØW010 4.989  -1.945  24.890  3.783   -9.704  2.163
  RØW011 5.221  -2.154  27.259  4.640  -11.246  2.361
  RØW012 5.221  -1.945  27.259  3.783  -10.155  1.974
END OF DATA
CRØSS PRODUCT             MATRX1
CØVARIANCE                MATRX1
CØRRELATION               MATRX1
```

CC/F

DEPARTMENT

FORTRAN STATEMENT

```
PRINT OBSERVATIONS        MATRX1  LP
PRINT MEANS               MATRX1  LP
PRINT MEANS               MATRX1  LP   S
PRINT CØRRELATION         MATRX1  LP
REGRESSIØN ANALYSIS       MATRX1        CØVA
DEPENDENT VARIABLE        LNCULI
INDEPENDENT VARIABLES AT SIG LEVEL  99.00
  VARILVVARECTVASQLVVASQLEVAMLVE
PRINT REGRESSION LP
DEPENDENT VARIABLE        LNCULI
INDEPENDENT VARIABLES AT SIG LEVEL  99.00
  VARILVVARECT
PRINT REGRESSION LP
GETØFF
****
```

CC/F

```
                    13/47/57    22/07/76     ICL  1900 STATISTICAL ANALYSIS    XDS3/22
REGRESSION ANALYSIS     COVA     MATRX1    CUT OFF PARAMETER  .100000E- 5
DEPENDENT VARIABLF    LNCULI      DEGREES OF FREEDOM               6
INDEPENDENT VARIARLES AT SIGNIFICANT LFVEL      99.00 X
  VARILV  VARECT  VASQLV  VASQLE  VAMLVE
   VARIABLES     IN THE REGRESSION SET

 VAR      REGRESSION        STANDARD        CONFIDENCE   T STAT  PART     MULTIPLE          E S S
 NAME        COEFF            ERROR           INTERVAL                CORR  CORRELATION
VARILV -    12.9947108     .101370E  2                   1.28  -0.46  0.987           .286528E  0
VARECT       6.8463338     .642788E  1                   1.07   0.40  0.988           .267452E  0
VASQLV       0.3467439     .840642E  0                   0.41   0.17  0.989           .231303E  0
VASQLF -     1.6002637     .576856E  0                   2.77  -0.75  0.976           .513417E  0
VAMLVE -     3.3558364     .120615E  1                   2.78  -0.75  0.976           .514770E  0
   VARIABLES NOT IN THE REGRESSION SET
 VAR
 NAME                                                T STAT  PART     MULTIPLE          E S S
                                                             CORR  CORRELATION
E.S.S.          .224925E  0
RESIDUAL ERROR  .193617E  0
MULT CORR       0.990
INTERCEPT TERM          45.3913390
```

APPENDIX IV

NAME

DEPARTMENT

Pa

FORTRAN STATEMENT

```
JØB∇:EPP8057,REGSAN,JD(JT∇100,MZ∇30K)
UASTATSXDS3∇∇PAGE,LINES∇1000
SANLIFLP
ØBSERVATION MATRIX        MATRIX
CØL NAMES                 MATRIX
  VARILVVARECTVASQLVVASQLEVAMLVELNCULI
MATRIX                    MATRIX
  RØW001 4.777  -2.488  22.819  6.190  -11.885 3.944
  RØW002 4.777  -2.103  22.819  4.422  -10.046 3.595
  RØW003 4.777  -2.017  22.819  4.068   -9.635 3.332
  RØW004 4.973  -2.488  24.730  6.190  -12.372 3.211
  RØW005 4.973  -2.103  24.730  4.422  -10.458 3.016
  RØW006 4.973  -2.103  24.730  4.422  -10.458 2.939
  RØW007 4.973  -2.017  24.730  4.068  -10.030 2.833
  RØW008 5.205  -2.488  27.092  6.190  -12.950 2.434
  RØW009 5.205  -2.103  27.092  4.422  -10.946 2.298
  RØW010 5.205  -2.017  27.092  4.068  -10.498 2.208
  RØW011 5.205  -2.017  27.092  4.068  -10.498 2.104
END ØF DATA
CRØSS PRØDUCT             MATRIX
CØVARIANCE                MATRIX
CØRRELATION               MATRIX
PRINT ØBSERVATIONS        MATRIX  LP
```

CCF

NAME

DEPARTMENT

FORTRAN STATEMENT

```
PRINT MEANS               MATRIX  LP
PRINT MEANS               MATRIX  LP   S
PRINT CØRRELATIØN         MATRIX  LP
REGRESSIØN ANALYSIS       MATRIX        CØVA
DEPENDENT VARIABLE        LNCULI
INDEPENDENT VARIABLES AT SIG LEVEL  99.00
  VARILVVARECTVASQLVVASQLEVAMLVE
PRINT REGRESSIØN LP
DEPENDENT VARIABLE        LNCULI
INDEPENDENT VARIABLES AT SIG LEVEL 99.00
  VARILVVARECT
PRINT REGRESSIØN LP
GETØFF
****
```

CCF

```
                    16/42/35    11/08/76     ICL  1900 STATISTICAL ANALYSIS    XDS3/25
REGRESSION ANALYSIS     COVA    MATRIX    CUT OFF PARAMETER  .100000E- 5
DEPENDENT VARIABLE     LNCULI     DEGREES OF FREEDOM              5
INDEPENDENT VARIABLES AT SIGNIFICANT LEVEL      99.00 %
  VARILV  VARECT  VASQLV  VASQLE  VAMLVE
   VARIABLES      IN THE REGRESSION SET

 VAR      REGRESSION        STANDARD      CONFIDENCE   T STAT  PART    MULTIPLE          E S S
 NAME        COEFF           ERROR         INTERVAL            CORR  CORRELATION
VARILV      62.4403845    .491271E  2                    1.27   0.49  0.907           .773437E  0
VARECT      19.9328396    .361282E  2                    0.55   0.24  0.926           .620159E  0
VASQLV -     6.3865373    .483833E  1                    1.32  -0.51  0.905           .788278E  0
VASQLE       5.4365110    .693009E  1                    0.78   0.33  0.921           .656520E  0
VAMLVE       0.8572893    .303654E  1                    0.28   0.13  0.929           .593889E  0
E.S.S.            .584571E  0
RESIDUAL ERROR  .341927E  0
MULT CORR         0.930
INTERCEPT TERM       -  122.5965160
```

APPENDIX V

```
DATA


   X[1]          Y

← 0.00          0.00
 0.000000    0.000000
← 36.82         2.83
 36.82000    2.830000
← 43.31        3.55
 43.31000    3.550000
← 50.10        4.80
 50.10000    4.800000
← 52.18        3.93
 52.18000    3.930000
← 58.18        4.07
 58.18000    4.070000
← 58.25        4.10
 58.25000    4.100000
← 63.40        4.70
 63.40000    4.700000
← 71.03        5.55
 71.03000    5.550000
← 80.07        6.33
 80.07000    6.330000
← 104.34       7.70
 104.3400    7.700000




INDEPENDENT VARIABLE X1


XBAR          56.15273

YBAR          4.323636

VARIANCE      0.151904


LINEAR REGRESSION OF Y ON X1

     Y =  0.177894  +    0.0738 X1

CORRELATION COEFFICIENT  R=  0.982



95% CONFIDENCE LIMITS:

  INTERCEPT  -0.473916     TO    0.829703

    SLOPE       0.0632     TO      0.0844

      R         0.931      TO      0.996

← -1
```

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Number of Tests	Cutting speed V_W (m/min)	Equivalent chip thickness h_W (mm)	Cutter Life T (mins)
1	63.19	0.075	143.2
2	75.96	0.116	120.8
3	95.75	0.116	61.8
4	95.75	0.143	41.8
5	120.65	0.043	72.4
6	120.65	0.116	39.0
7	120.65	0.116	38.2
8	120.65	0.143	16.6
9	146.82	0.116	20.4
10	146.82	0.143	8.7
11	185.12	0.116	10.6
12	185.12	0.143	7.2

Table 1.

Cutter life Test Results in Down-Cut Milling

Materials : Tool Steel
(B.H.N. 238)

Cutter: Walter Cutter

Number of Tests	Cutting speed V_s (m/min)	Equivalent Chip Thickness h_s (mm)	Cutter Life T (mins)
1	118.75	0.083	51.6
2	118.75	0.122	36.4
3	118.75	0.133	28.4
4	144.51	0.083	24.8
5	144.51	0.122	20.8
6	144.51	0.122	18.9
7	144.51	0.133	17.0
8	182.21	0.083	11.4
9	182.21	0.122	9.95
10	182.21	0.133	9.1
11	182.21	0.133	8.2

Table 2.

Cutter Life Test Results in Down-cut Milling.

Material : Tool Steel (B.H.N.238)

Cutter : the Sandvik Cutter

Number of Tests	Cutting speed V_s (m/min)	Equivalent Chip Thickness h_s (mm)	Cutter Life T (mins)
1	118.75	0.083	Two edges were chipped at the first pass
2	118.75	0.122	Three edges were chipped at the first pass
3	118.75	0.133	Three edges were chipped after 0.328 mm flank wear.
4	144.51	0.083	Two edges were chipped at the first pass
5	144.51	0.122	Two edges were chipped after 0.320 mm flank wear.
6	144.51	0.133	20.1
7	182.21	0.083	12.6
8	182.21	0.122	10.9
9	182.21	0.133	11.49
10	182.21	0.133	11.17
11	213.62	0.083	8.1
12	213.62	0.122	7.91
13	213.62	0.133	5.74

Table 3.

Cutter Life Tests Results in Up-Cut Milling

Material : Tool Steel
(B.H.N. 197)
Cutter : the Sandvik Cutter

Number of Tests	Cutting speed V_w (m/min)	Equivalent Chip Thickness h_w (nm)	Cutter Life T (mins)
1	120.65	0.091	Four edges were chipped at the first pass
2	120.65	0.127	Two edges were chipped after the 5 mins cutting
3	120.65	0.143	Two edges were chipped at the second pass.
4	146.82	0.091	Three edges were chipped at the first pass.
5	146.82	0.127	Two edges were chipped at the first pass.
6	146.12	0.143	Five edges were chipped at the first pass.
7	185.12	0.091	Two edges were chipped at the second pass.
8	185.12	0.127	9.48
9	185.12	0.143	Three edges were chipped at the second pass.

Table 4.

Cutter Life Test Results in Up-Cut Milling

Material : Tool Steel
(B.H.N.197)
Cutter : the Walter Cutter

Test No.	Metal Removal Rate (in cm^3/min)	Power required at the cutter in H.P.
5	17.25	1.73
1	22.90	1.83
2	29.03	2.20
7	30.38	2.30
3	32.14	2.40
8	50.10	3.50
4	52.84	3.60
9	56.05	4.37
10	61.18	4.60
6	72.81	5.50
12	77.10	5.80
11	87.49	6.70

Table 5

Power Required at the Walter Cutter in Down-cut Milling

Material : Tool Steel
(B.H.N. 238)

Test No.	Metal Removal Rate in cm^3/min	Power Required at the cutter in H.P.
1	36.83	2.83
4	43.31	3.55
8	50.10	4.80
3	52.18	3.93
2	58.18	4.07
5	58.25	4.10
7	63.40	4.70
6	71.03	5.55
10 and 11	80.07	6.33
9	104.34	7.70

Table 6

Power Required at the Sandvik Cutter in Down-Cut Milling

Material : Tool Steel
(B.H.N. 238)

Test No.	Metal Removal Rate in cm^3/min	Power Required at the cutter in H.P.
7	52.54	3.5
6	66.95	4.0
11	73.40	5.97
9 and 10	85.88	6.30
13	95.67	6.50
12	97.51	6.57
8	104.26	7.37

Table 7

Power required at the Sandvik Cutter in Up-cut Milling

Material : Tool Steel
(B.H.N. 197)

Test No.	Cutting speed V_w (in m/min)	Feed per tooth f (in mm/tooth)	Surface Finish (C.L.A.) (in μm)
1	63.19	0.224	2.5
2	75.96	0.235	0.64
3	95.75	0.233	0.44
4	95.75	0.286	0.58
5	120.75	0.148	0.44
6	120.75	0.227	0.49
7	120.75	0.285	0.44
8	120.75	0.286	0.36
9	146.82	0.235	0.51
10	146.82	0.297	0.54
11	185.82	0.235	0.44
12	185.82	0.292	0.48

Table 8

Surface Finish (C.L.A. index) in Down-cut Milling

Material : Tool Steel
(B.H.N. 238)
Cutter : the Walter
Cutter

Test No.	Cutting speed V_s (in m/min)	Feed per tooth (in mm/tooth)	Surface Finish (C.L.A.) (in μm)
1	118.75	0.185	0.46
2	118.75	0.226	0.33
3	118.75	0.286	0.27
4	144.75	0.185	0.31
5	144.75	0.297	0.27
6	144.75	0.235	0.30
7	144.75	0.297	0.35
8	182.21	0.186	0.46
9	182.21	0.235	0.20
10	182.21	0.292	0.20
11	182.21	0.292	0.18

Table 9

Surface Finish (C.L.A. index) in Down-cut Milling.

Material : Tool Steel (B.H.N. 238)

Cutter : the Sandvik Cutter

Test No.	Cutting speed V_s (in m/min)	Feed per tooth (in mm/tooth)	Surface Finish (C.L.A.) (in μm)
6	144.51	0.286	0.88
7	182.21	0.186	0.18
8	182.21	0.235	0.85
9	182.21	0.292	0.23
10	182.21	0.292	0.25
11	213.62	0.159	0.47
12	213.62	0.249	0.28
13	213.62	0.306	0.45

Table 10

Surface Finish (C.L.A.index) in Up-cut Milling

Material : Tool Steel
(B.H.N.197)
Cutter : The Sandvik
Cutter

Test No.	Cutting speed V_w (in m/min)	Maximum Area = d.f s_{max} (in mm^2)	P.T.P.VIB. AMP. in Axial direction (in μ m)	P.T.P.VIB.AMP in Feed direction (in μ m)
1	63.19	0.569	9	30
2	75.96	0.357	7	27
3	95.75	0.294	7	24
4	95.75	0.543	9	31
5	120.65	0.225	8	25
6	120.65	0.633	14	42
7	120.65	0.219	5	19
8	120.65	0.363	8	24
9	146.82	0.357	7	25
10	146.82	0.377	8	23
11	185.82	0.477	14	30
12	185.82	0.371	10	22

Table 11

Amplitudes of Vibrations in Axial and Feed directions in Down-Cut Milling

Material: Tool Steel
(B.H.N. 238)
Cutter : the Walter
Cutter

Test No.	Cutting speed V_s (in m/min)	Maximum Area = d.f s_{max} (in mm^2)	P.T.P.VIB.AMP in Axial direction (in μm)	P.T.P.VIB.AMP in Feed direction (in μm)
1	118.75	0.305	9	27
2	118.75	0.431	11	34
3	118.75	0.363	10	25
4	144.51	0.281	7	17
5	144.51	0.377	6	21
6	144.51	0.448	6	23
7	144.51	0.377	6	20
8	182.21	0.236	7	14
9	182.21	0.597	10	35
10	182.21	0.371	8	20
11	182.21	0.371	8	20

Table 12

Amplitudes of Vibrations in Axial and Feed directions in Down-cut Milling

Material : Tool Steel
(B.H.N. 238)
Cutter : the Sandvik
Cutter.

Test No.	Cutting speed V_s (in m/min)	Maximum Area = d.f. s_{max} (in mm^2)	P.T.P.VIB.AMP in Axial Direction (in μm)	P.T.P.VIB.AMP. in Feed Direction (in μm)
6	144.51	0.406	9	30
7	182.21	0.262	4	14
8	182.21	0.597	7	22
9	182.21	0.429	7	20
10	182.21	0.429	7	20
11	213.62	0.323	5	18
12	213.62	0.411	6	16
13	213.62	0.407	5	20

Table 13

Amplitudes of Vibrations in Axial and Feed directions in Up-cut Milling

Material : Tool Steel
(B.H.N. 197)
Cutter : the Sandvik
cutter.

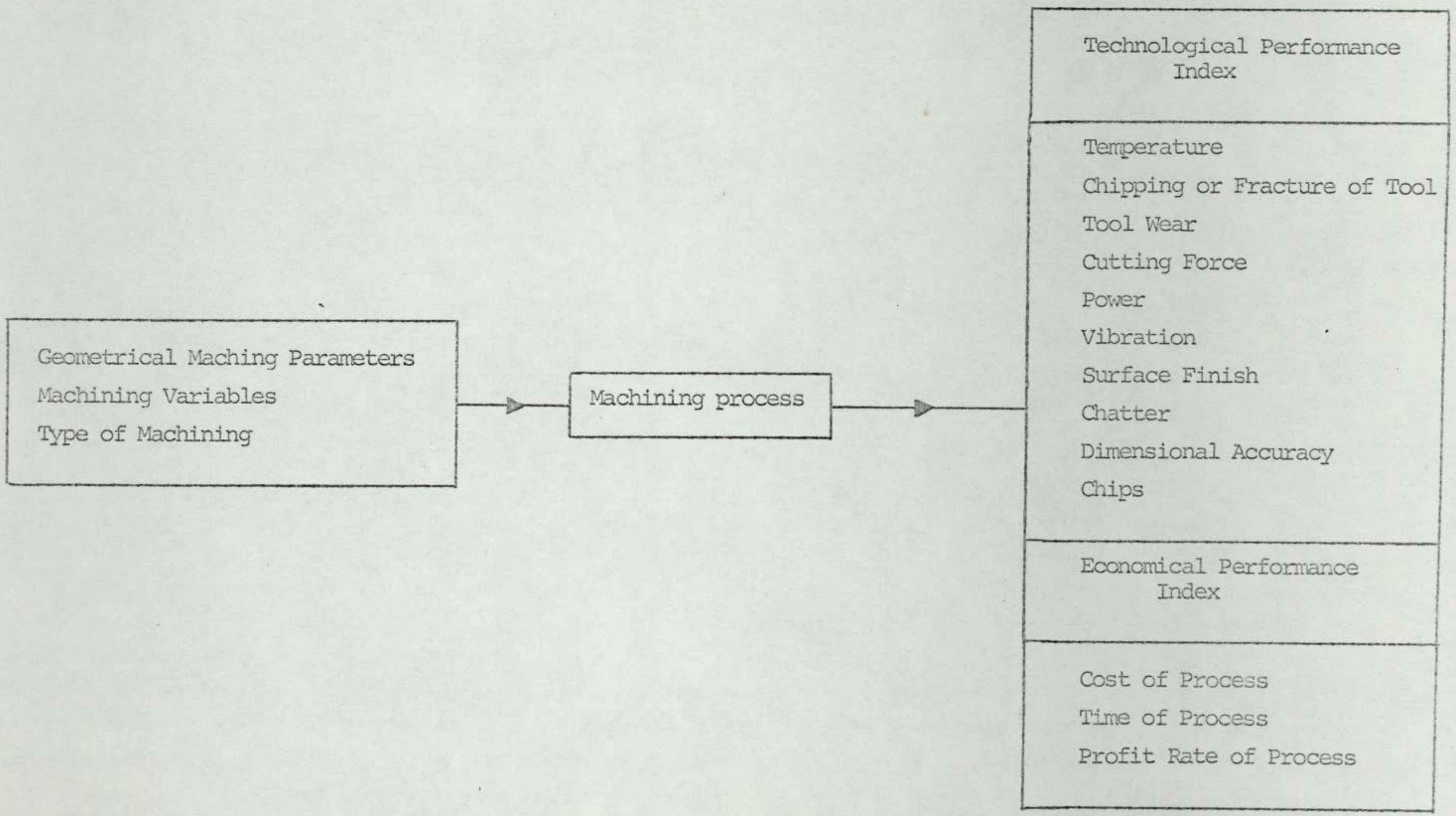


Fig. 1. Responses of Machining Process

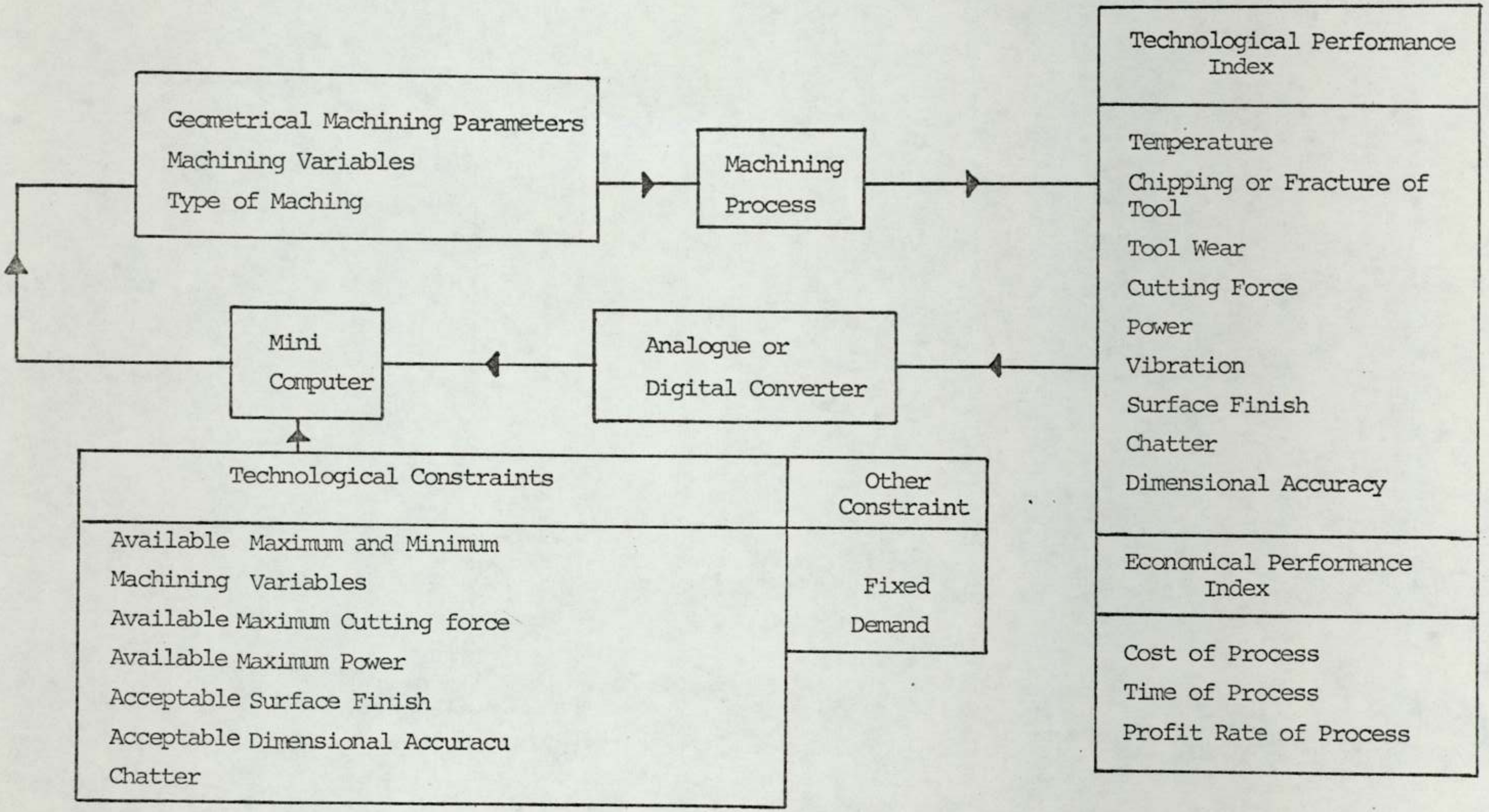


Figure 2. Controlled Machining Process

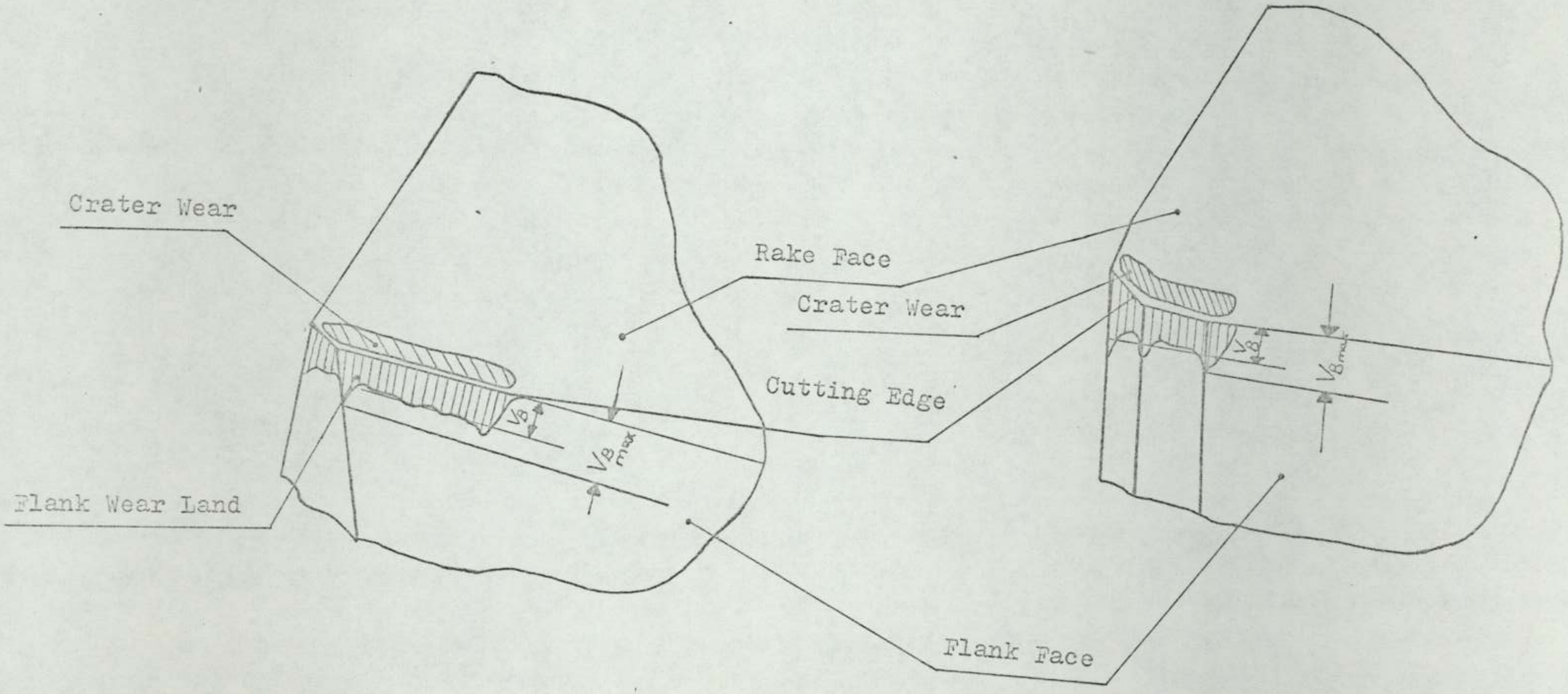


Fig.3 General Configuation of Wear of Cutting Edge

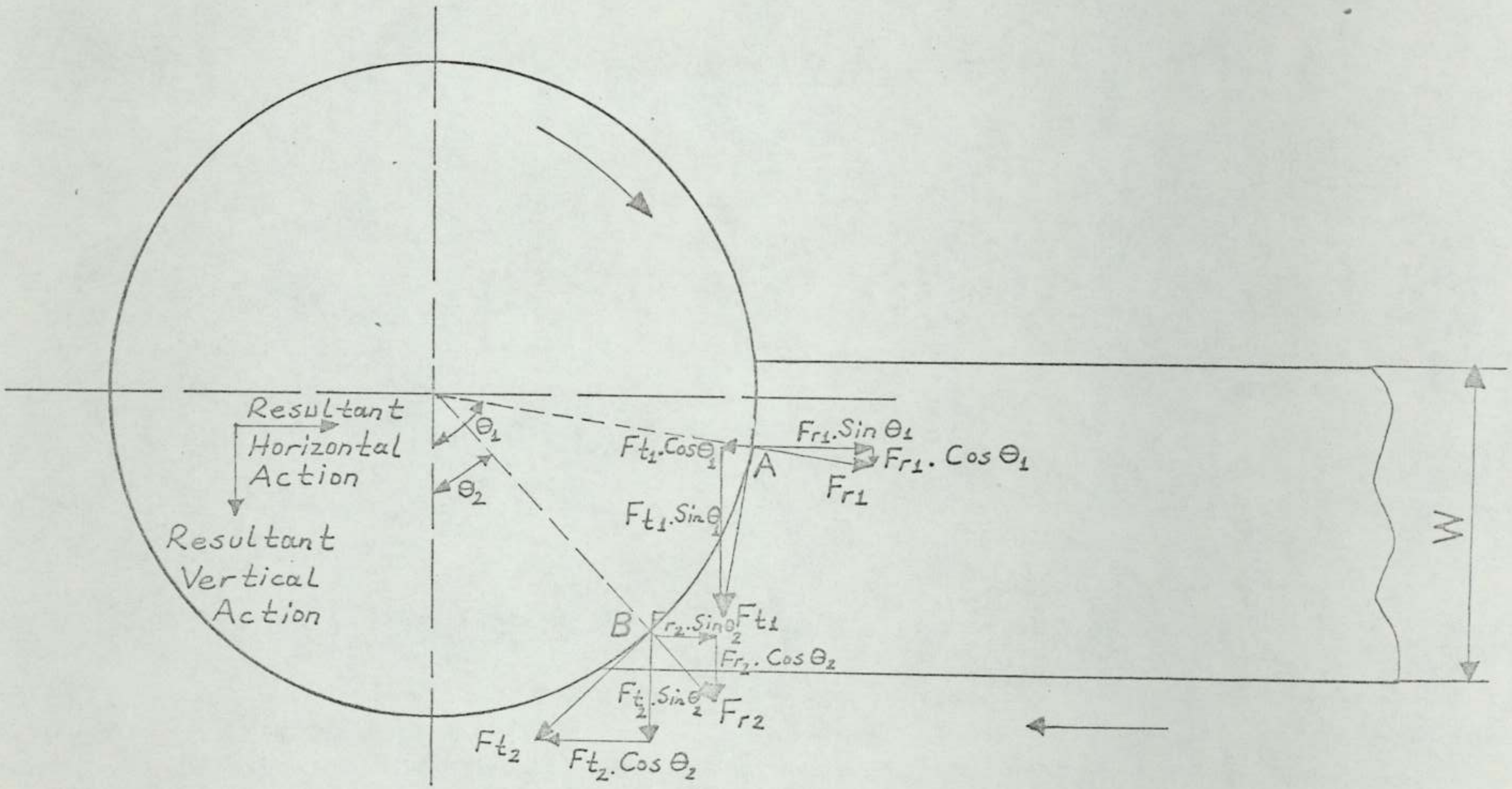


Fig.4 Resolution Diagram of Forces in Down-Cut Face Milling

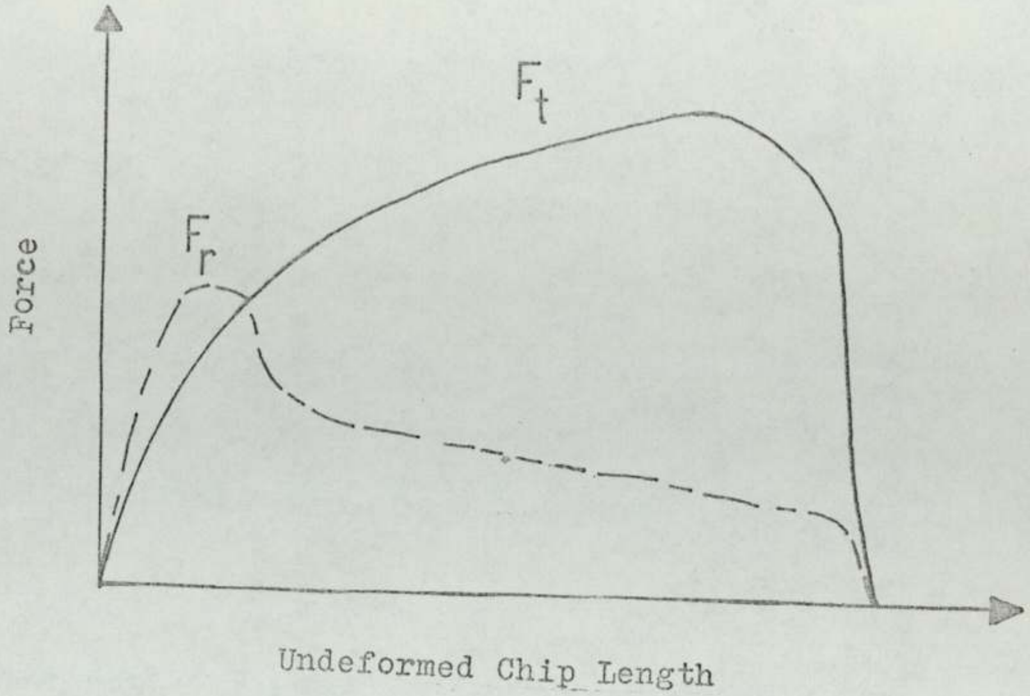


Fig.5 Relationship between Forces Acting on Cutter Tooth and Undeformed Chip Thickness in Up-Cut Peripheral Milling

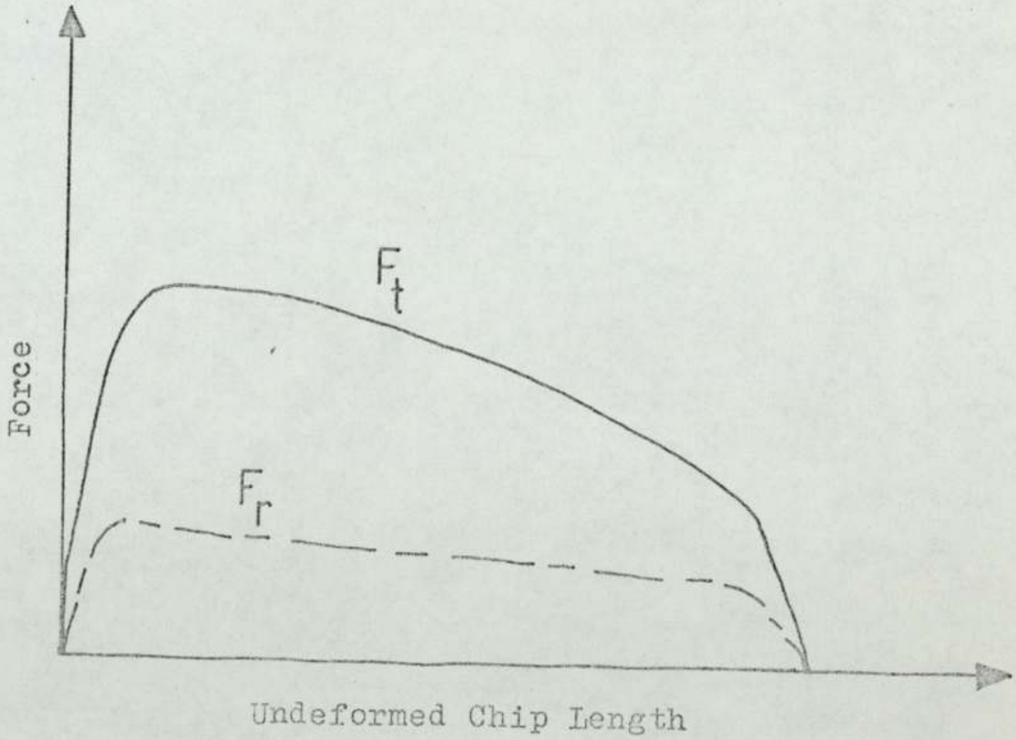
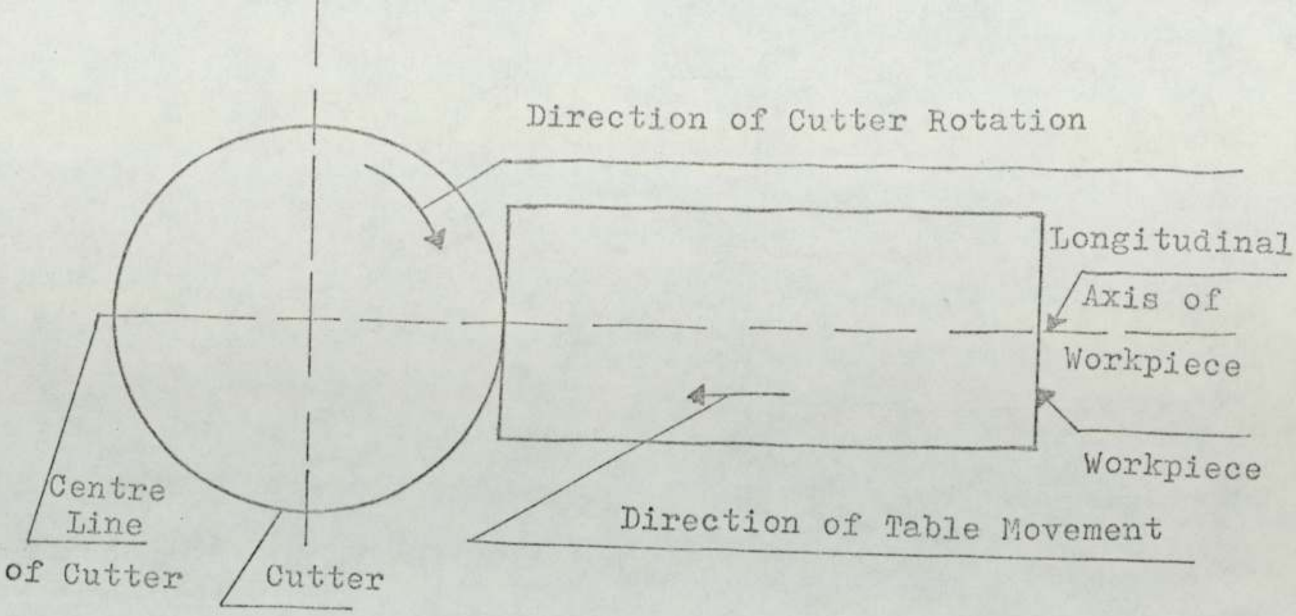
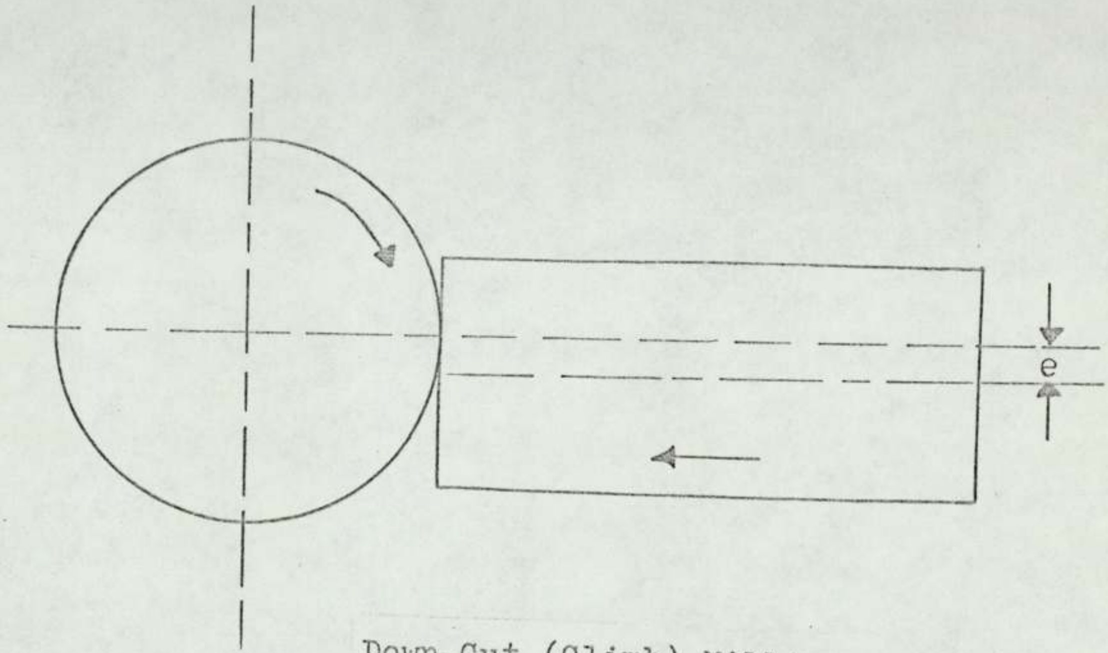


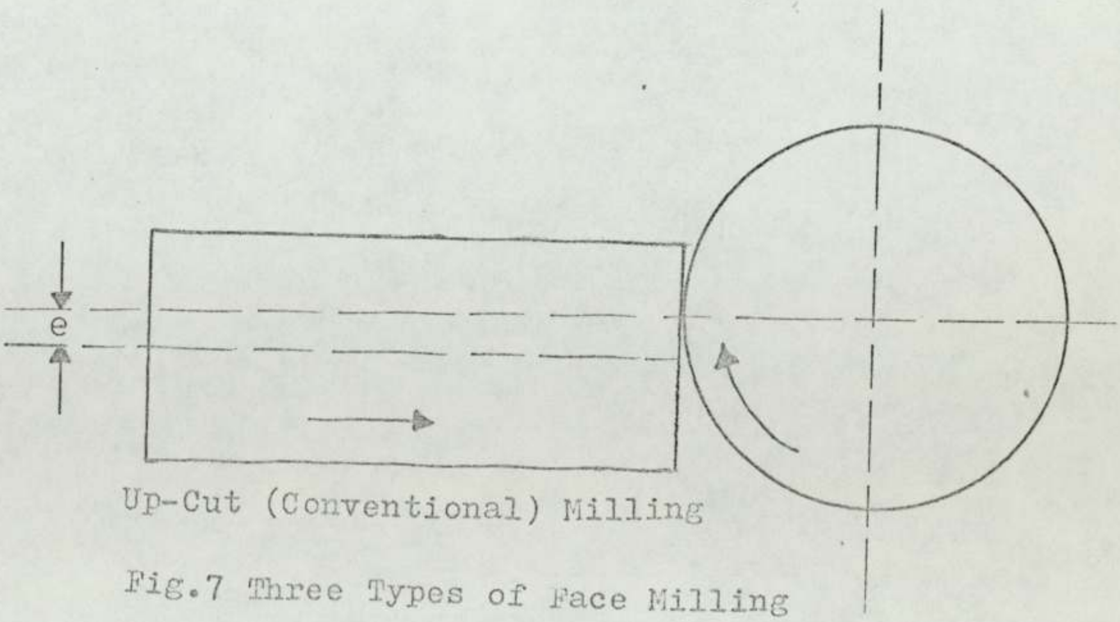
Fig.6 Relationship between Forces Acting on Cutter Tooth and Undeformed Chip Thickness in Down-Cut Peripheral Milling



Central Milling

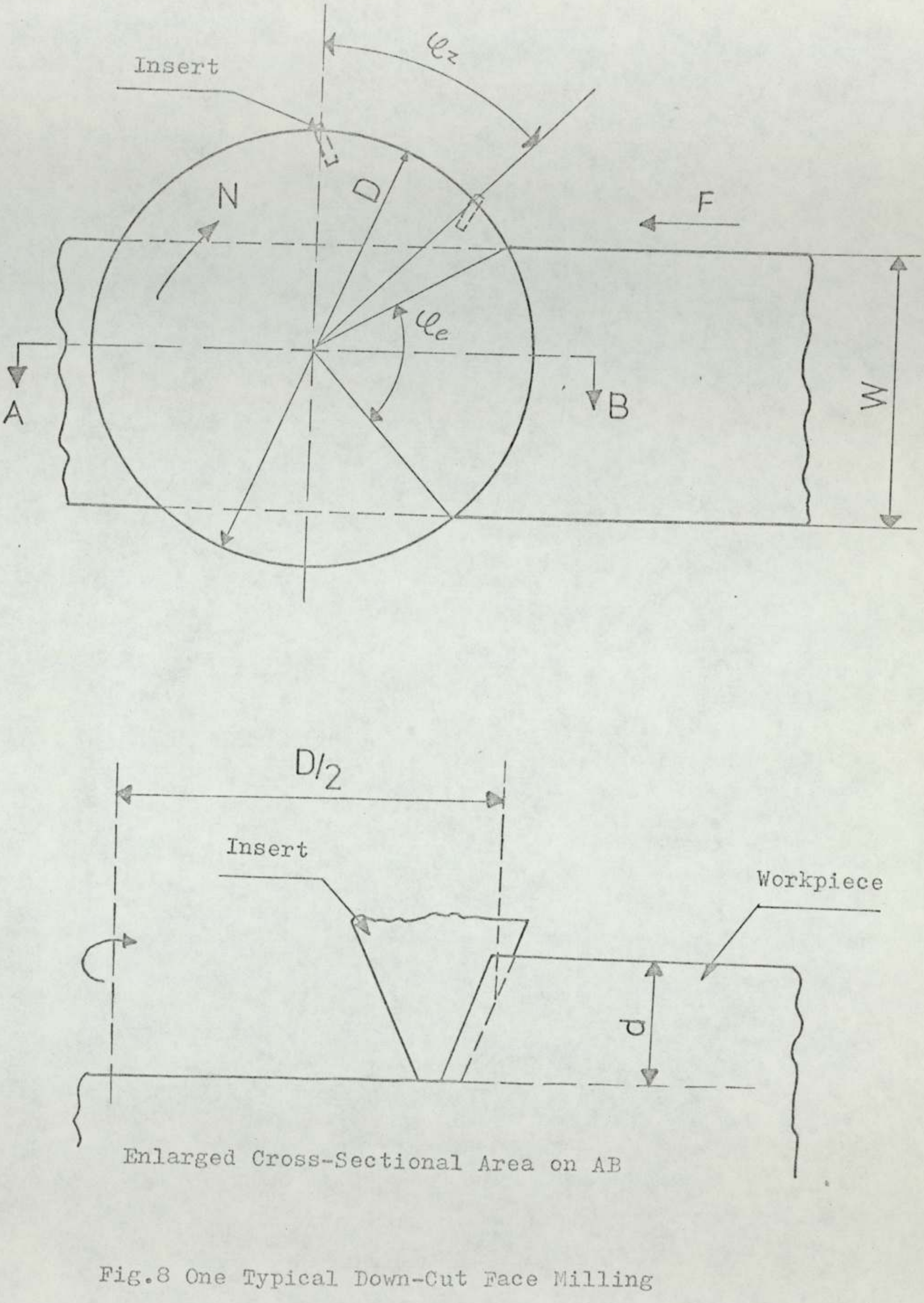


Down-Cut (Climb) Milling



Up-Cut (Conventional) Milling

Fig.7 Three Types of Face Milling



Enlarged Cross-Sectional Area on AB

Fig.8 One Typical Down-Cut Face Milling

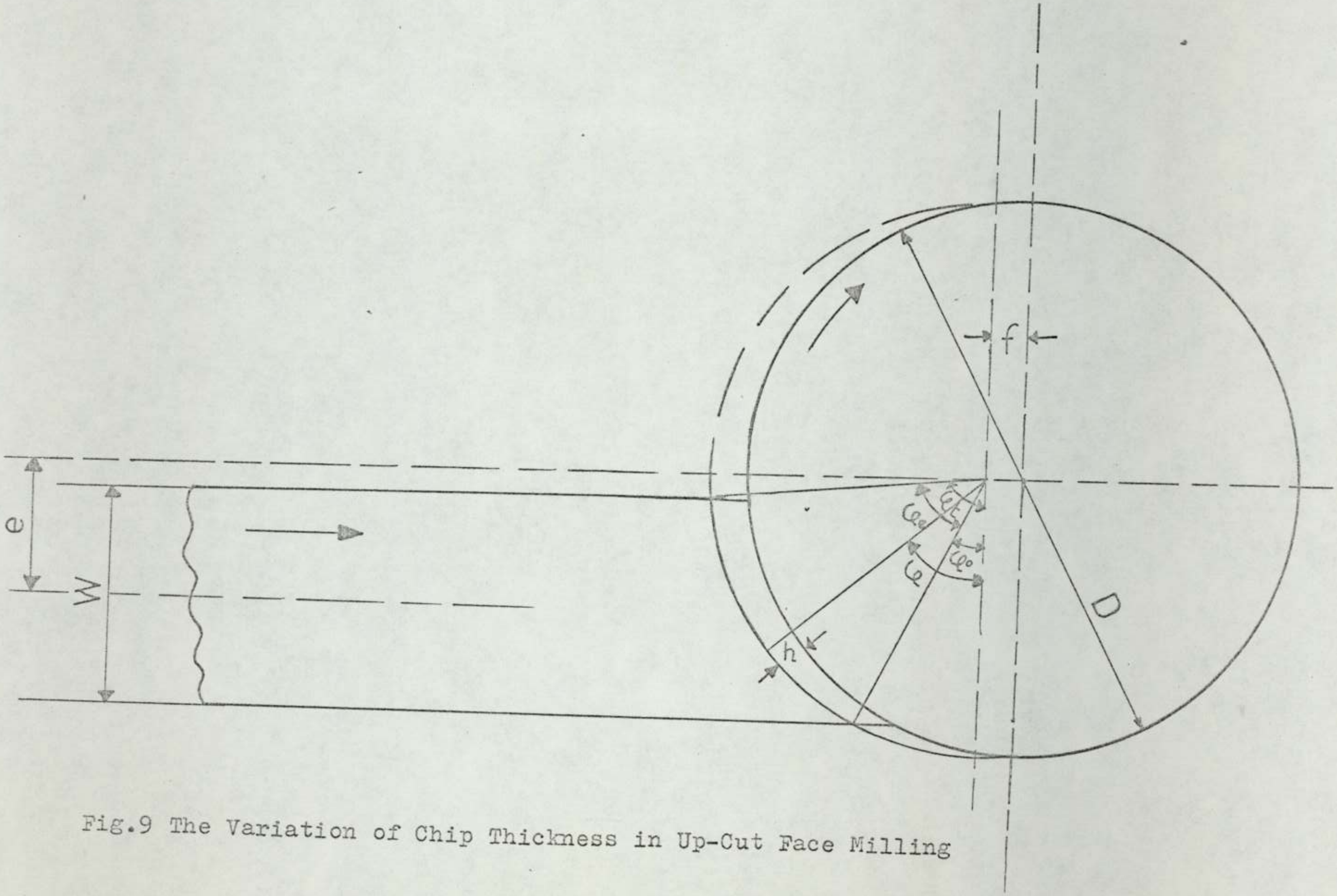


Fig.9 The Variation of Chip Thickness in Up-Cut Face Milling

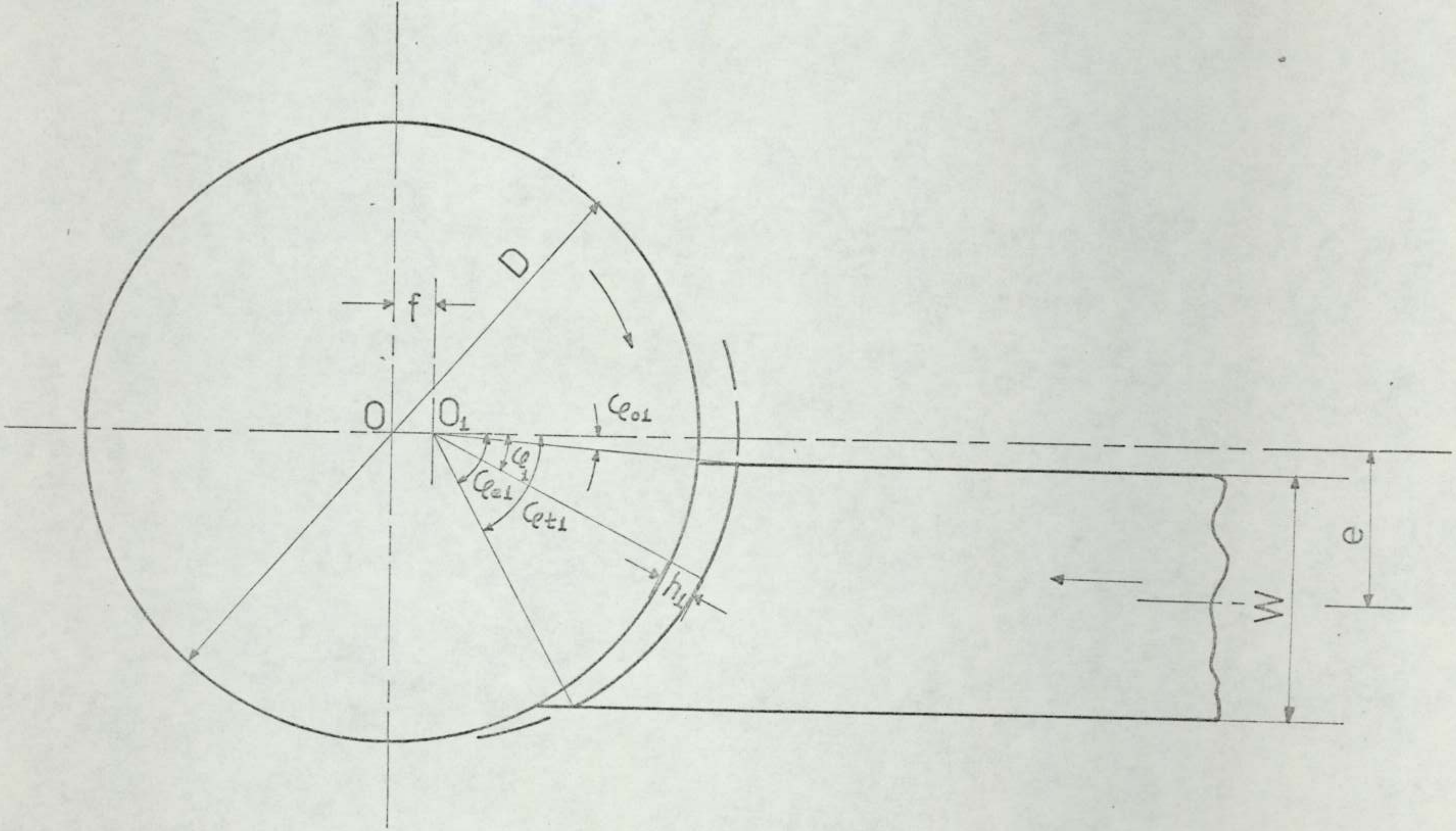


Fig. 10 The Variation of Chip Thickness in Down-Cut Milling

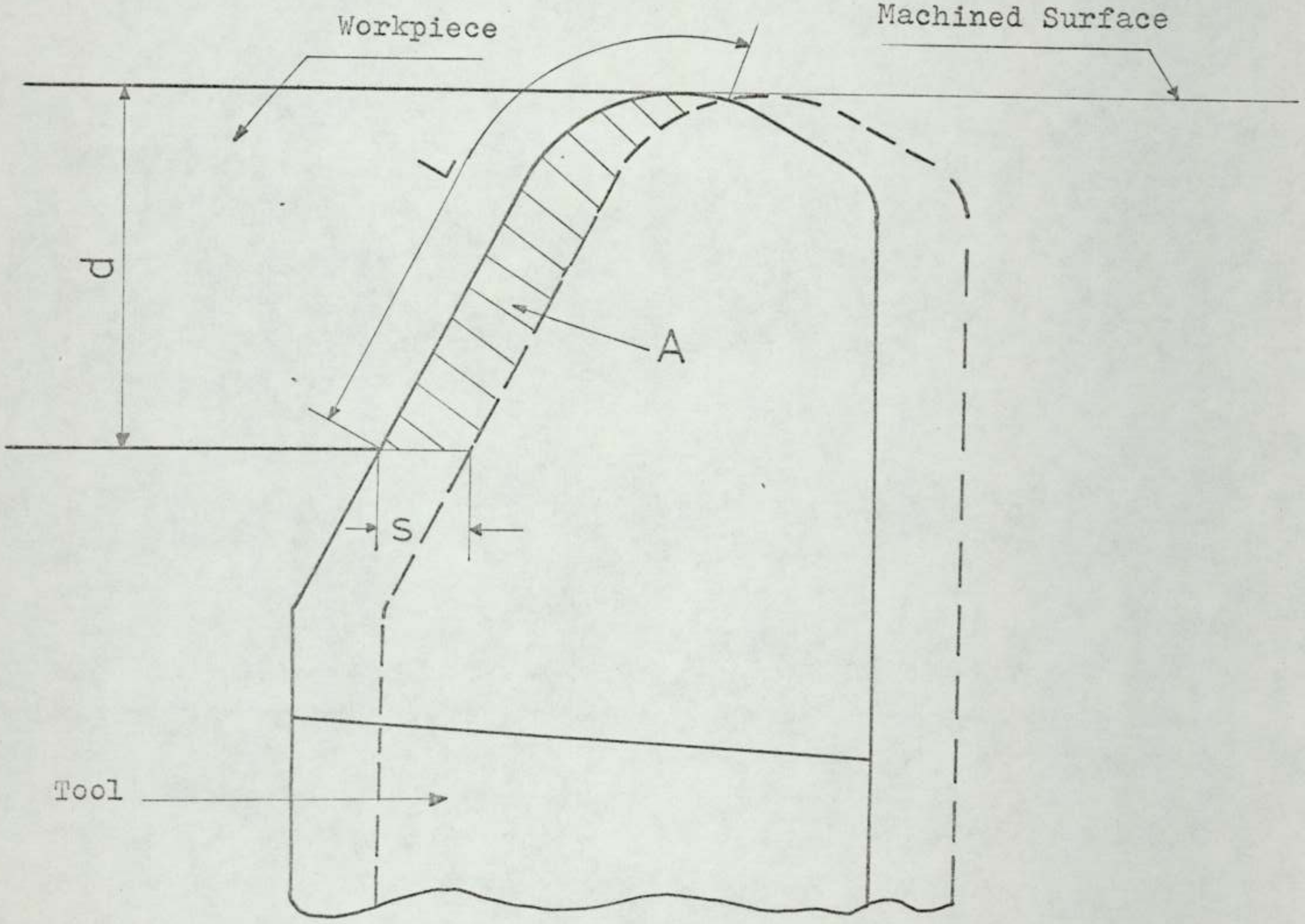


Fig. 11 General Configuration of Area Cut A and length engaged with workpiece L

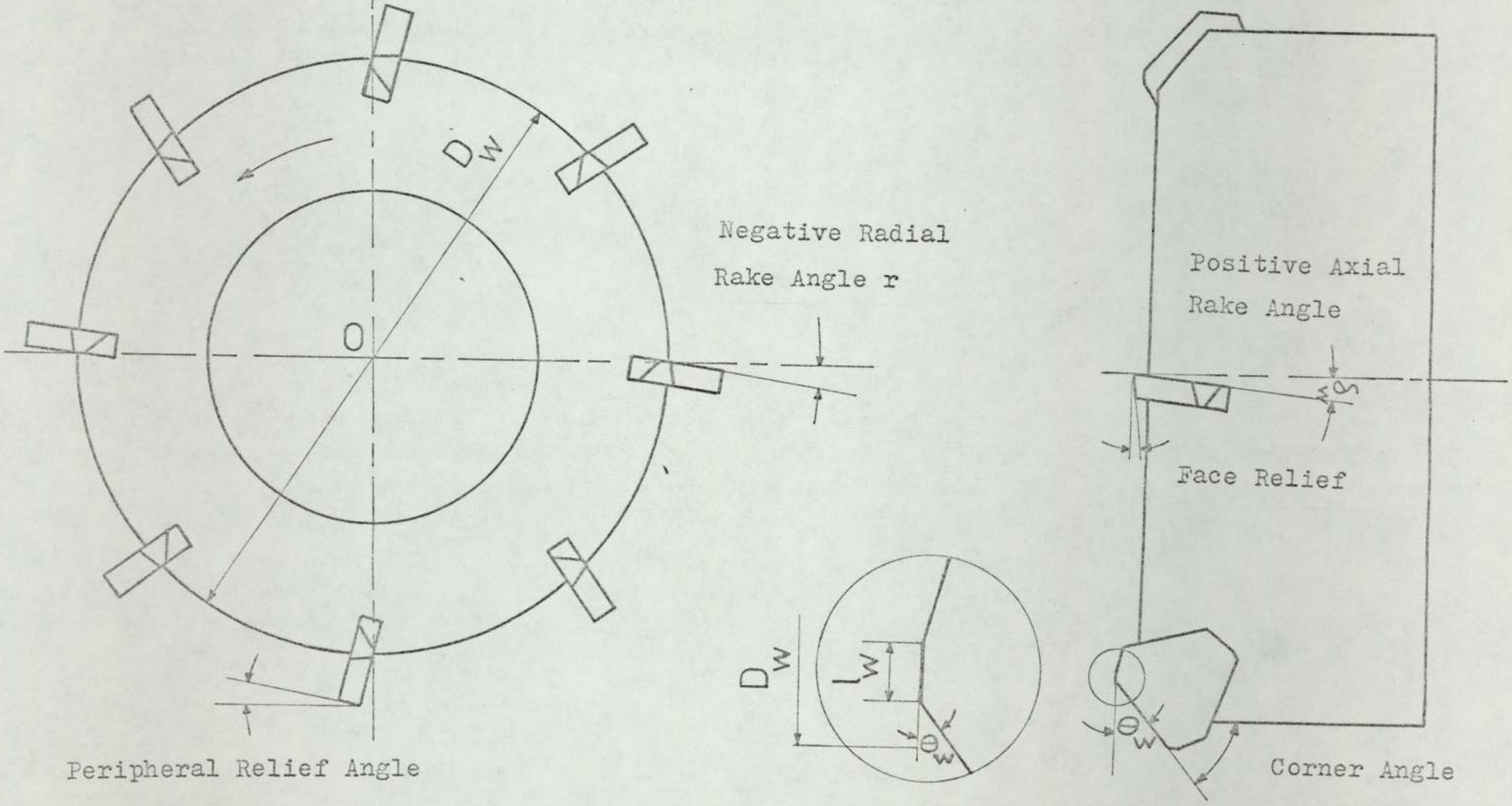


Fig. 12 Wendelnovex F244 Walter Milling Cutter with Indexable Rigth Hand P25 inserts

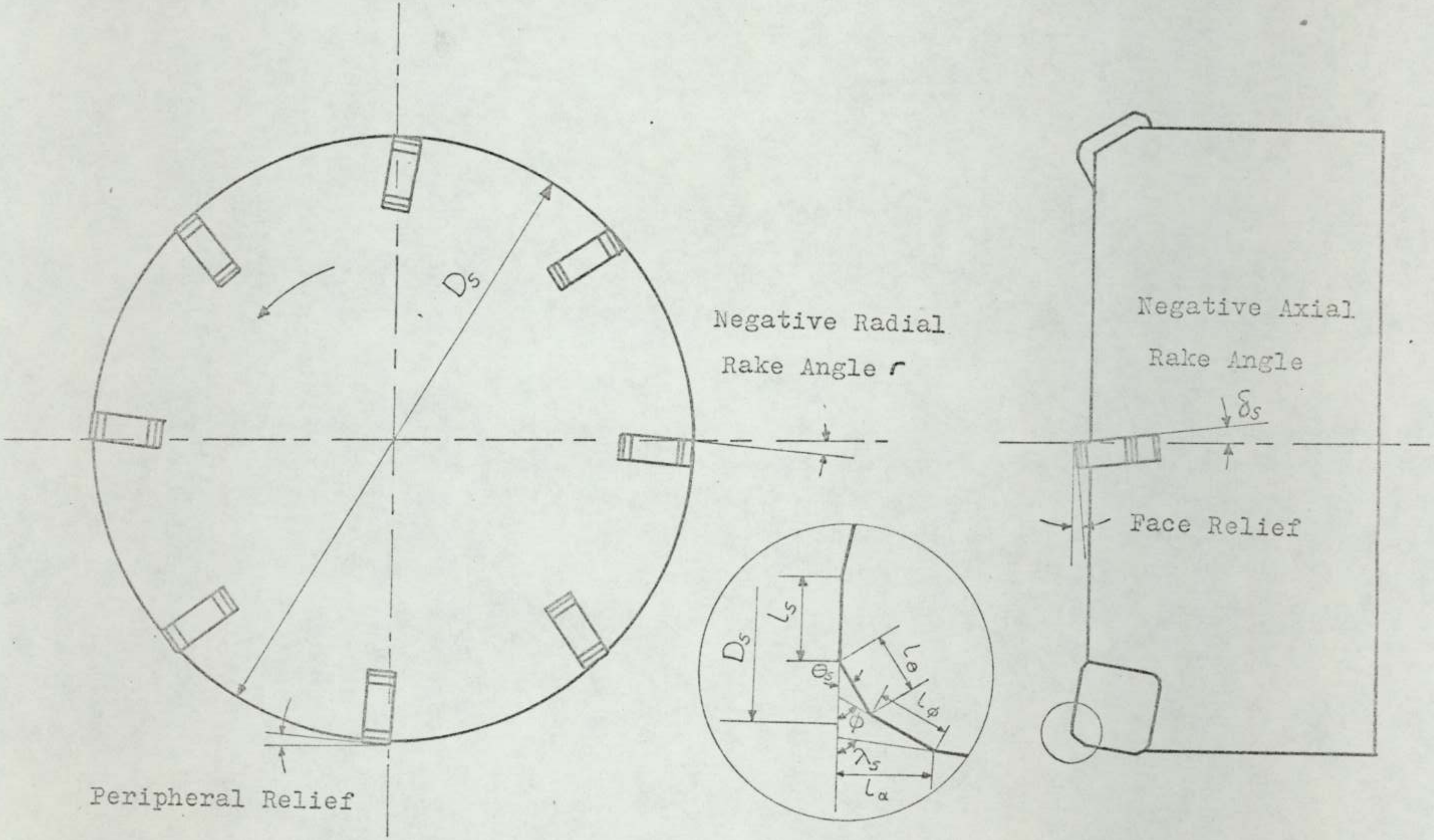


Fig.13 T-Max 265.1 Sandvik Milling Cutter with Indexable Right Hand P25 Inserts

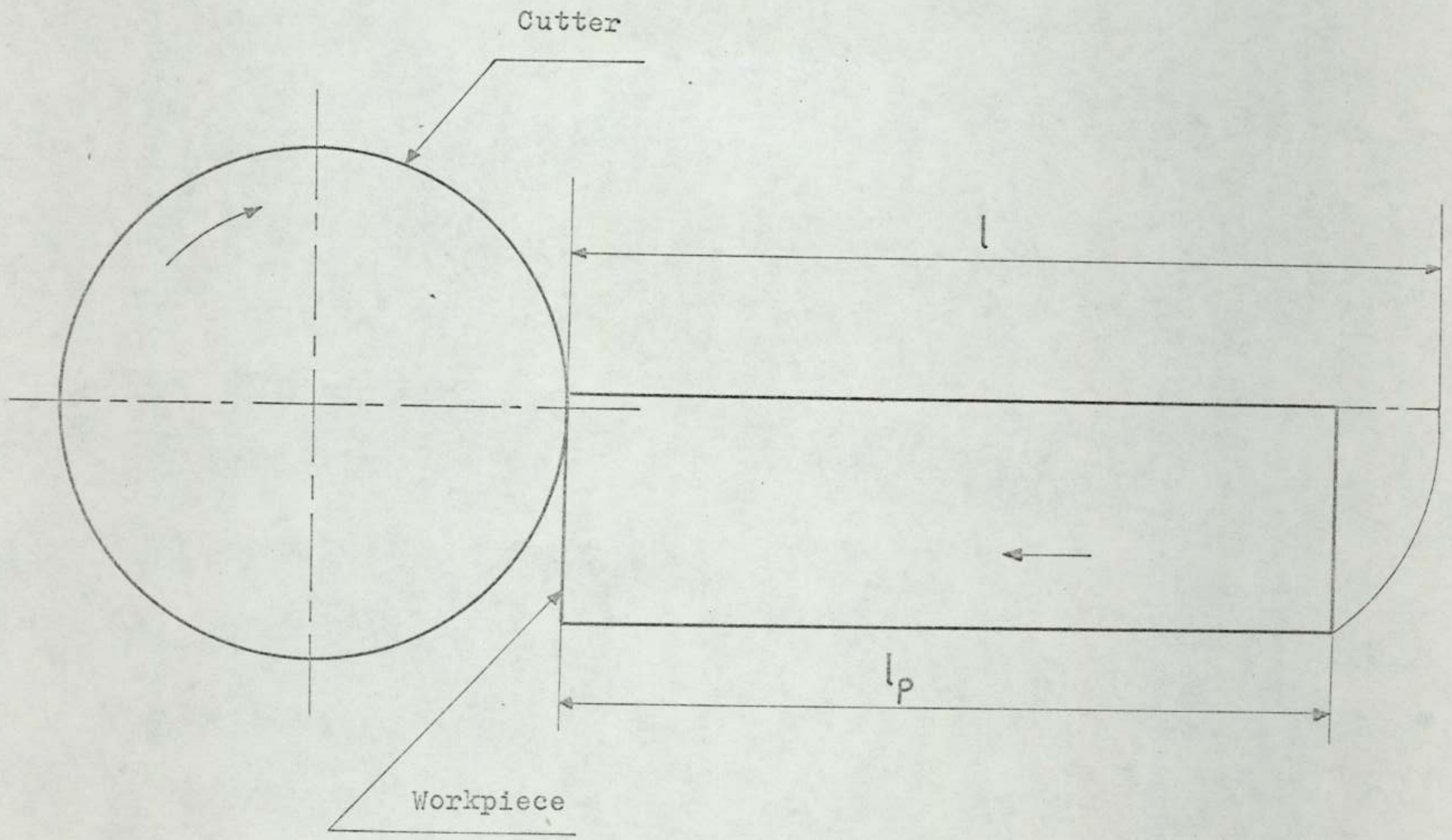


Fig.14 The Length l to Cut the Given Material

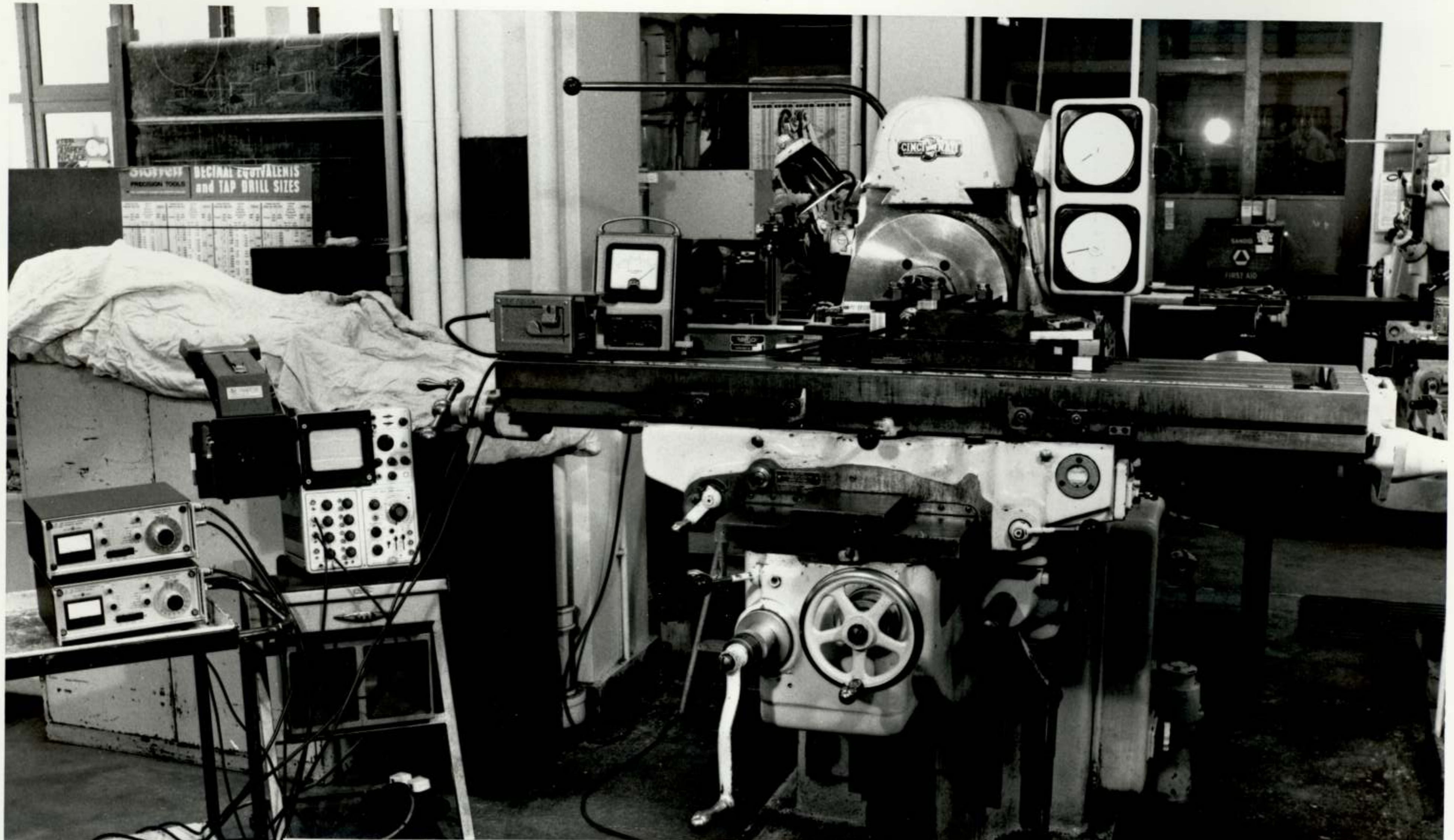


Fig.15 General View of the Machine Tool with the Equipment

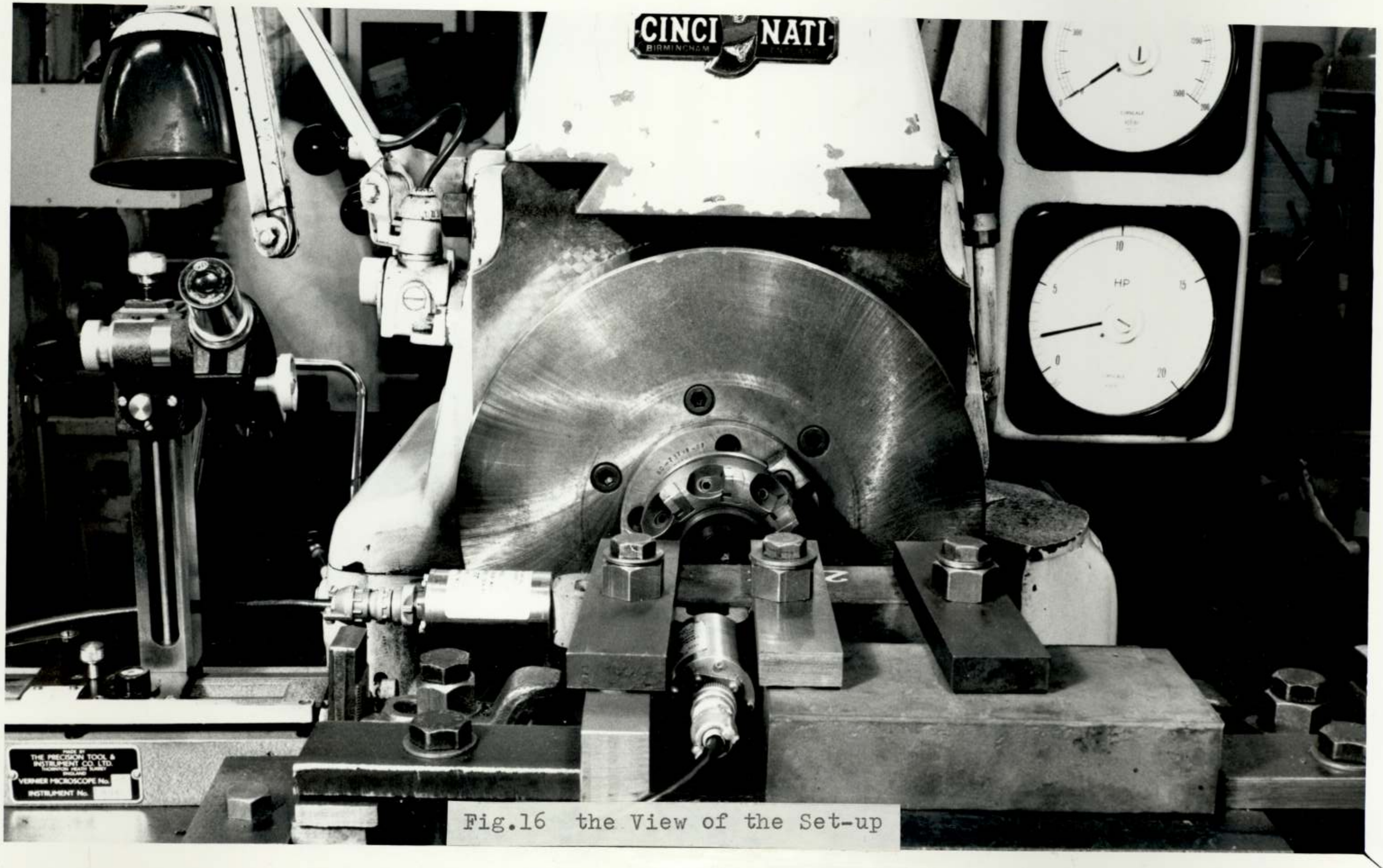


Fig.16 the View of the Set-up

Fig.17 General View of the Walter Cutter with one Workpiece

Fig.18 the Top View of One of the Inserts using with the Walter Cutter

Fig.19 General View of the Sandvik Cutter with One Workpiece

Fig.20 the Top View of One of the Inserts using
with the Sandvik Cutter

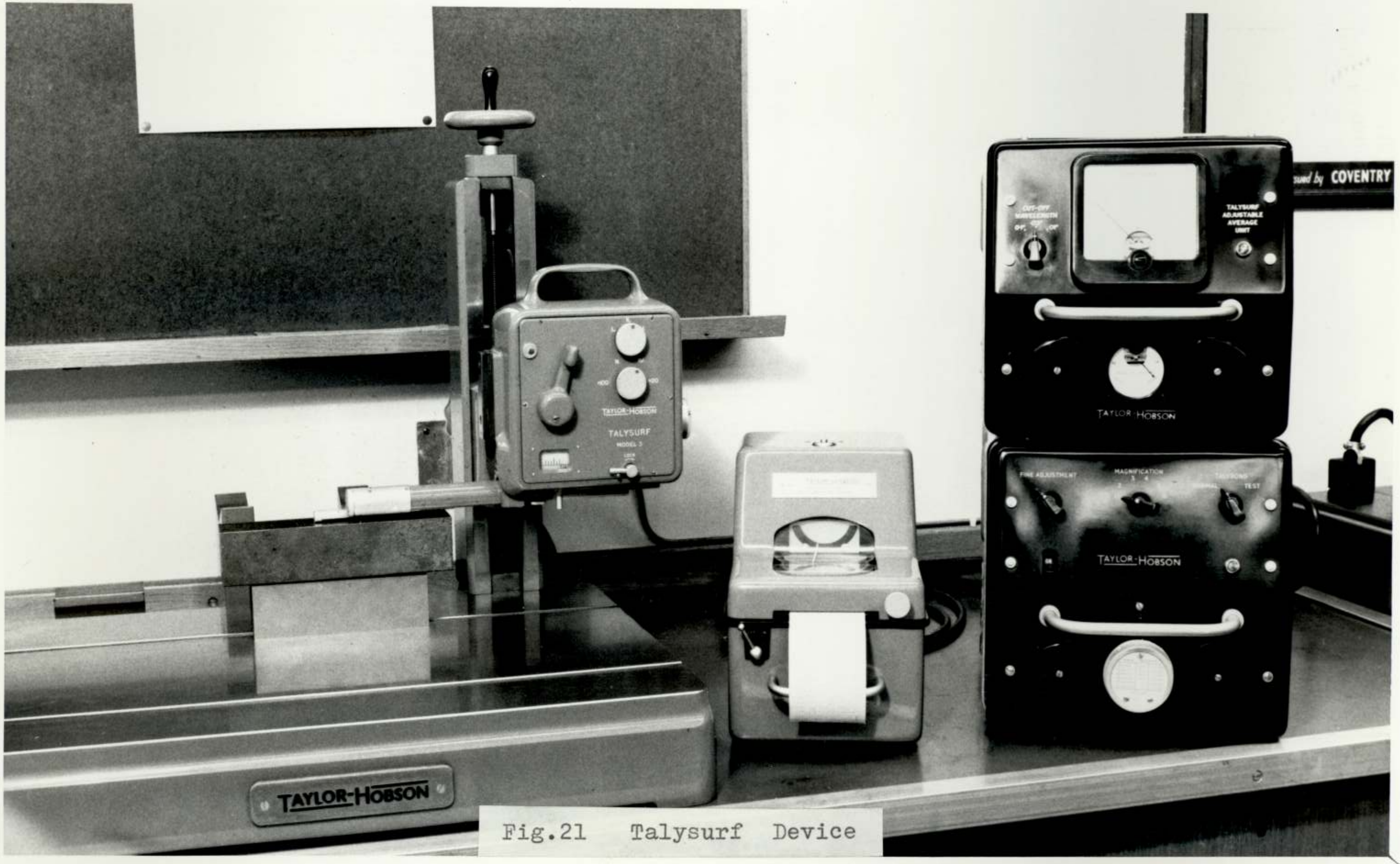


Fig.21 Talysurf Device

Fig.22 Chips Obtained under the Conditions of Cutting Speed of 182.21 m/min,F 1.666 m/min,d 2.03 mm,W 57 mm

Fig.23 Crater Wear on One Insert using with the Sandvik Cutter

Fig.24 Crater Wear on One Insert using with the Walter Cutter

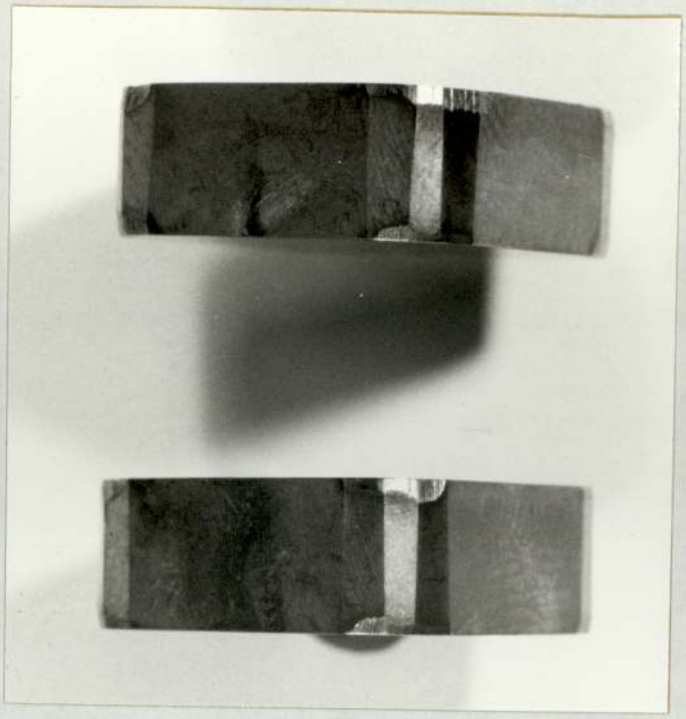


Fig.25 Flank Wear on One Insert using with the Sandvik Cutter

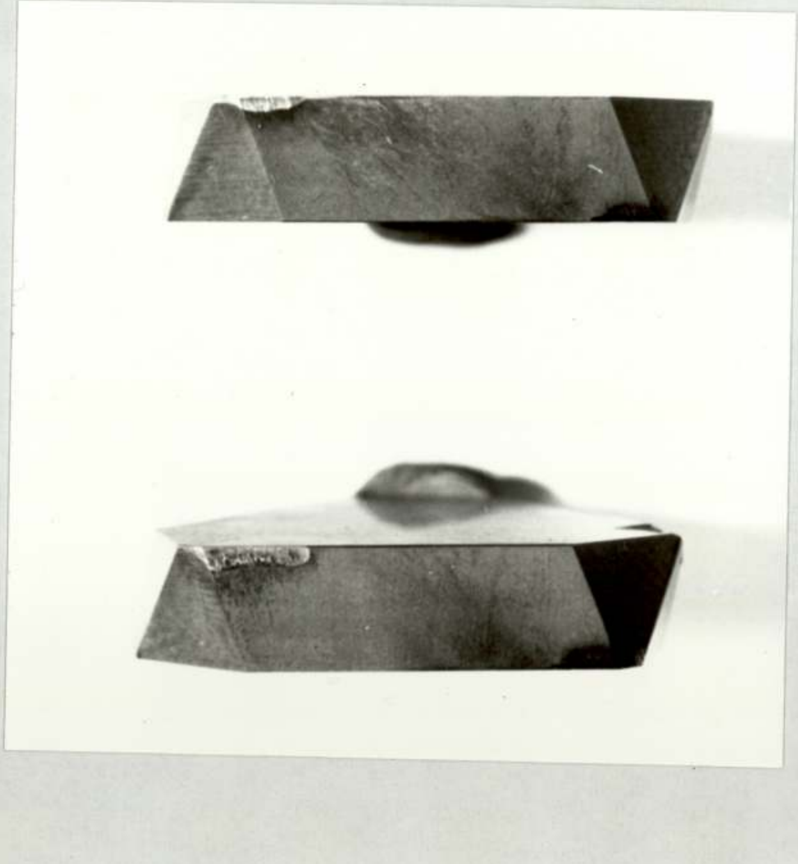
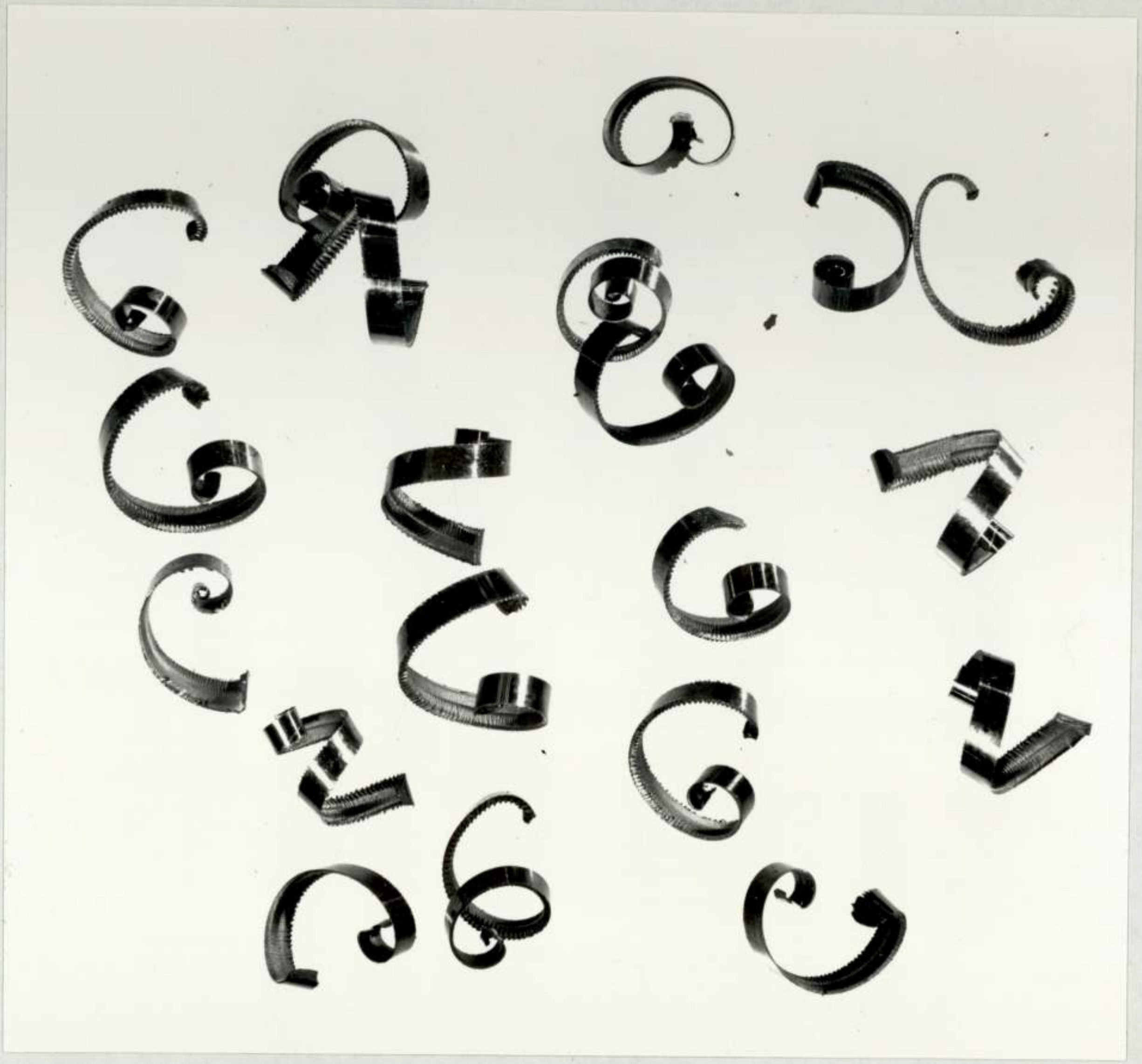


Fig.26 Flank Wear on One Insert using with the Walter Cutter



Material: Tool Steel(B.H.N.238)

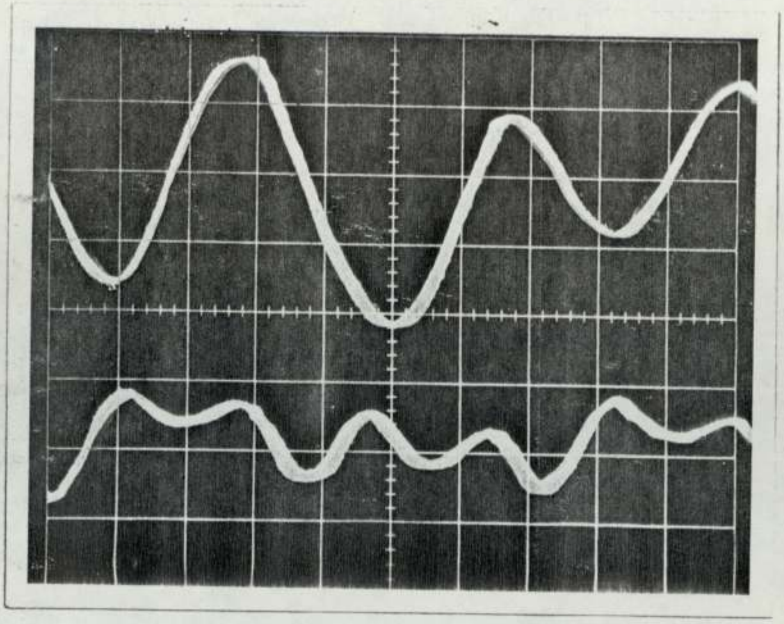
Cutter: the Sandvik Cutter

Fig.27 Chips Obtained During Cutter Life Tests in Down-Cut Milling

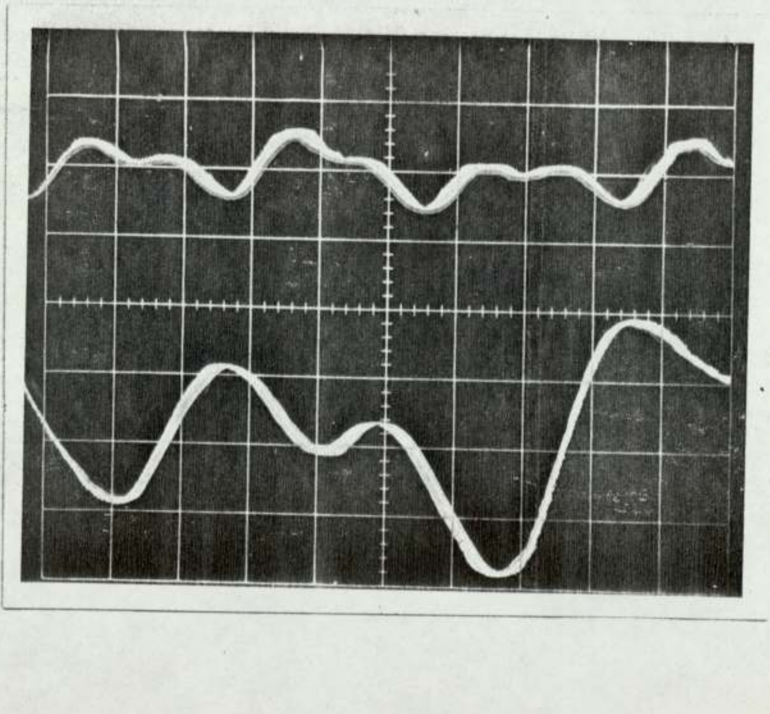
Material: Tool Steel(B.H.N.238)

Cutter: the Walter Cutter

Fig.28 Chips Obtained During Cutter Life Tests in Down-Cut Milling



Test No.1 V_s=118.75 m/min , S_{max}=0.305 mm^2

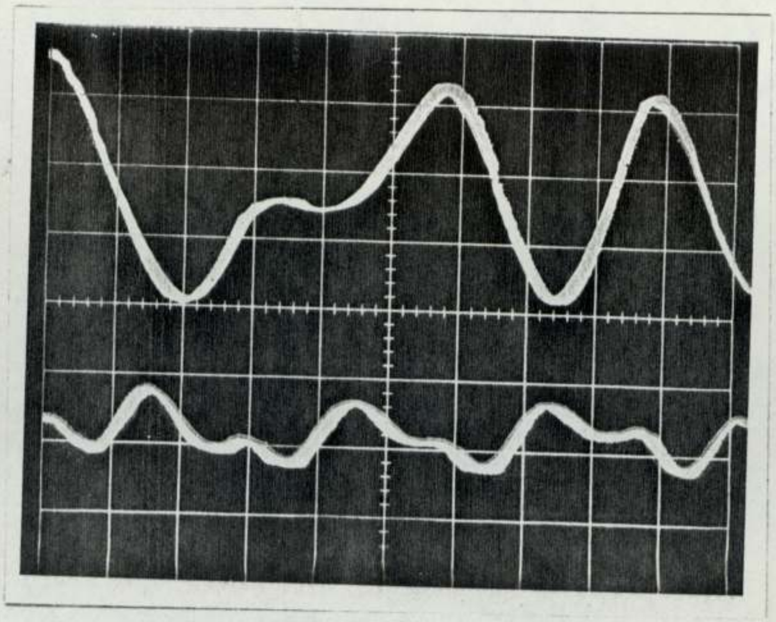


Test No.5 V_s=144.51 m/min , S_{max}=0.377 mm^2

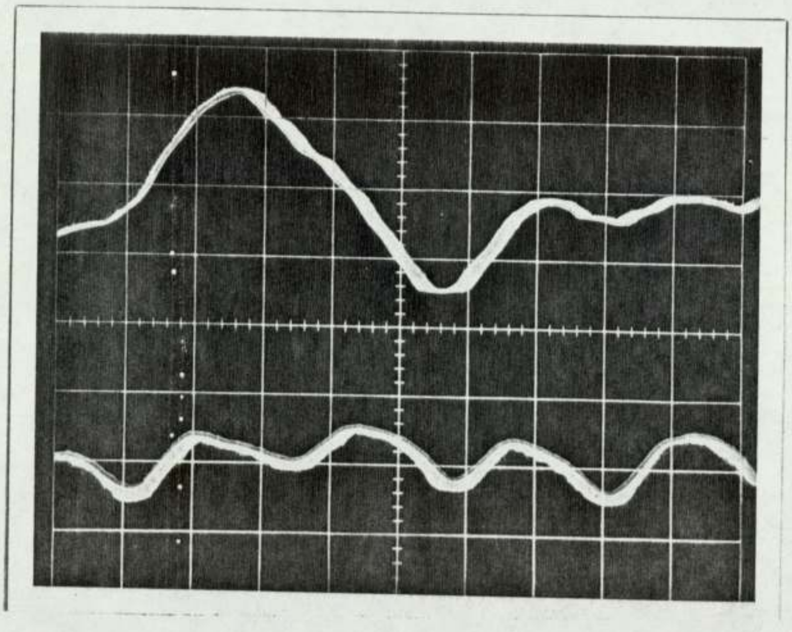
in Vertical line 0.1 volts/div 1 m/div

in Horizantal line 5 msec/div

Fig.29 Vibrations of Workpiece in Feed and Axial Directions During Down-Cut Milling



Test No.6 V_s=144.51 m/min , S_{max}=0.448 mm^2

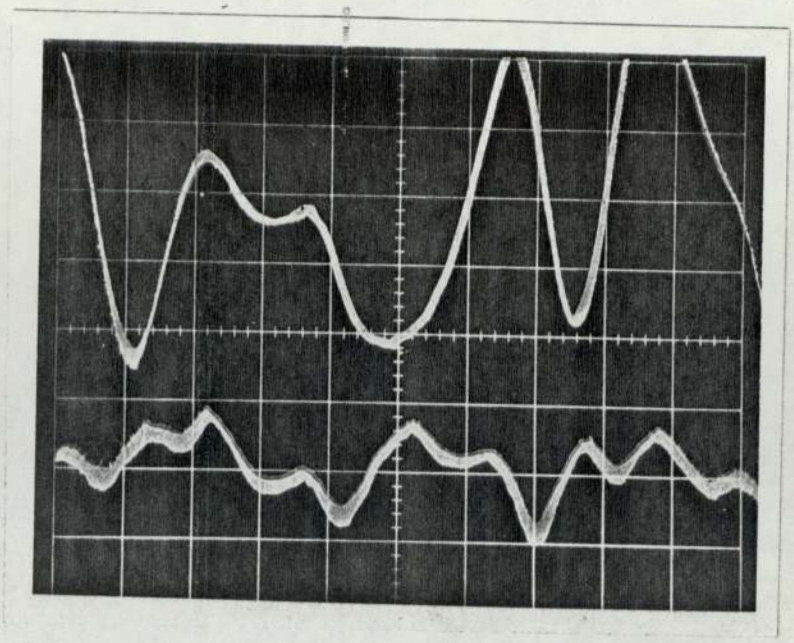


Test No.10 V_s=182.21 m/min , S_{max}=0.371 mm^2

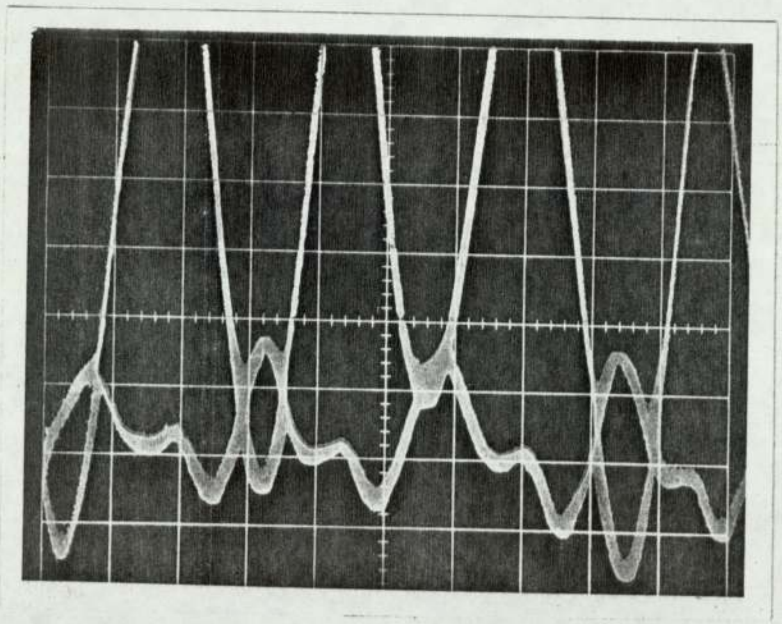
in Vertical line 0.1 volts/div= 1μm/div

in Horizantal line 5 msec/div

Fig.29 Vibrations of Workpiece in Feed and Axial Directions During Down-Cut Milling

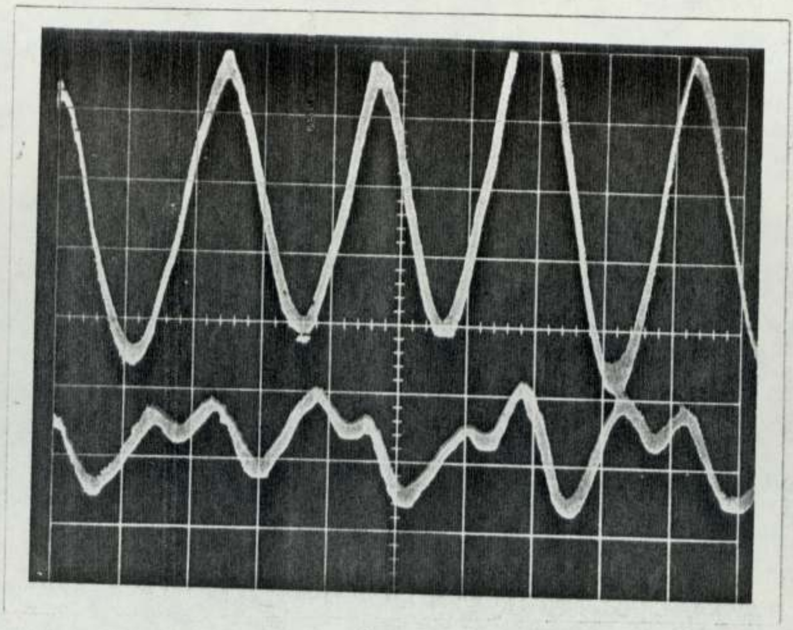


Test No.3 V_w=95.75 m/min , S_{max}=0.294 mm^2

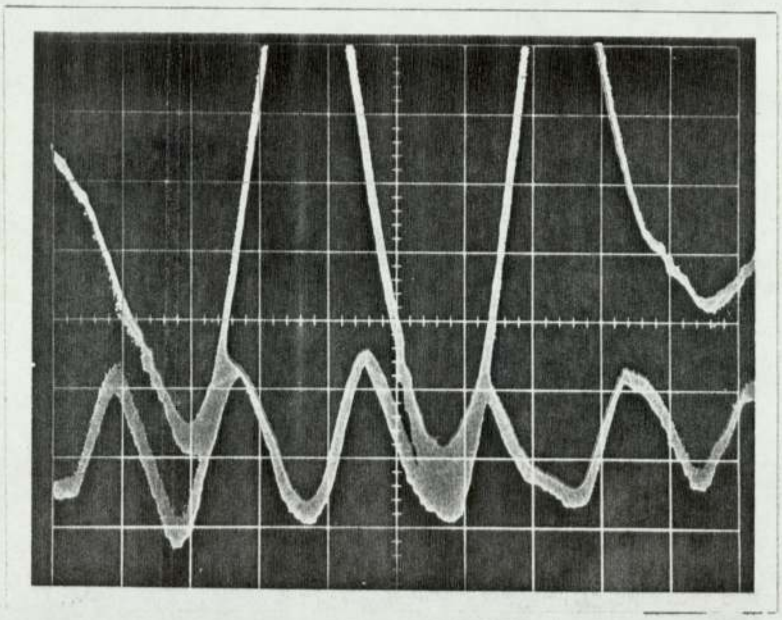


Test No.6 V_w=120.65 m/min , S_{max}= 0.633 mm^2
in Vertical line 0.1 volts/div.= 1μm/div.
in Horizantal line 5 msec/div.

Fig.30 Vibrations of Workpiece in Feed and Axial Directions During Down-Cut Milling



Test No.9 V_w=146.82 m/min , S_{max}= 0.357 mm^2

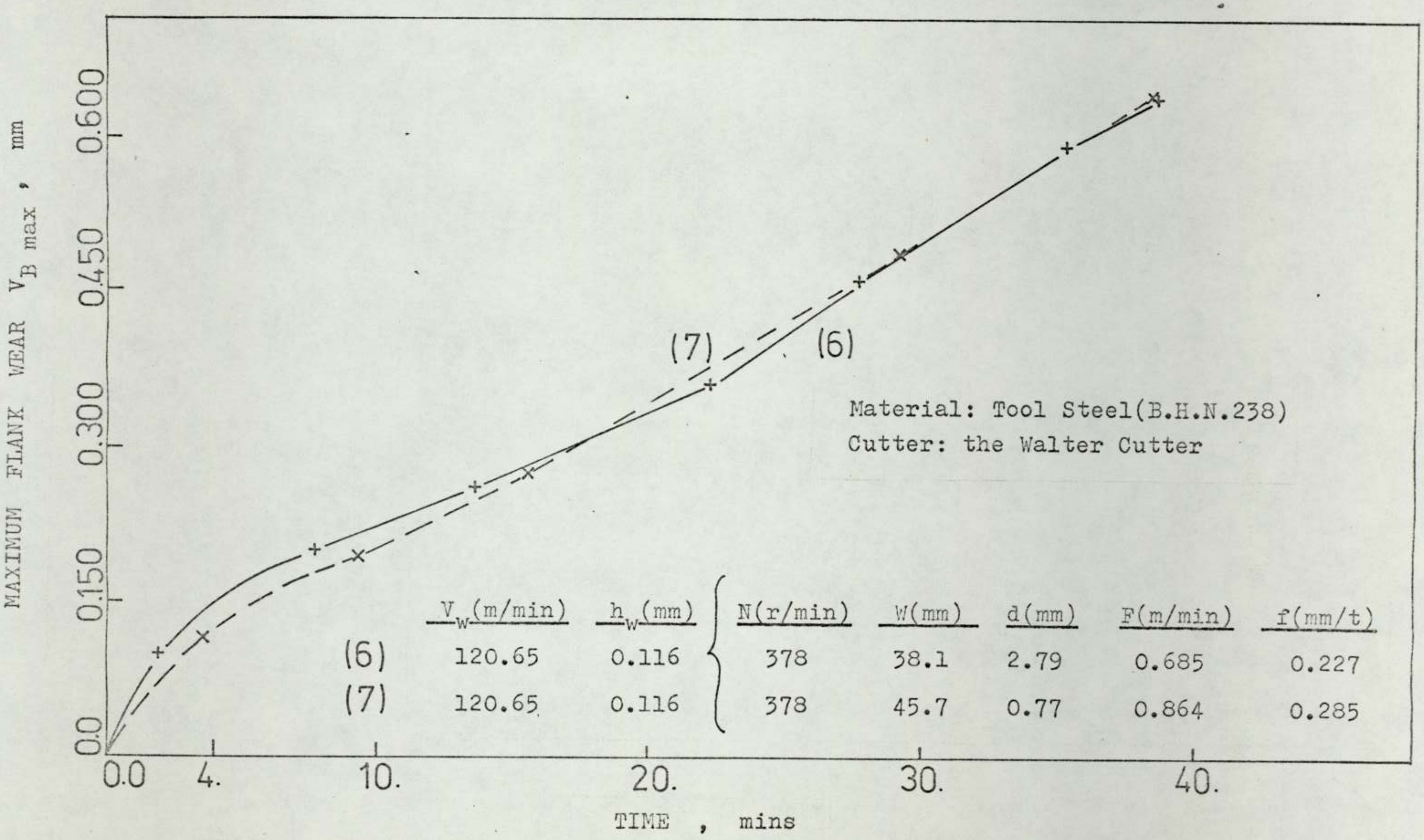


Test No.11 V_w=185.82 m/min , S_{max}=0.477 mm^2

in Vertical line 0.1 volts/div=1μm/div

in Horizantal line 5 msec/div

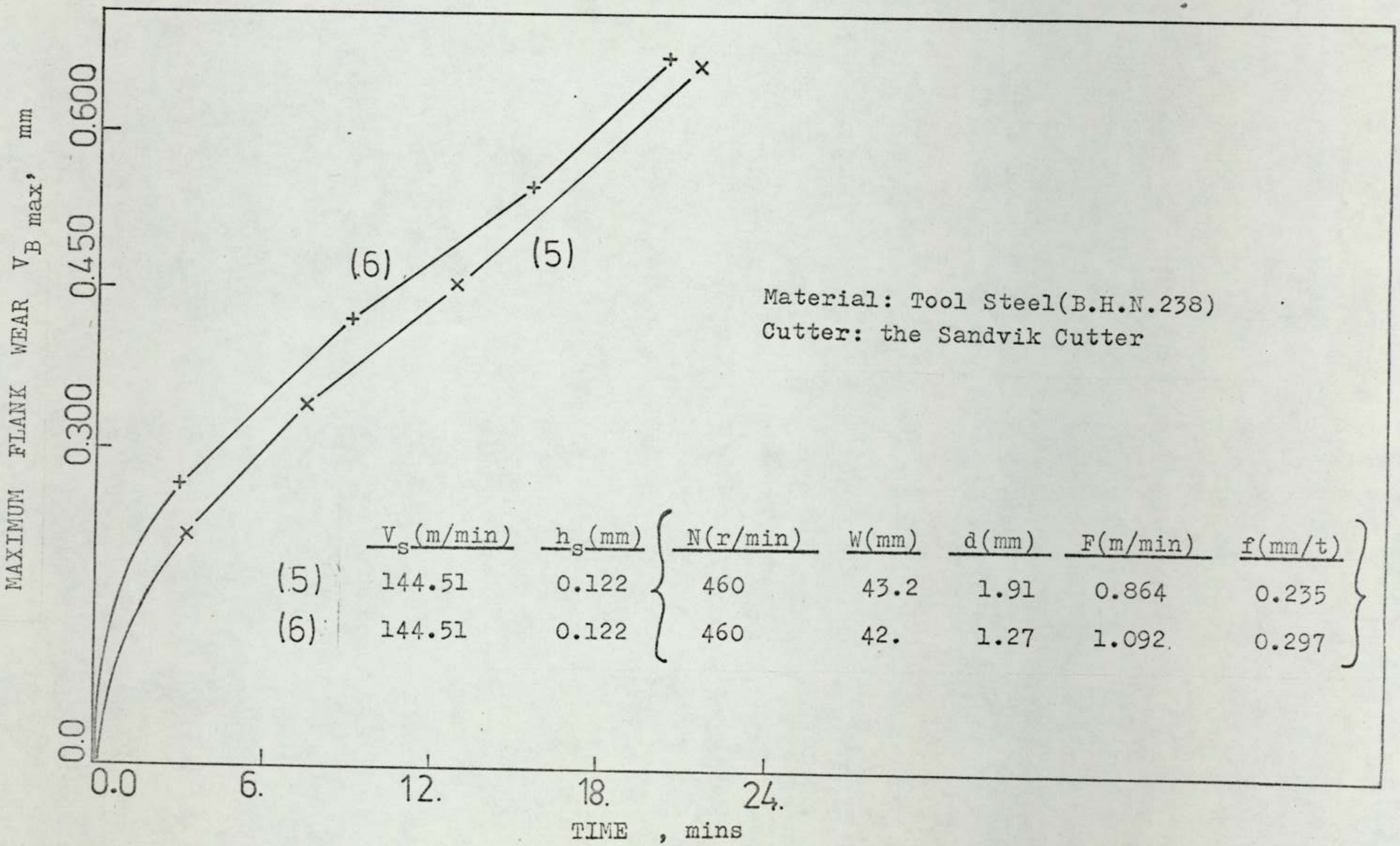
Fig.30 Vibrations of Workpiece in Feed and Axial Directions During Down-Cut Milling



Material: Tool Steel(B.H.N.238)
Cutter: the Walter Cutter

	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(6)	120.65	0.116	378	38.1	2.79	0.685	0.227
(7)	120.65	0.116	378	45.7	0.77	0.864	0.285

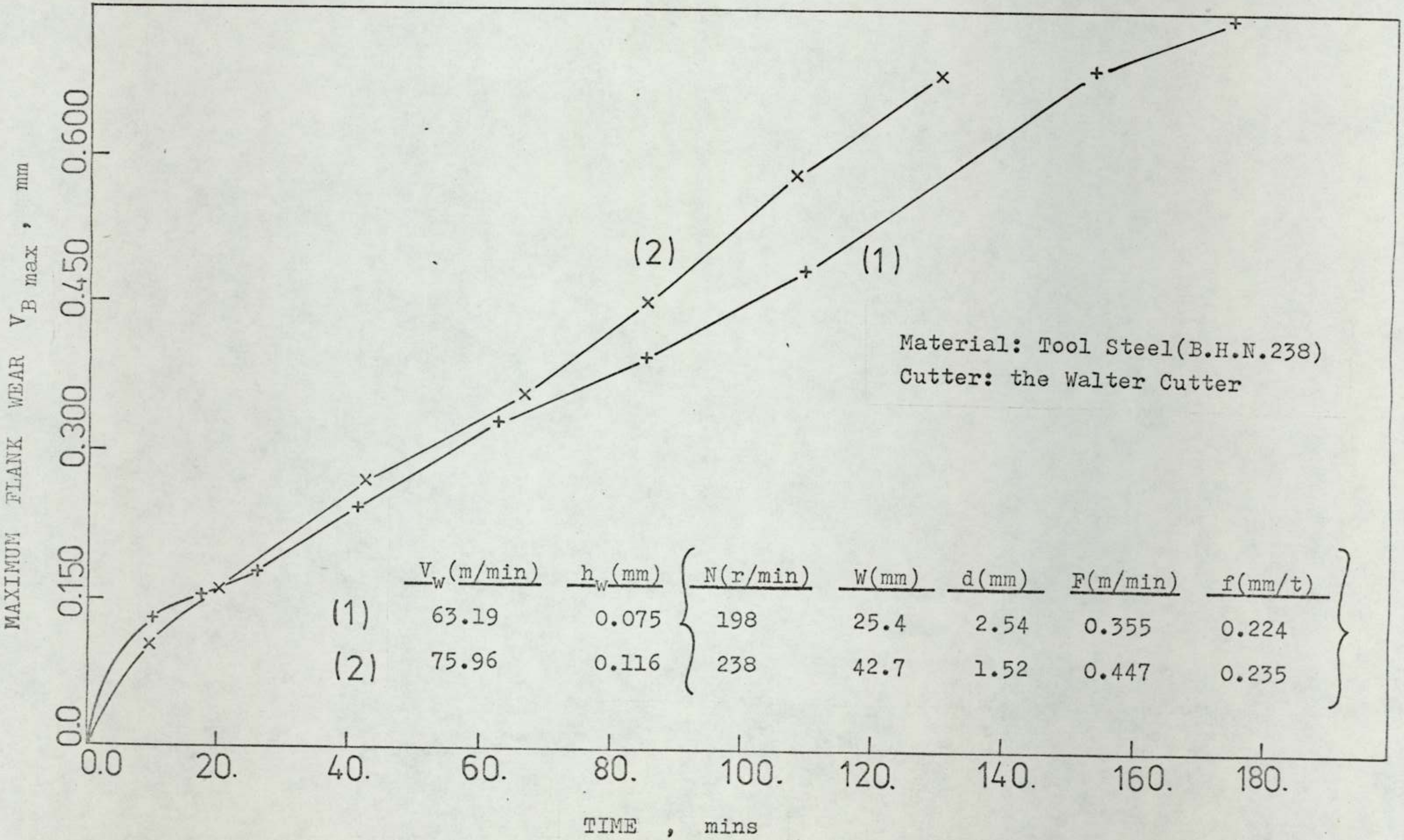
Fig. 31 the Validity of Equivalent Chip Thickness in Down-Cut Milling



Material: Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

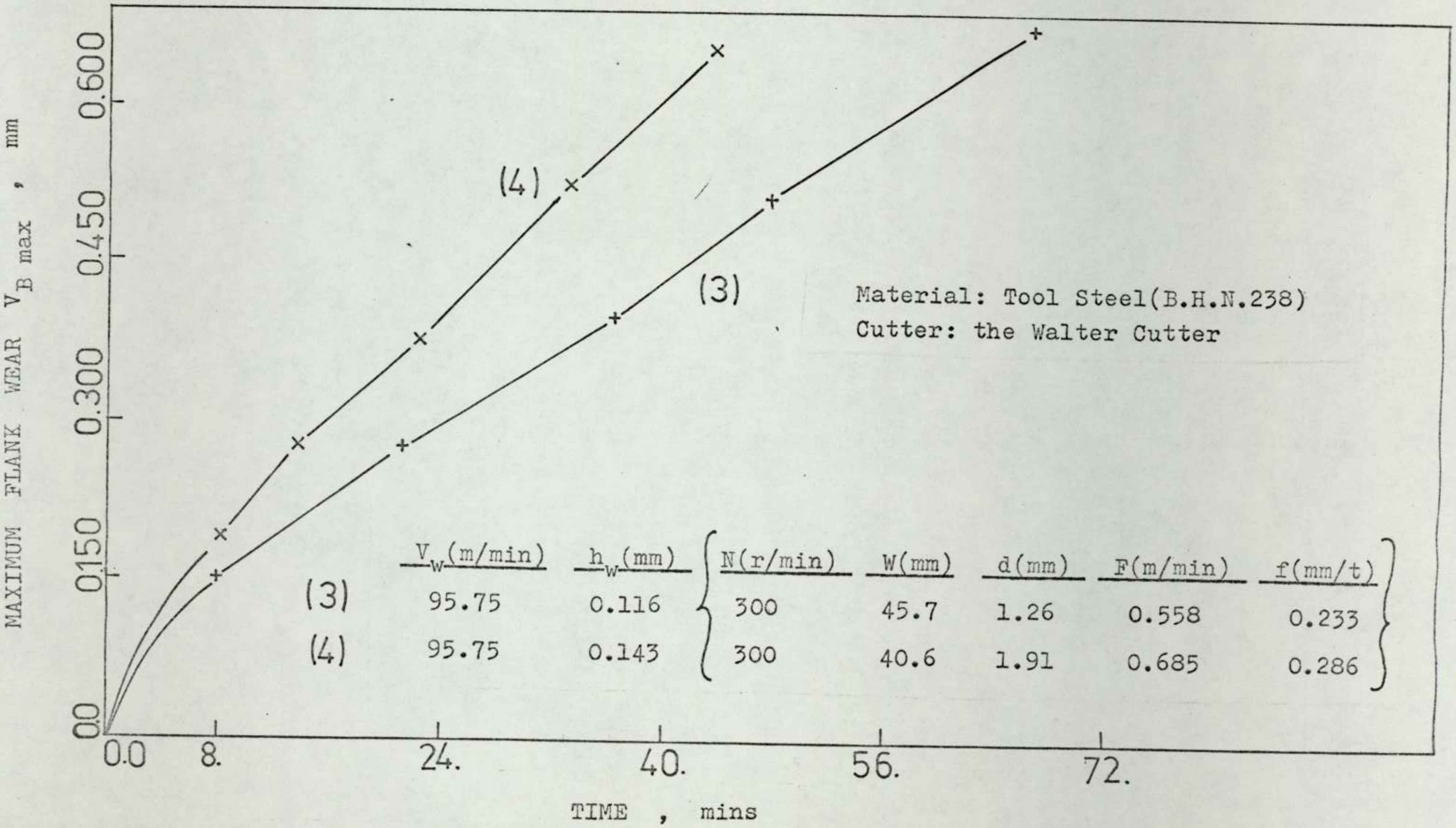
	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(5)	144.51	0.122	460	43.2	1.91	0.864	0.235
(6)	144.51	0.122	460	42.	1.27	1.092	0.297

Fig.32 the Validity of Equivalent Chip Thickness in Down-Cut Milling



	V_W(m/min)	h_W(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(1)	63.19	0.075	198	25.4	2.54	0.355	0.224
(2)	75.96	0.116	238	42.7	1.52	0.447	0.235

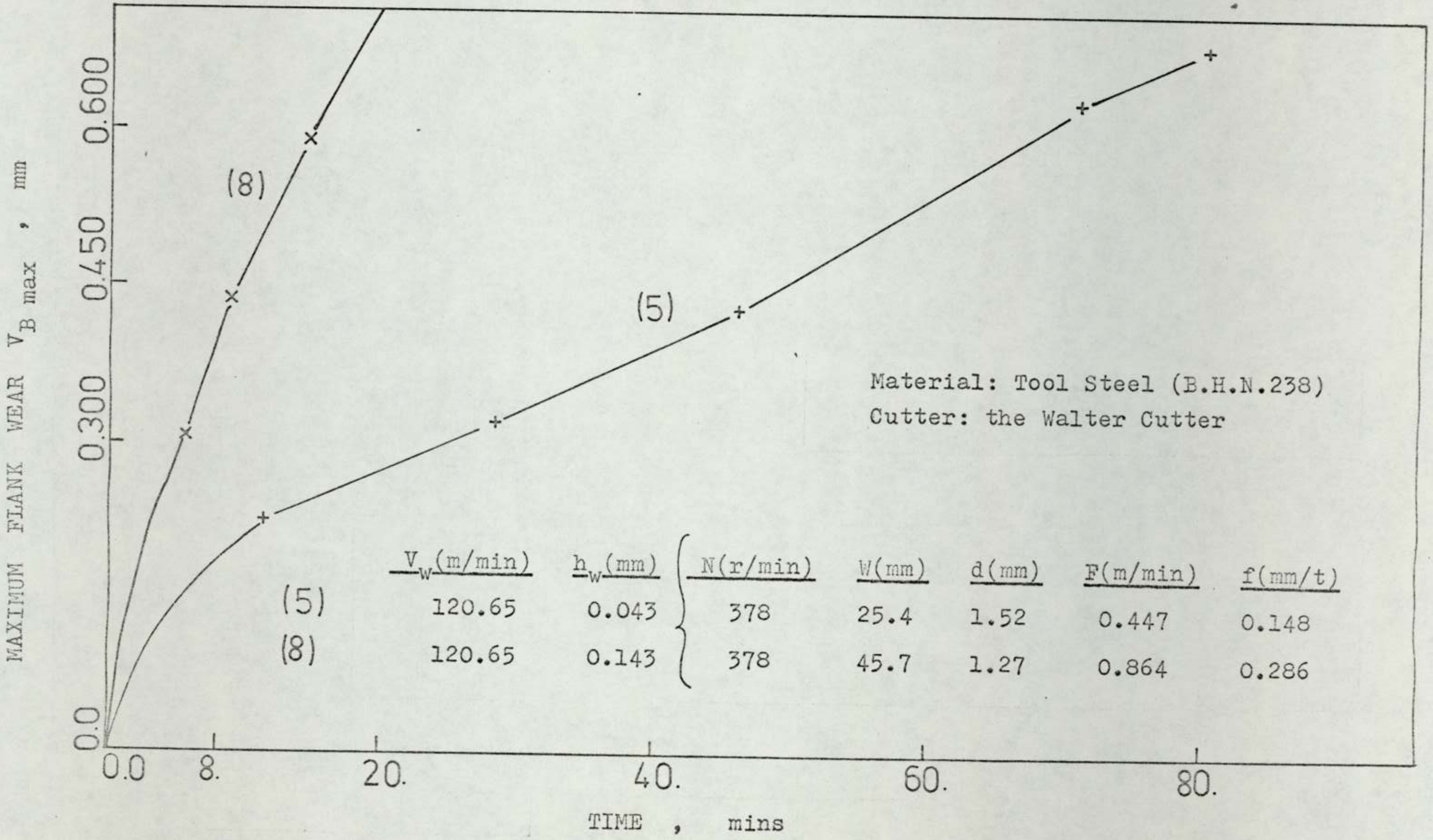
Fig.33 Wear-Time Progresses in Down-Cut Milling



Material: Tool Steel(B.H.N.238)
Cutter: the Walter Cutter

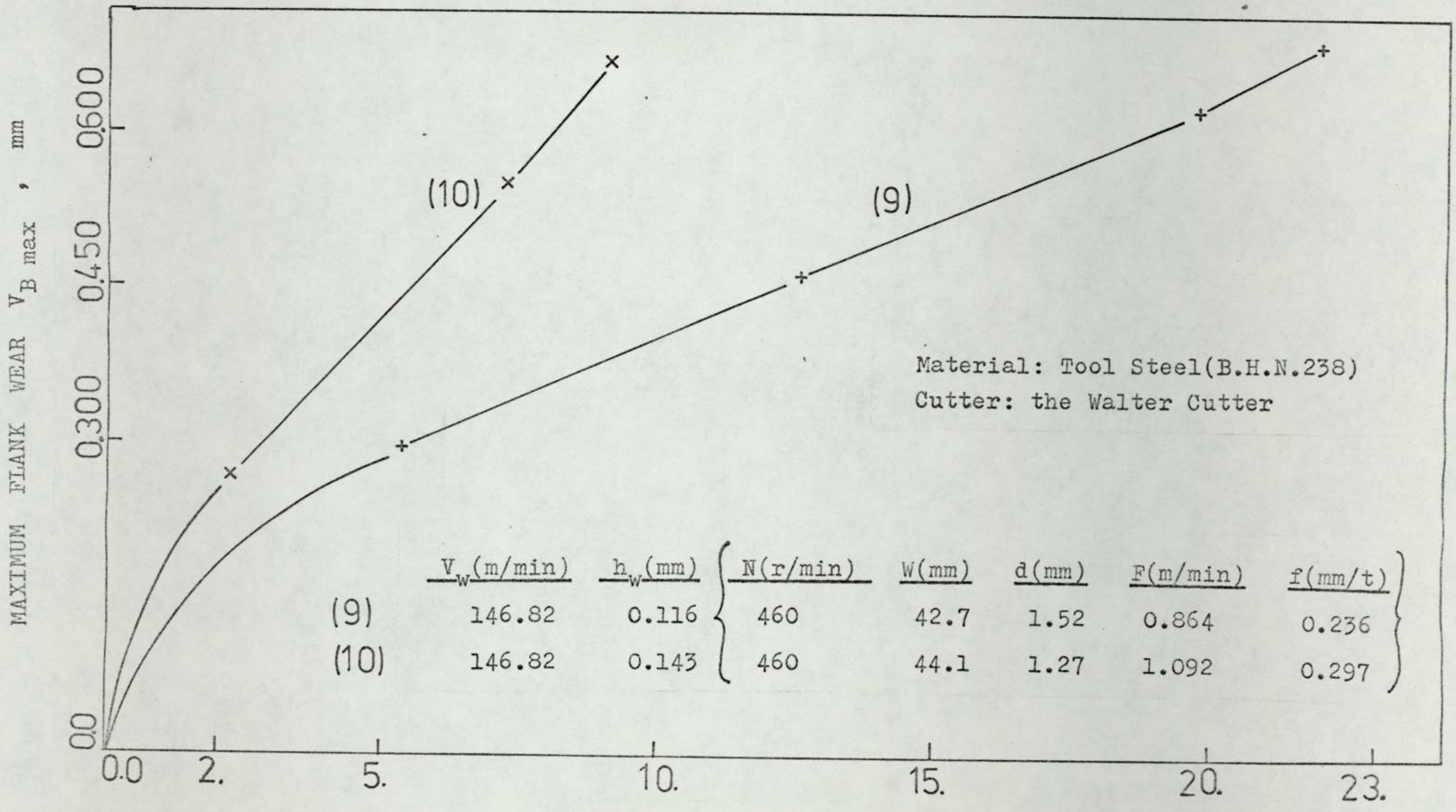
	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(3)	95.75	0.116	300	45.7	1.26	0.558	0.233
(4)	95.75	0.143	300	40.6	1.91	0.685	0.286

Fig. 34 Wear-Time Progresses in Down-Cut Milling



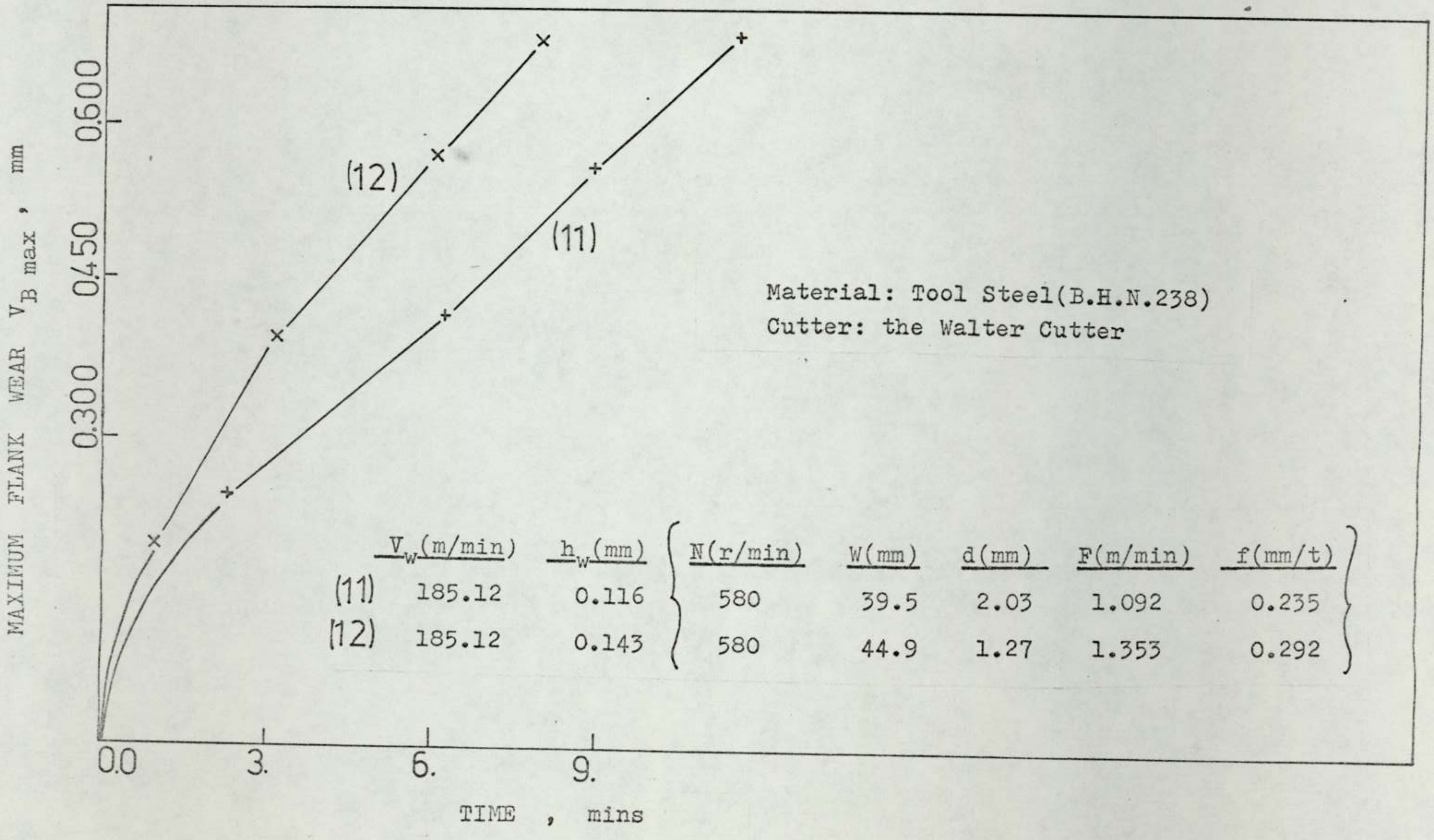
	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(5)	120.65	0.043	378	25.4	1.52	0.447	0.148
(8)	120.65	0.143	378	45.7	1.27	0.864	0.286

Fig. 35 Wear-Time Progresses in Down-Cut Milling



	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(9)	146.82	0.116	460	42.7	1.52	0.864	0.236
(10)	146.82	0.143	460	44.1	1.27	1.092	0.297

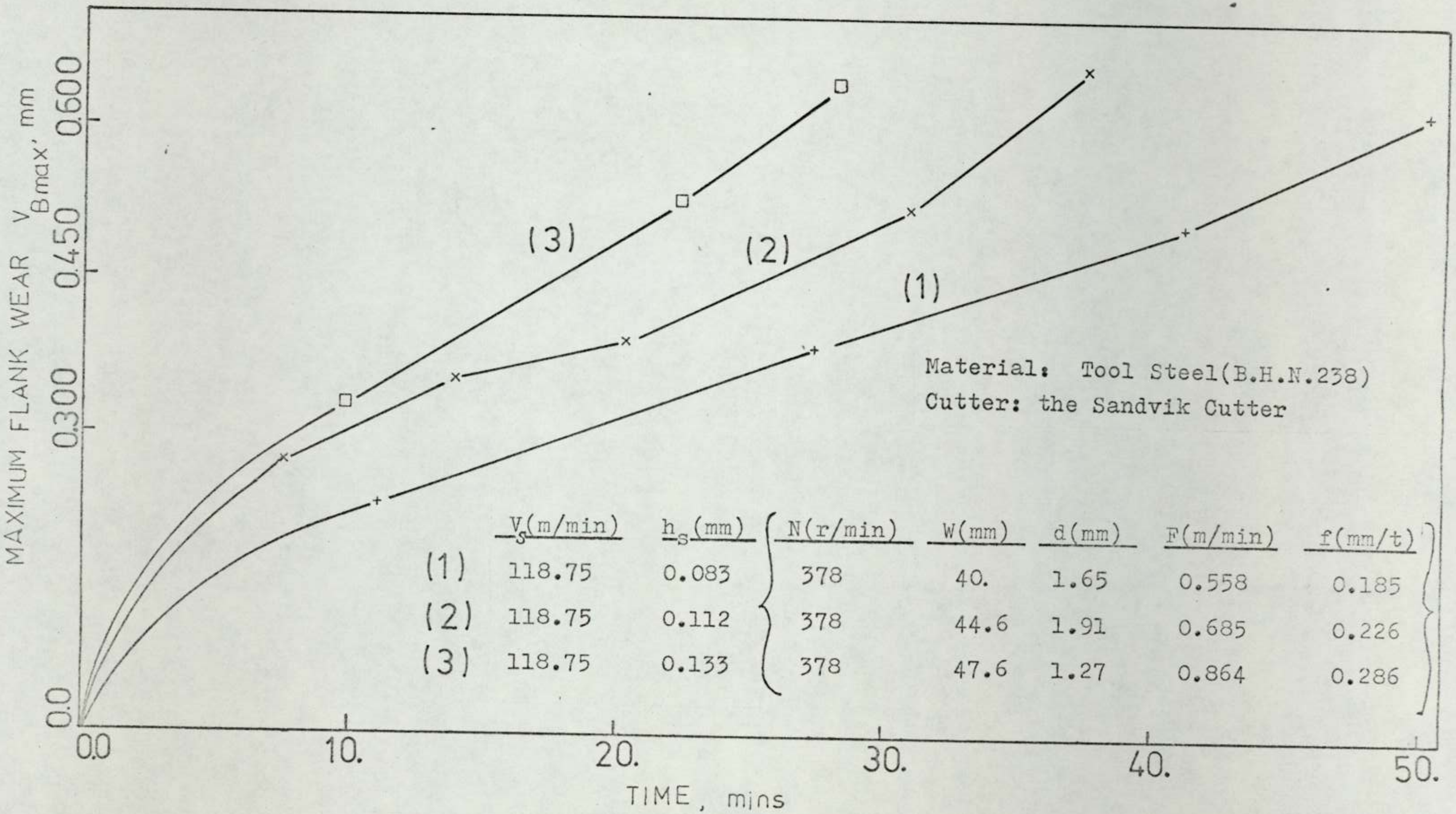
Fig.36 Wear-Time Progresses in Down-Cut Milling



Material: Tool Steel(B.H.N.238)
Cutter: the Walter Cutter

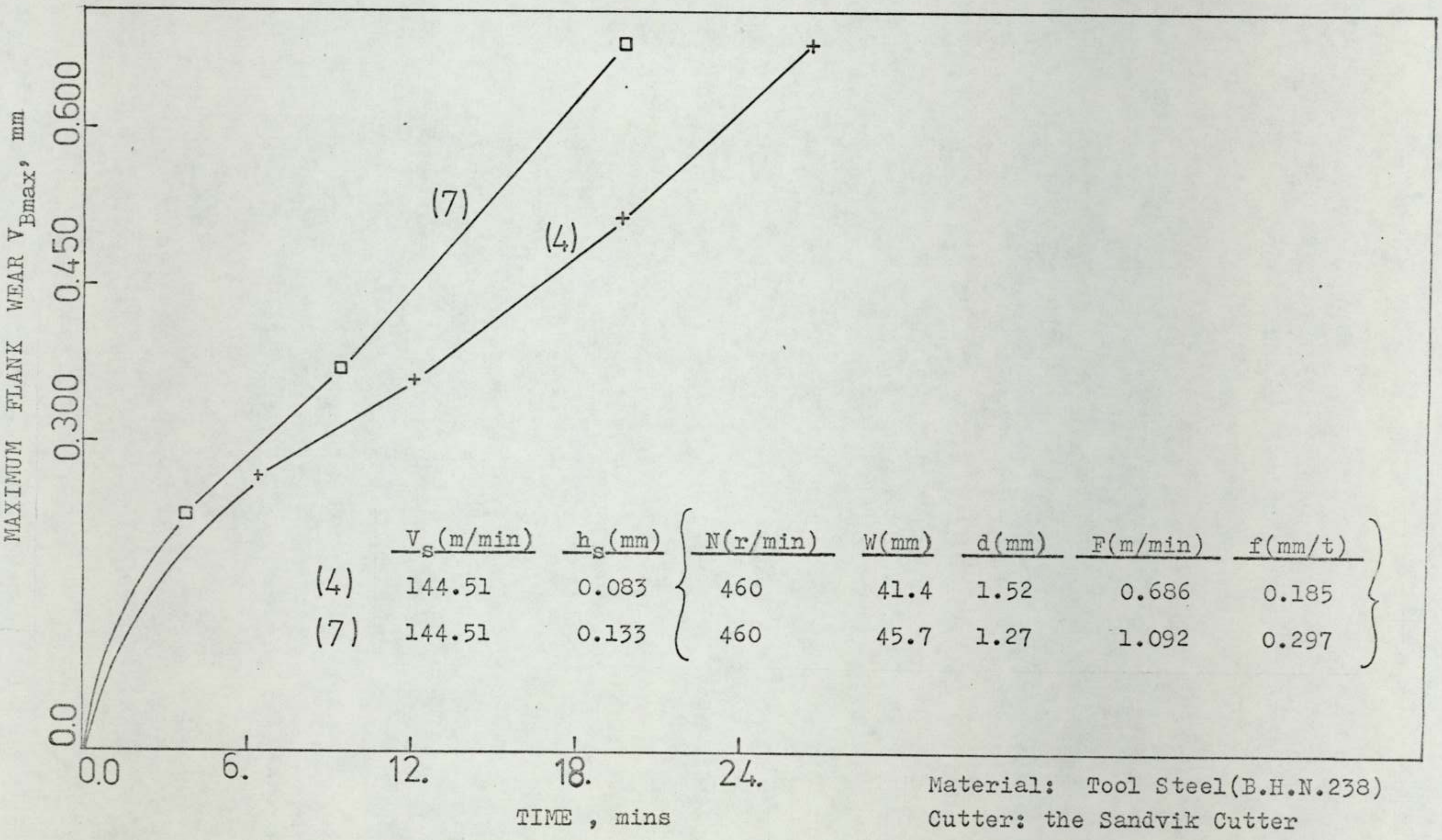
	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(11)	185.12	0.116	580	39.5	2.03	1.092	0.235
(12)	185.12	0.143	580	44.9	1.27	1.353	0.292

Fig. 37 Wear-Time Progresses in Down-Cut Milling



	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(1)	118.75	0.083	378	40.	1.65	0.558	0.185
(2)	118.75	0.112	378	44.6	1.91	0.685	0.226
(3)	118.75	0.133	378	47.6	1.27	0.864	0.286

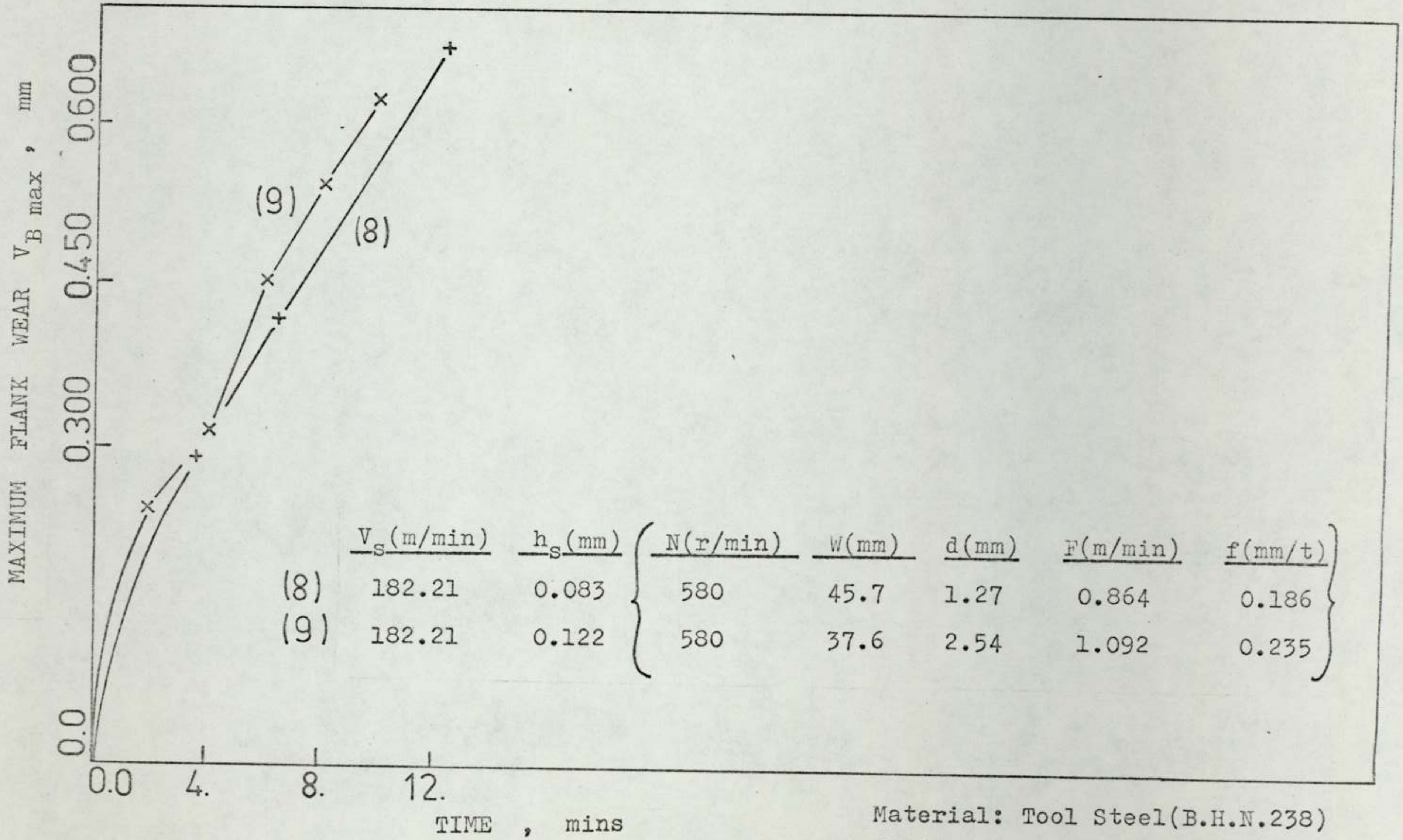
Fig.38 Wear-Time Progresses in Down-Cut Milling



	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(4)	144.51	0.083	460	41.4	1.52	0.686	0.185
(7)	144.51	0.133	460	45.7	1.27	1.092	0.297

Material: Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

Fig.39 Wear-Time Progresses in Down-Cut Milling



	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(8)	182.21	0.083	580	45.7	1.27	0.864	0.186
(9)	182.21	0.122	580	37.6	2.54	1.092	0.235

Material: Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

Fig.40 Wear-Time Progresses in Down-Cut Milling

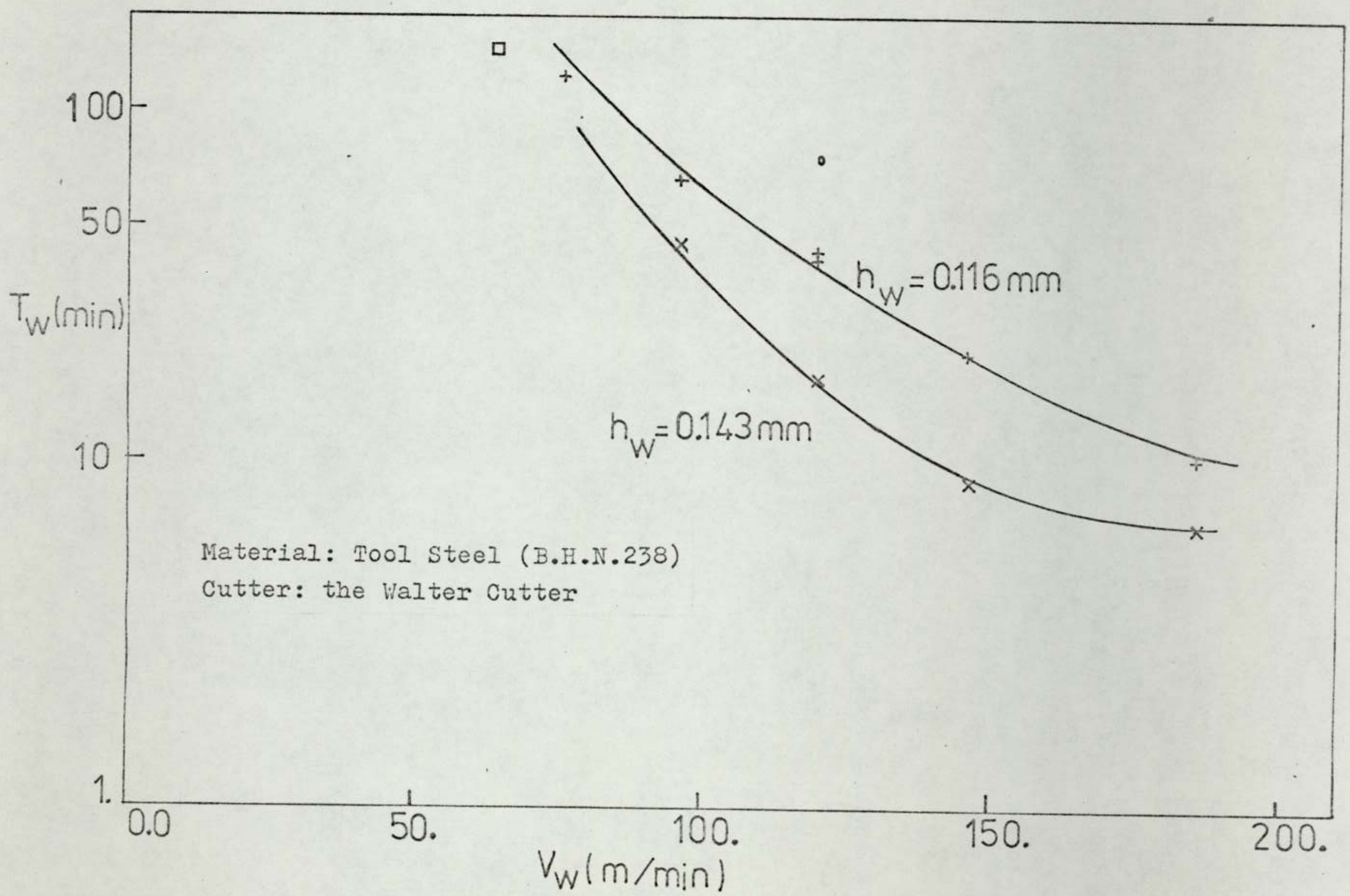


Fig. 41 Cutter Life Results in Down-Cut Milling

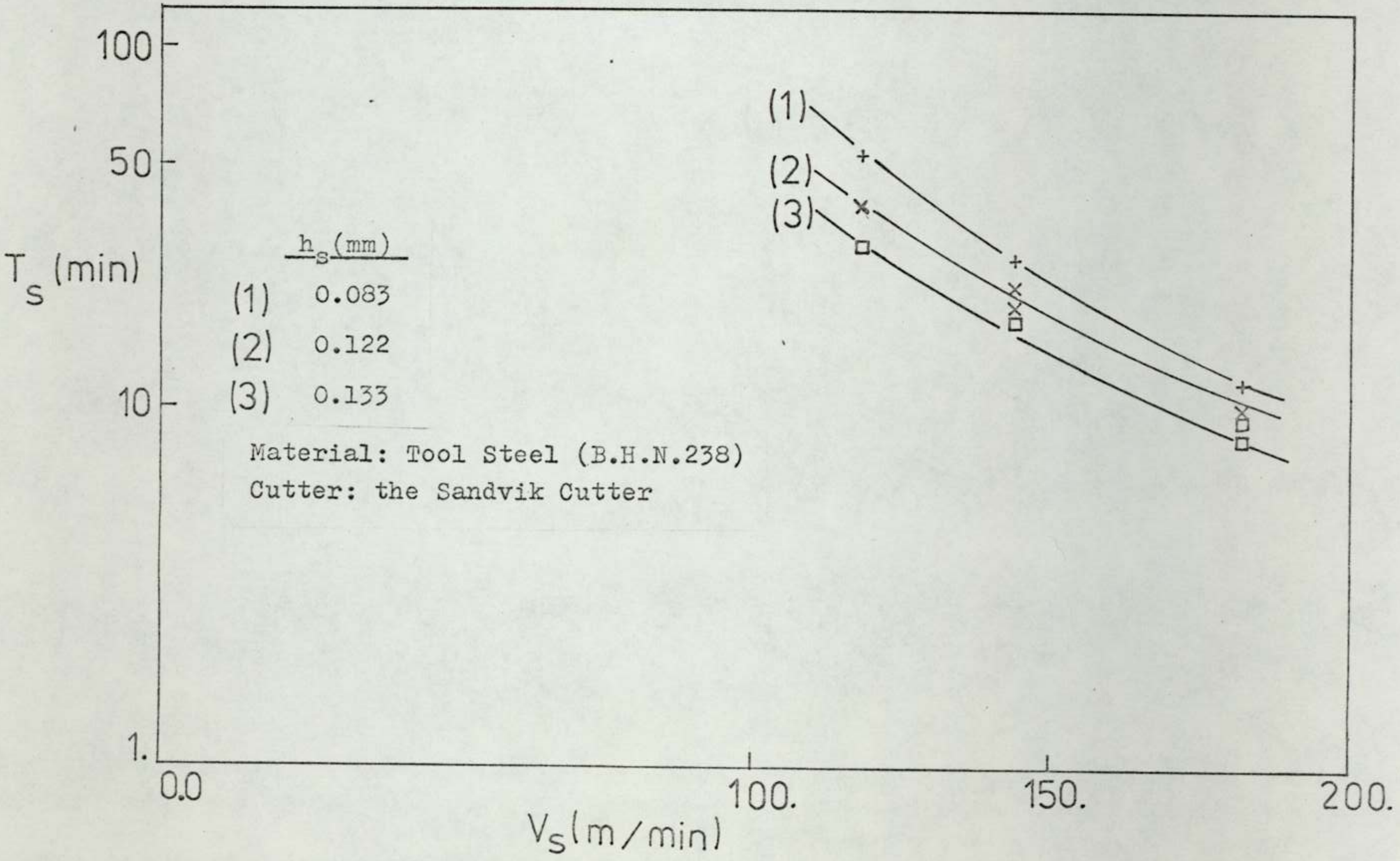
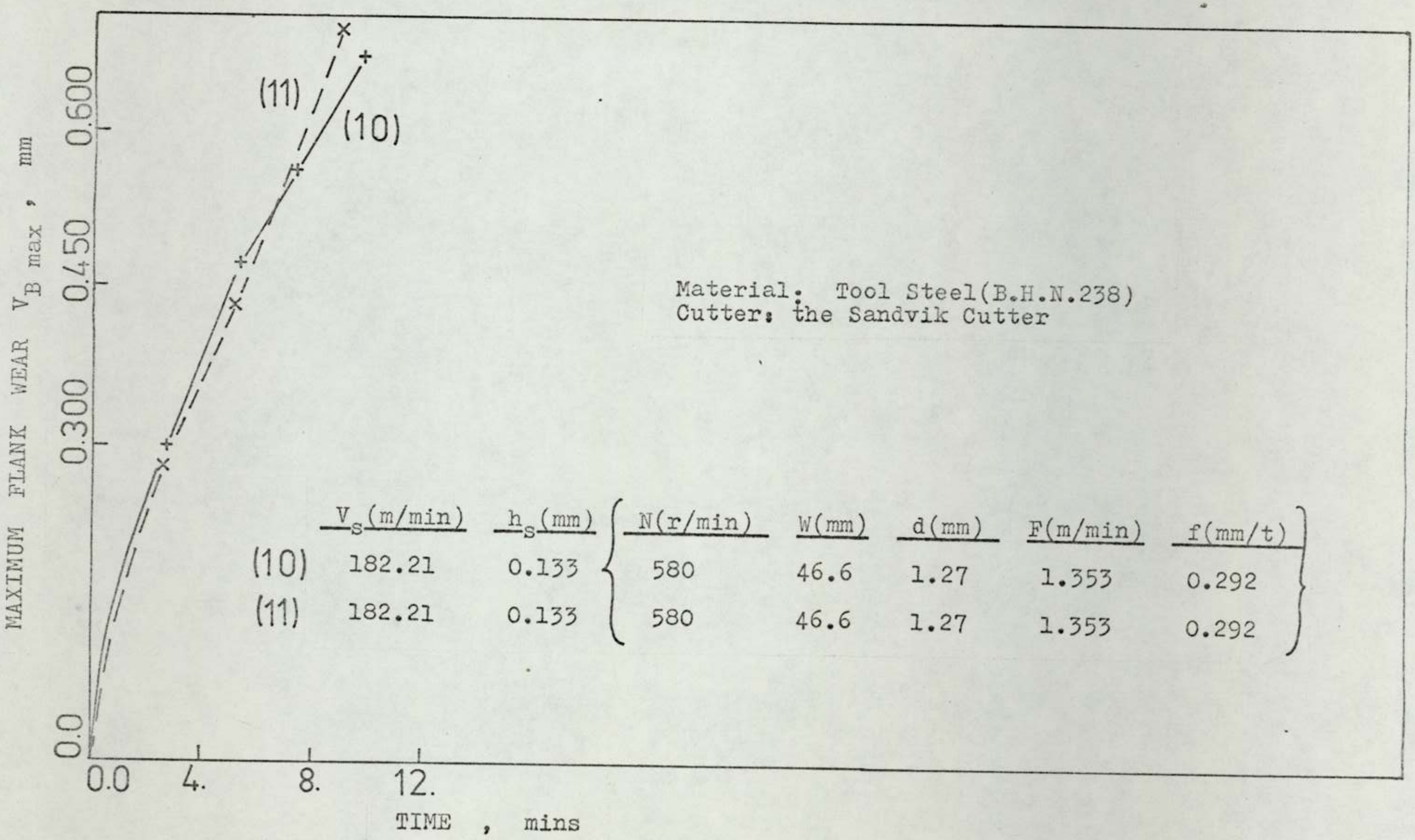


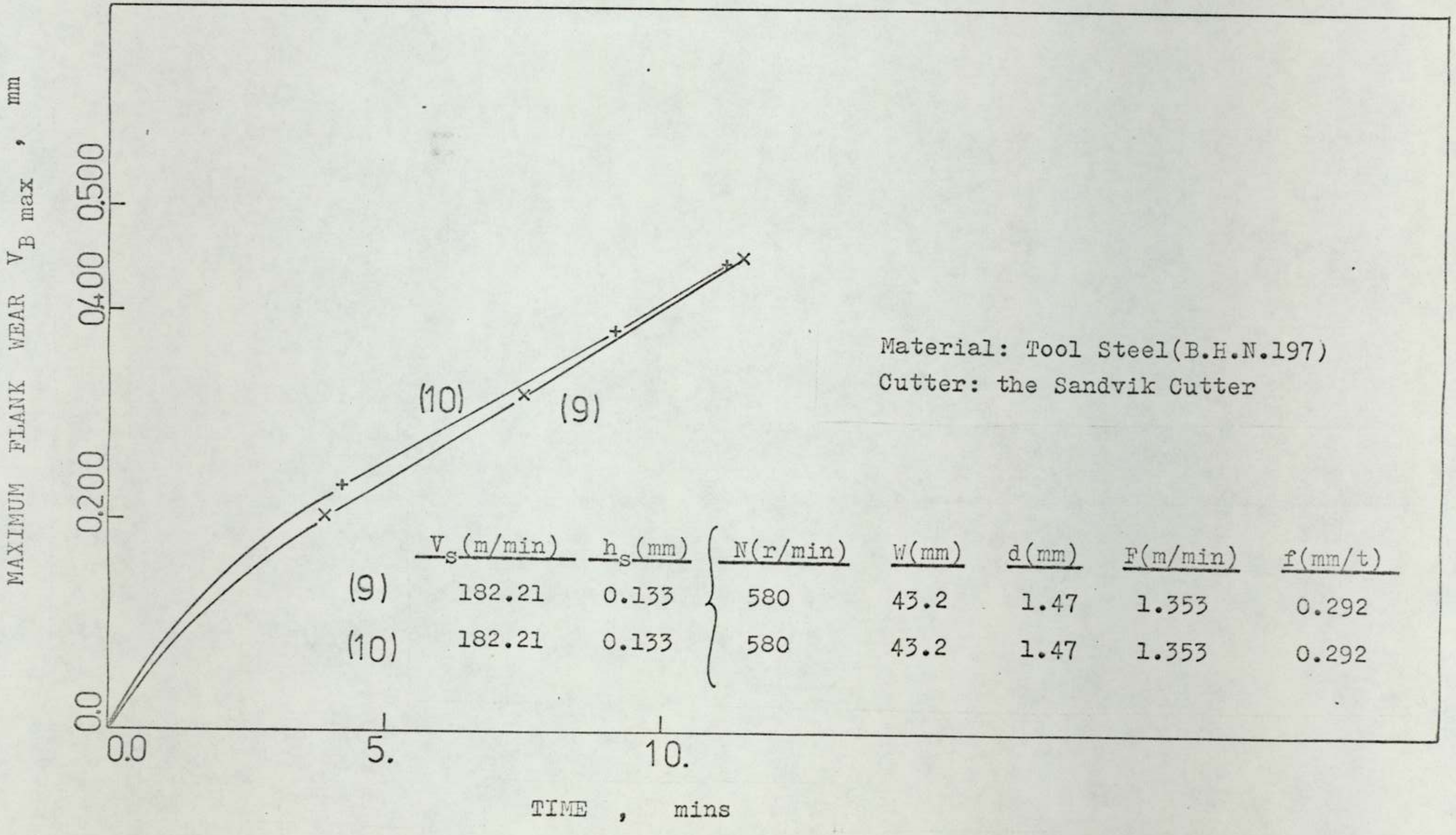
Fig.42 Cutter Life Results in Down-Cut Milling



Material. Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(10)	182.21	0.133	580	46.6	1.27	1.353	0.292
(11)	182.21	0.133	580	46.6	1.27	1.353	0.292

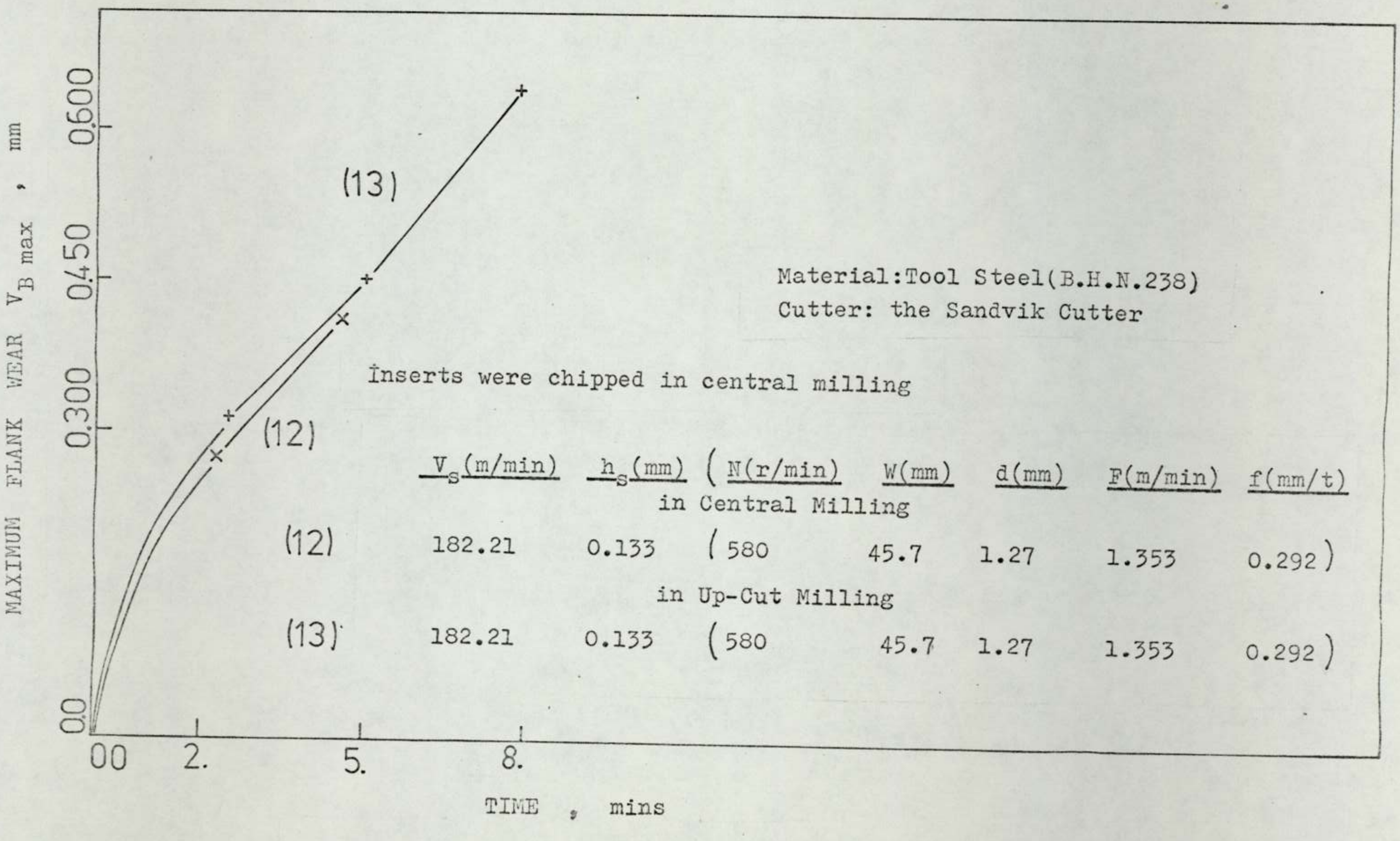
Fig.43 Wear-Time Progresses in Down-Cut Milling



Material: Tool Steel(B.H.N.197)
Cutter: the Sandvik Cutter

	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(9)	182.21	0.133	580	43.2	1.47	1.353	0.292
(10)	182.21	0.133	580	43.2	1.47	1.353	0.292

Fig.44 Wear-Time Progresses in Up-Cut Milling

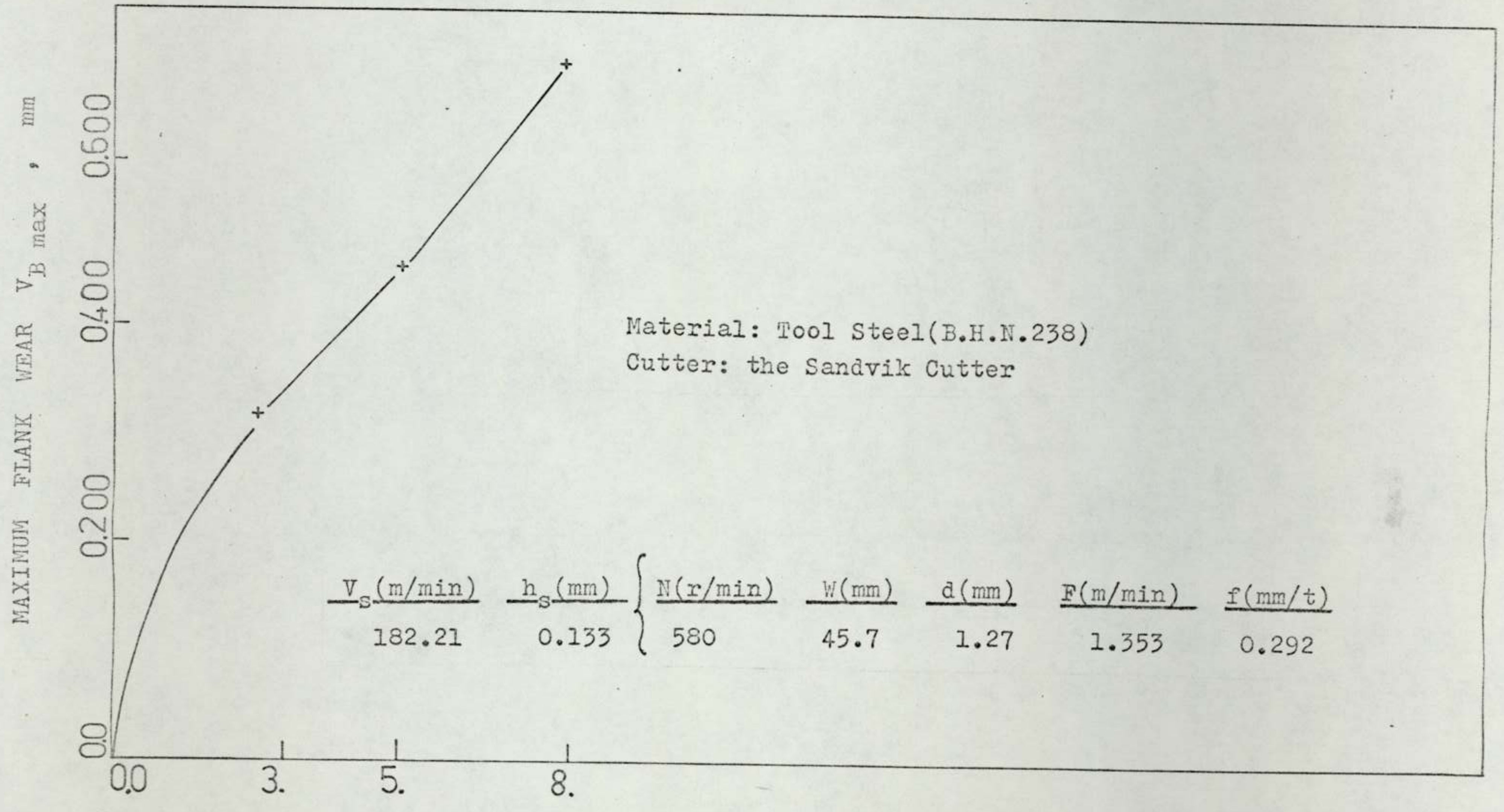


Material:Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

Inserts were chipped in central milling

	V_s(m/min)	h_s(mm)	(N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
			in Central Milling				
(12)	182.21	0.133	(580	45.7	1.27	1.353	0.292)
			in Up-Cut Milling				
(13)	182.21	0.133	(580	45.7	1.27	1.353	0.292)

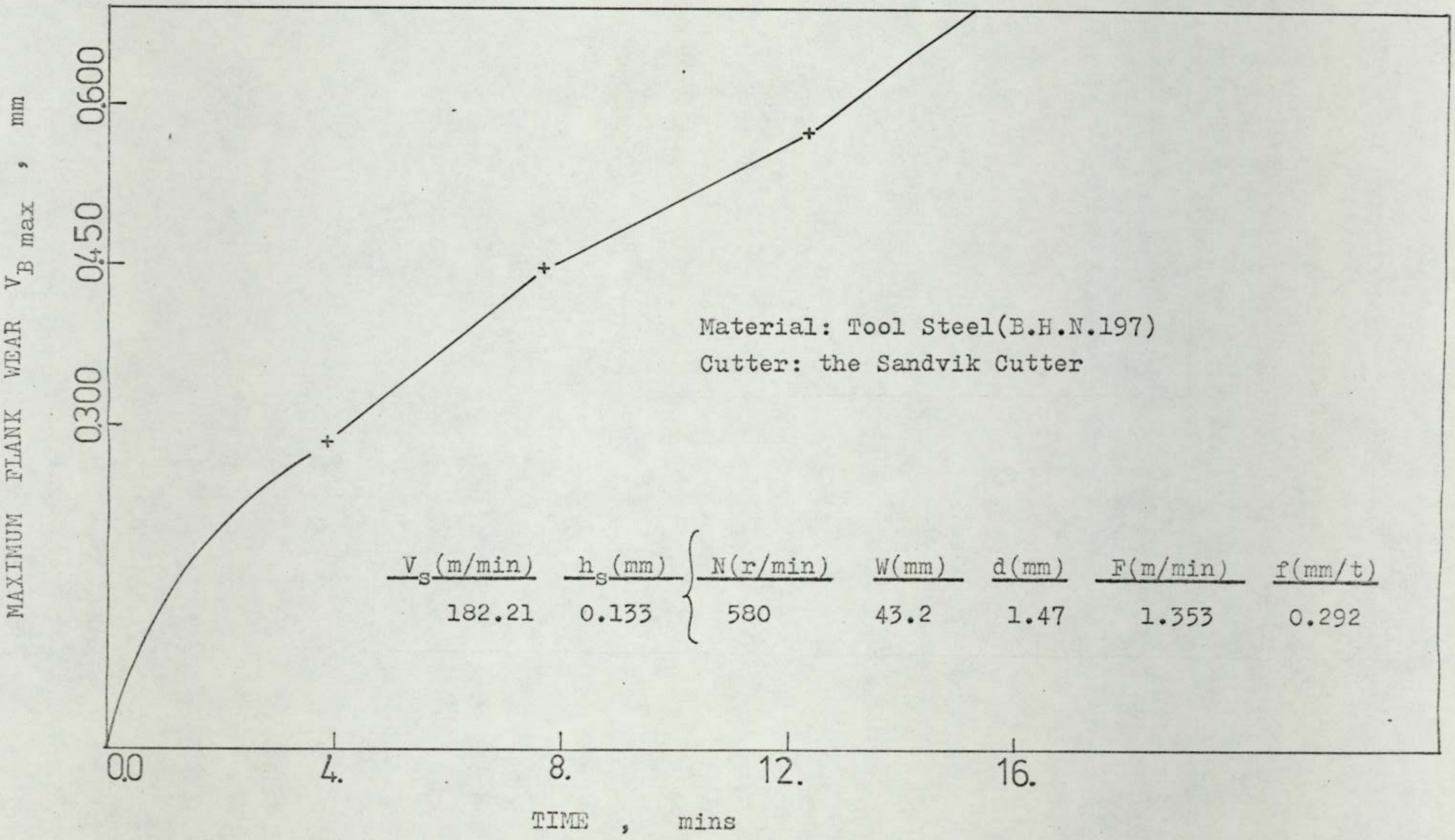
Fig.45 Wear-Time Progresses



Material: Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

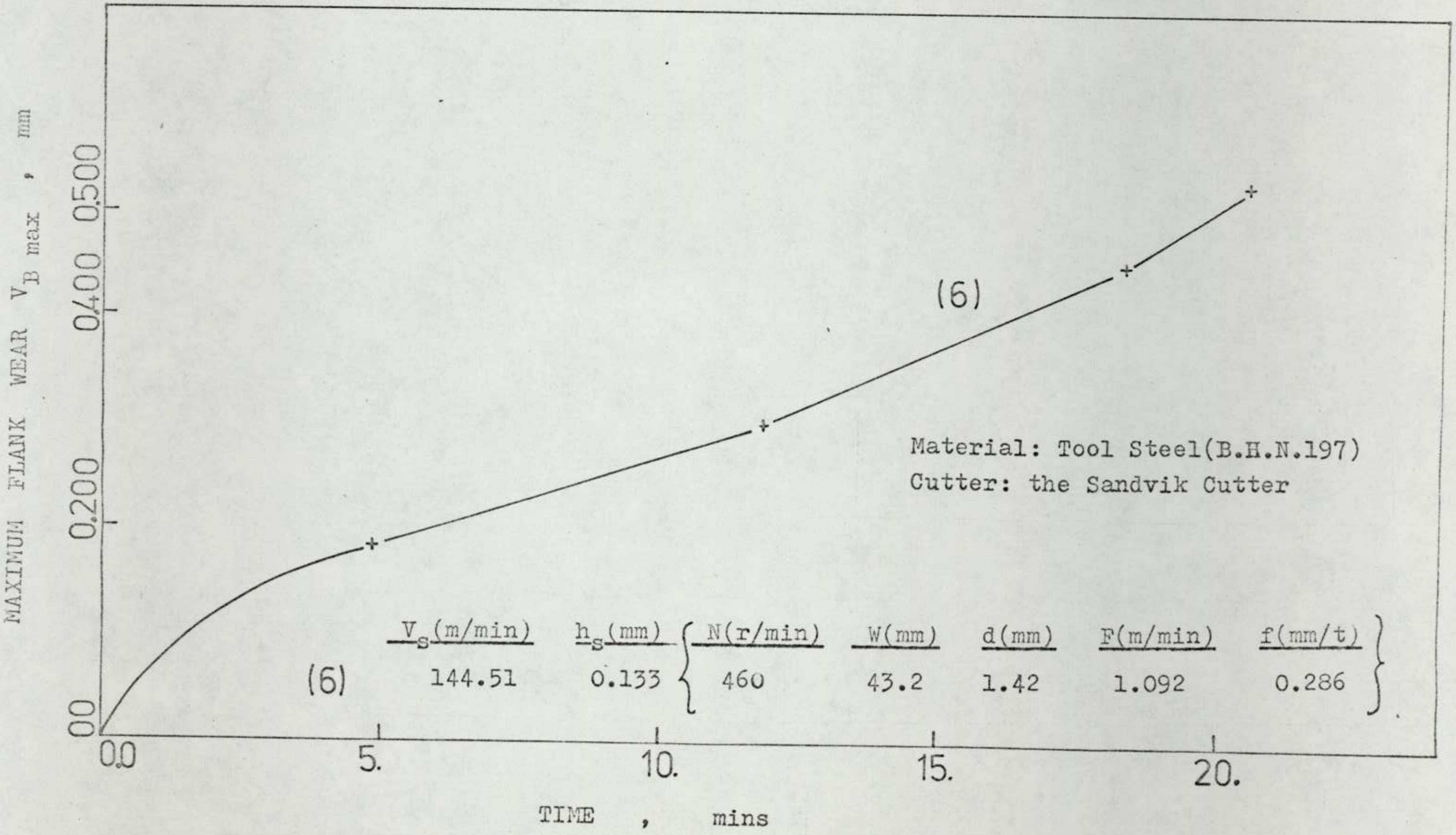
V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
182.21	0.133	580	45.7	1.27	1.353	0.292

Fig.45 Wear-Time Progress in Up-Cut Milling



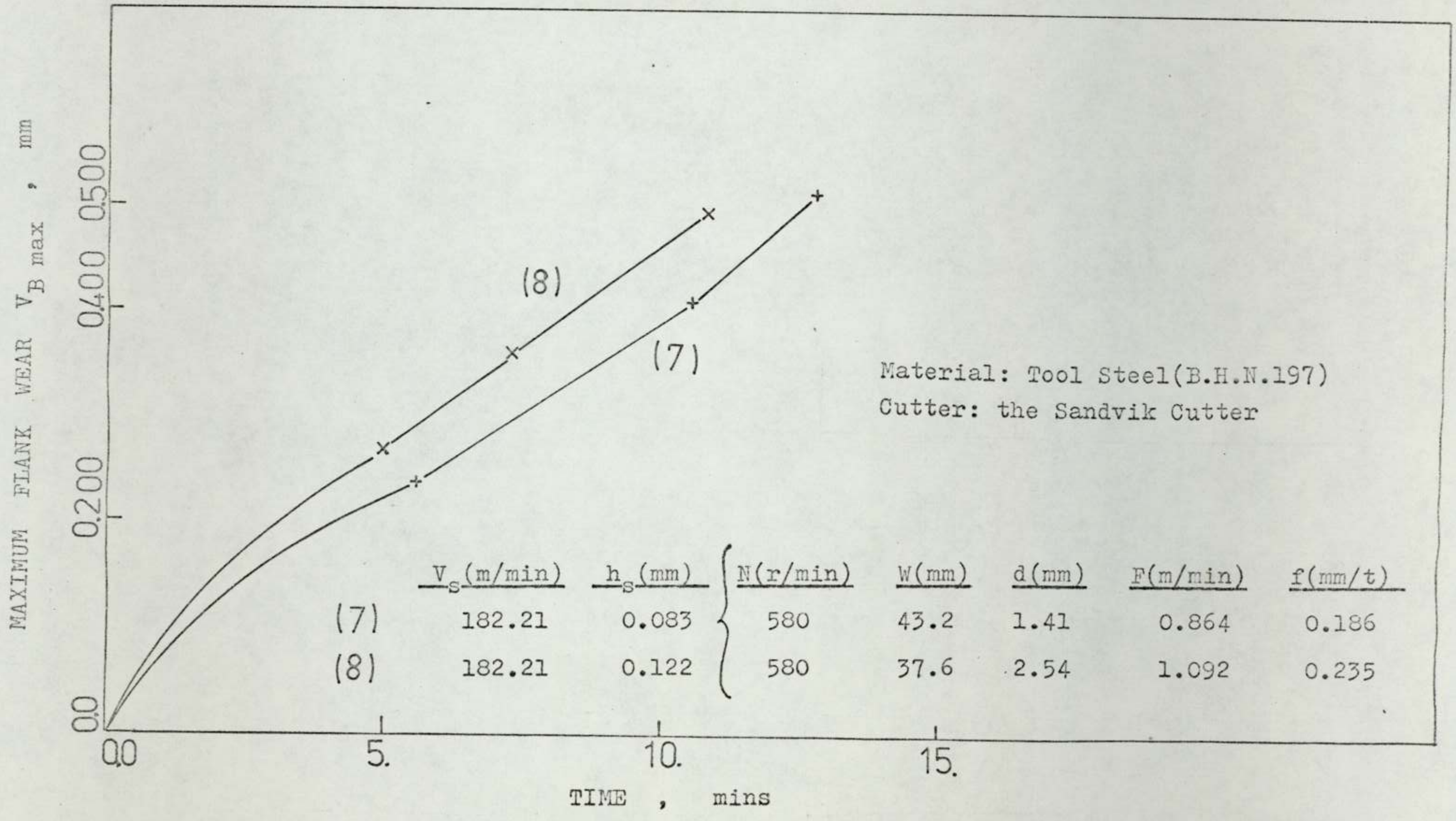
V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
182.21	0.133	580	43.2	1.47	1.353	0.292

Fig.46 Wear-Time Progresses in Down-Cut Milling



	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(6)	144.51	0.133	460	43.2	1.42	1.092	0.286

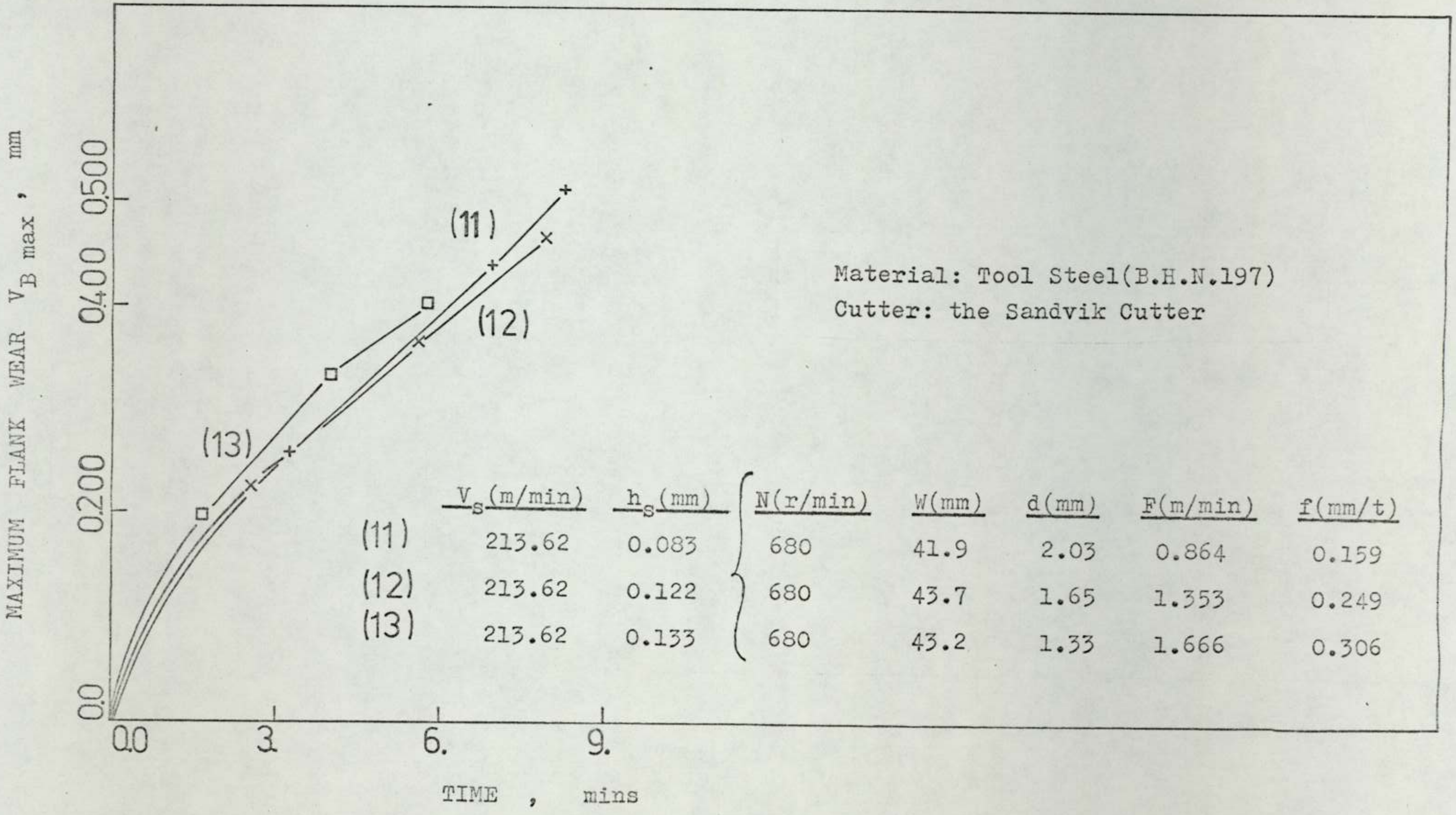
Fig. 47 Wear-Time Progress in Up-Cut Milling



Material: Tool Steel(B.H.N.197)
Cutter: the Sandvik Cutter

	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(7)	182.21	0.083	580	43.2	1.41	0.864	0.186
(8)	182.21	0.122	580	37.6	2.54	1.092	0.235

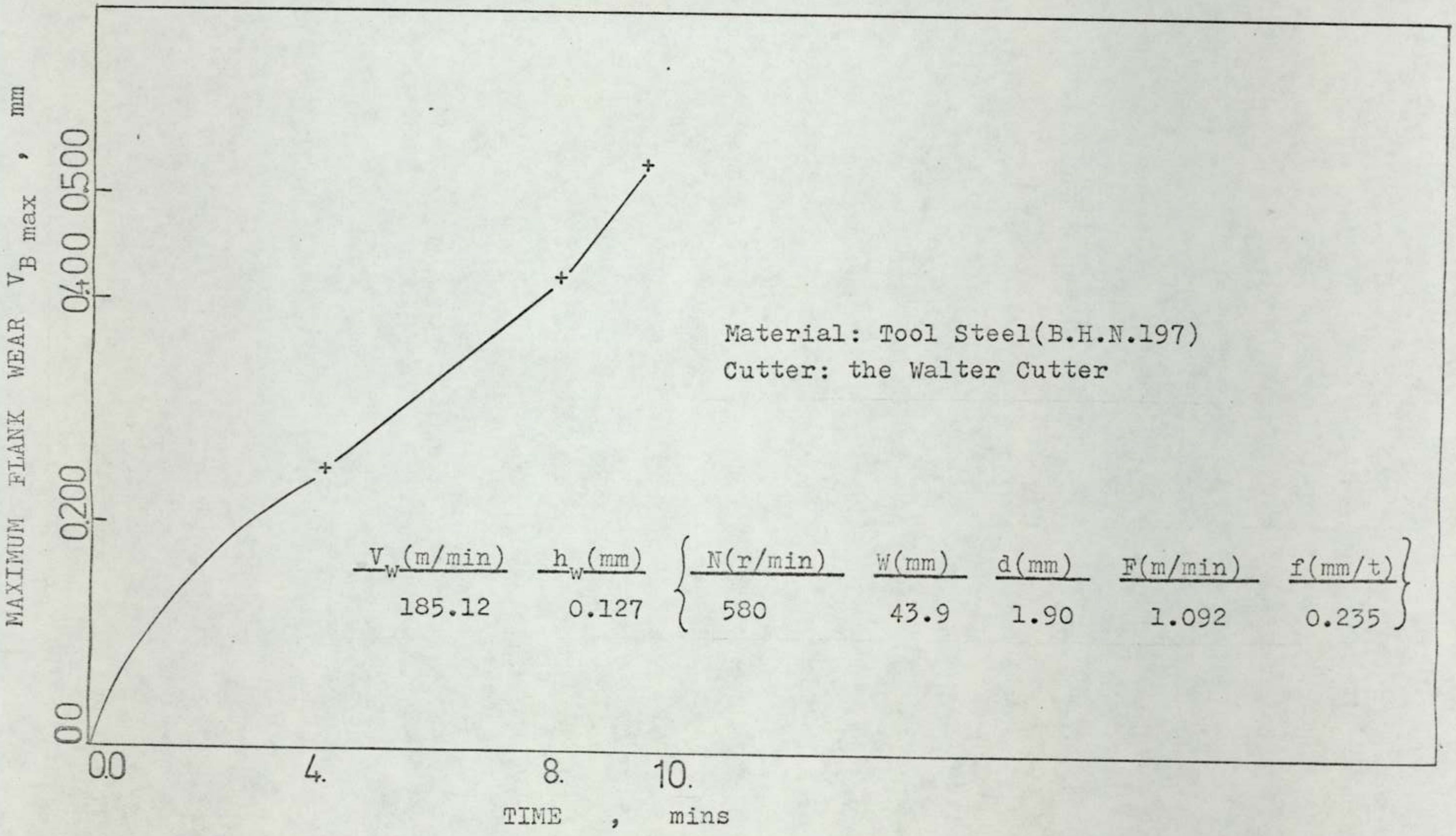
Fig.48 Wear-Time Progresses in Up-Cut Milling



Material: Tool Steel(B.H.N.197)
Cutter: the Sandvik Cutter

	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(11)	213.62	0.083	680	41.9	2.03	0.864	0.159
(12)	213.62	0.122	680	43.7	1.65	1.353	0.249
(13)	213.62	0.133	680	43.2	1.33	1.666	0.306

Fig.49 Wear-Time Progresses in Up-Cut Milling



V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
185.12	0.127	580	43.9	1.90	1.092	0.235

Fig.50 Wear-Time Progress in Up-Cut Milling

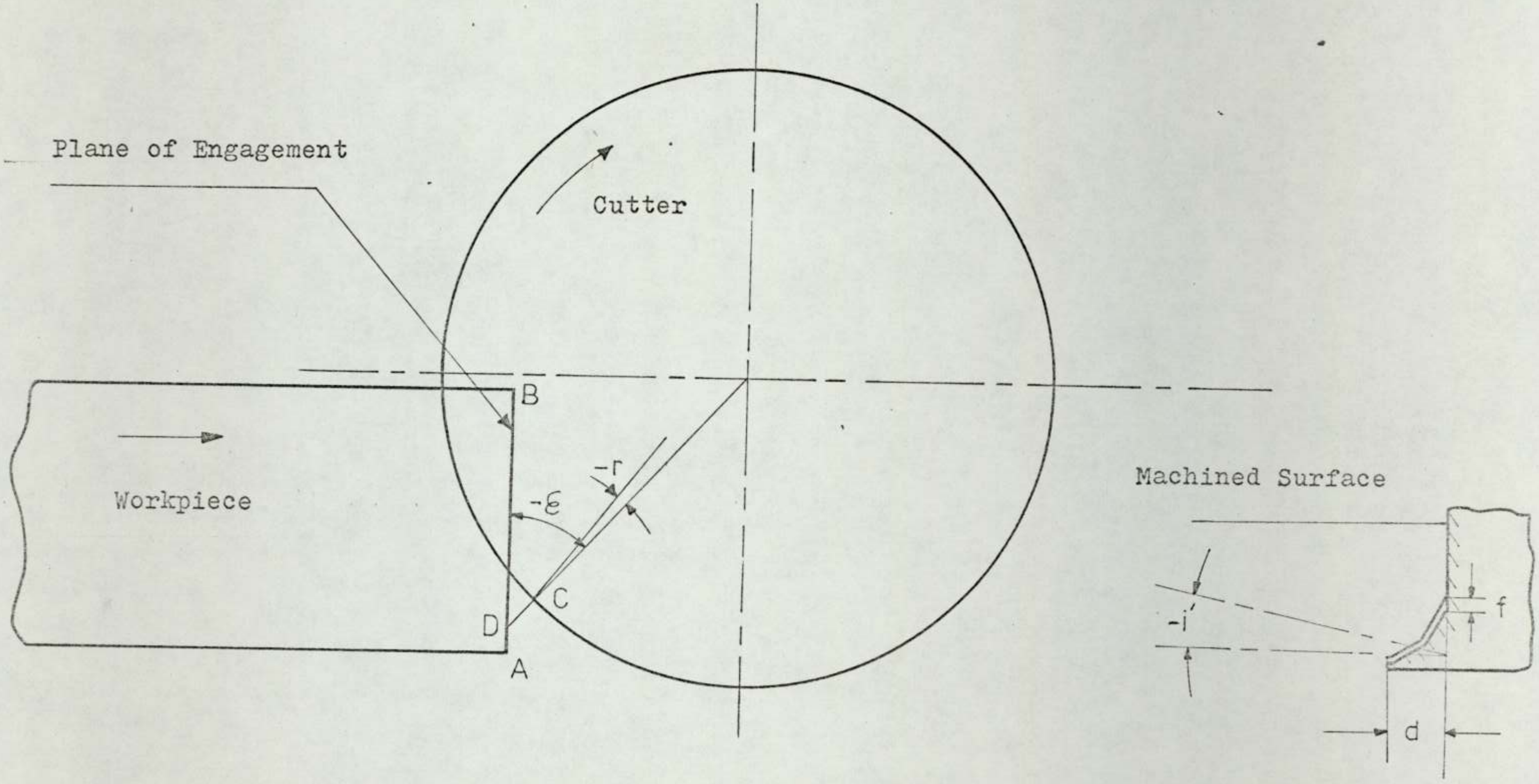


Fig.51 The Intersection Angle i′ in Up-Cut Milling using the Sandvik Cutter

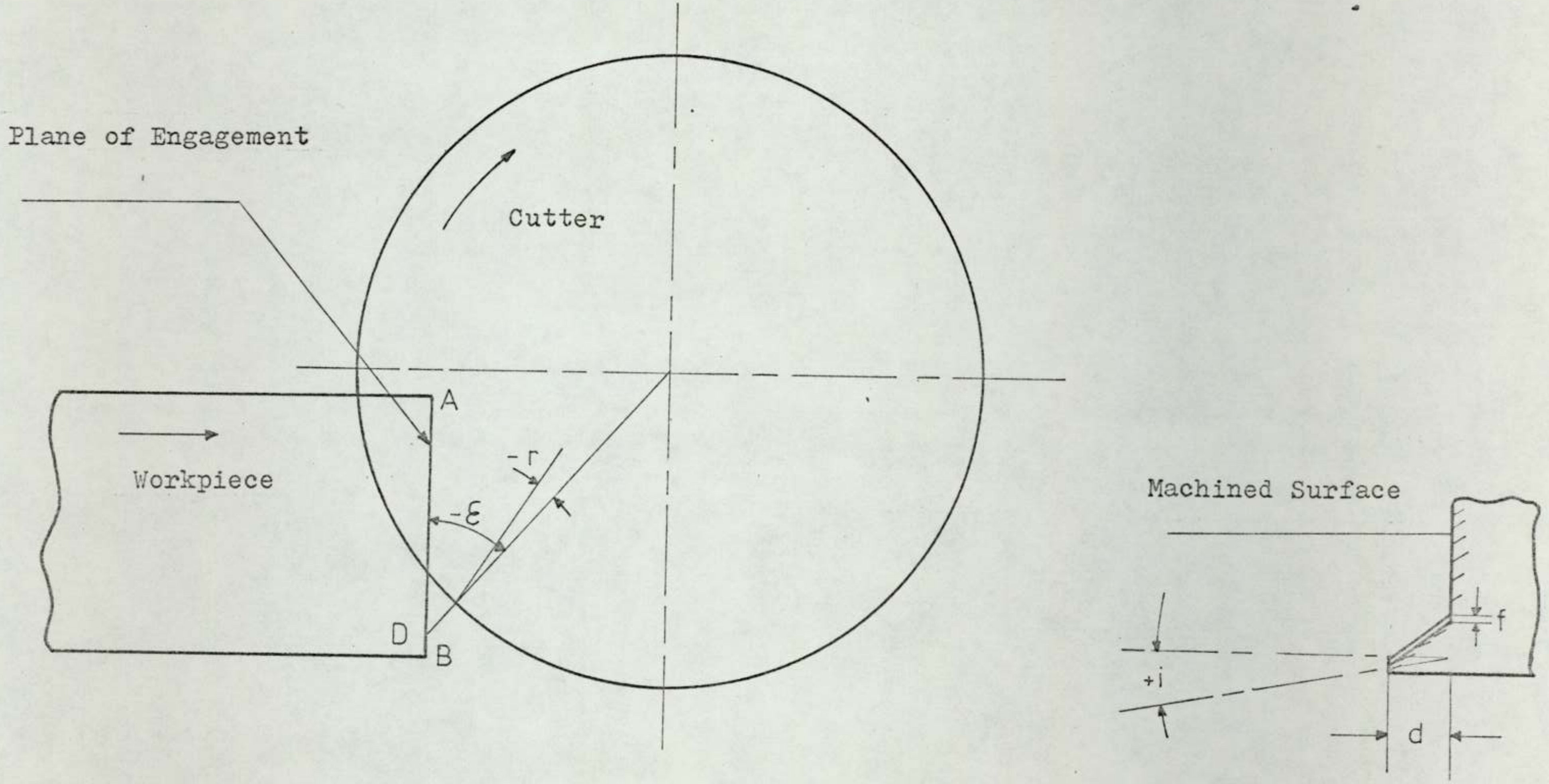


Fig.52 The Intersection Angle i′ in Up-Cut Milling using the Walter Cutter

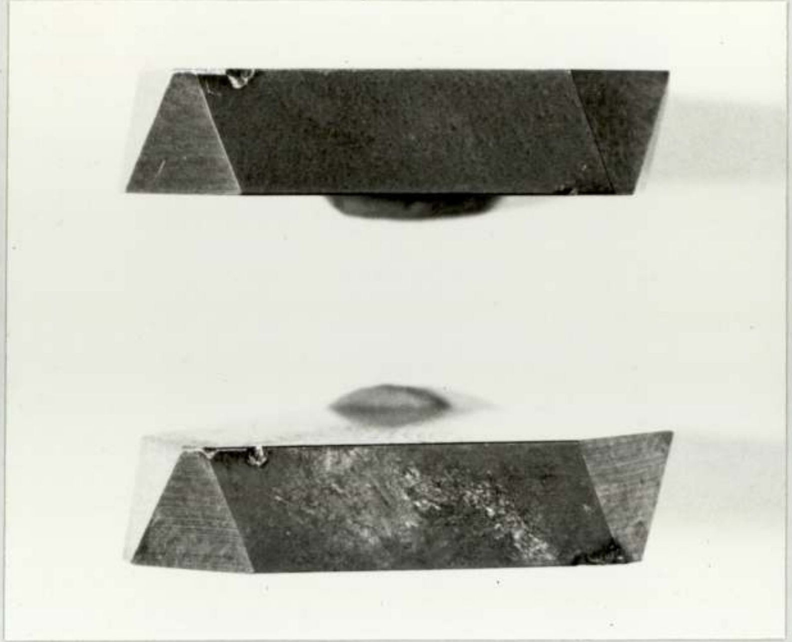


Fig.53 Chipping of Cutting Edges in Up-Cut Milling

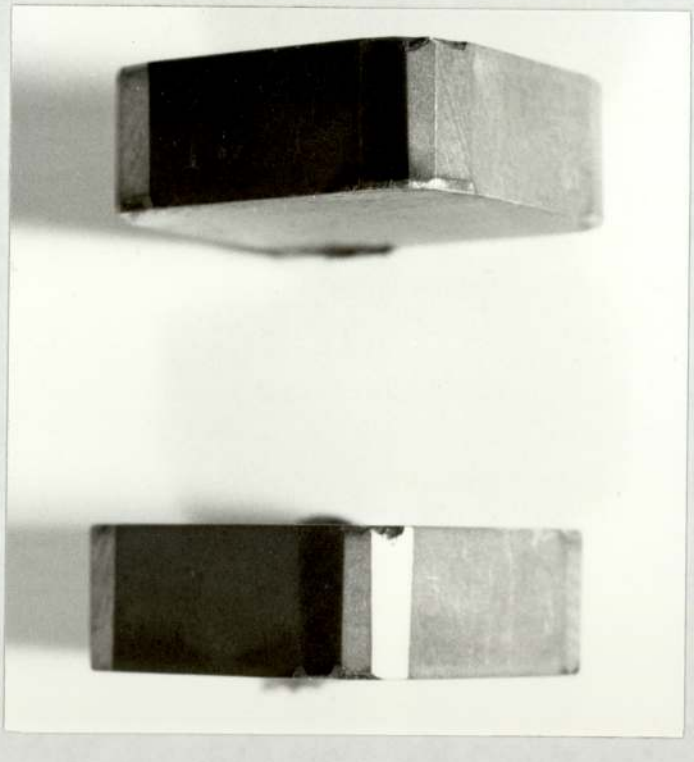


Fig.54 Chipping of Cutting Edges in Up-Cut Milling

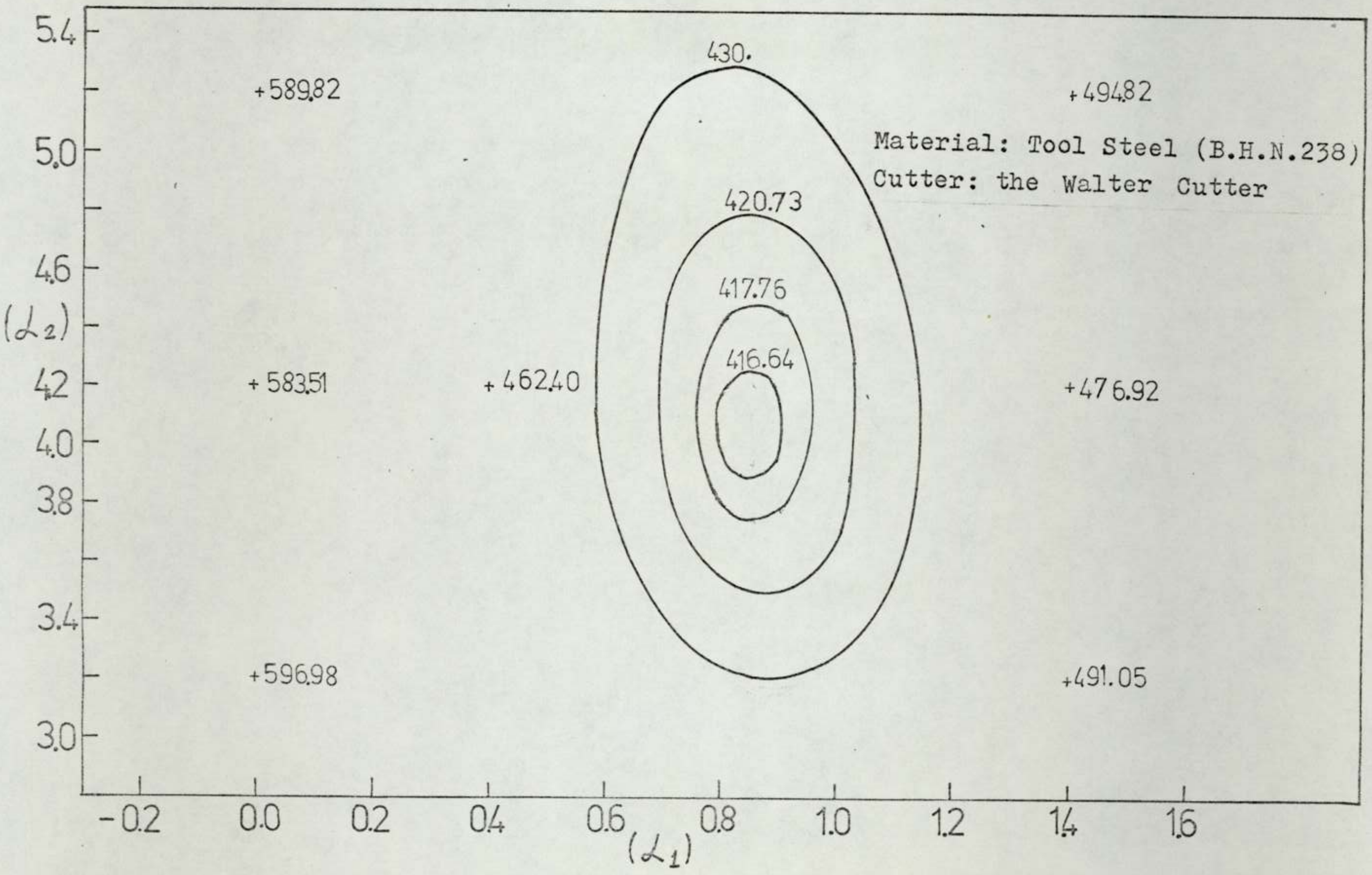


Fig.55 R.S.S. Contour Diagram in α_1-α_2 Plane

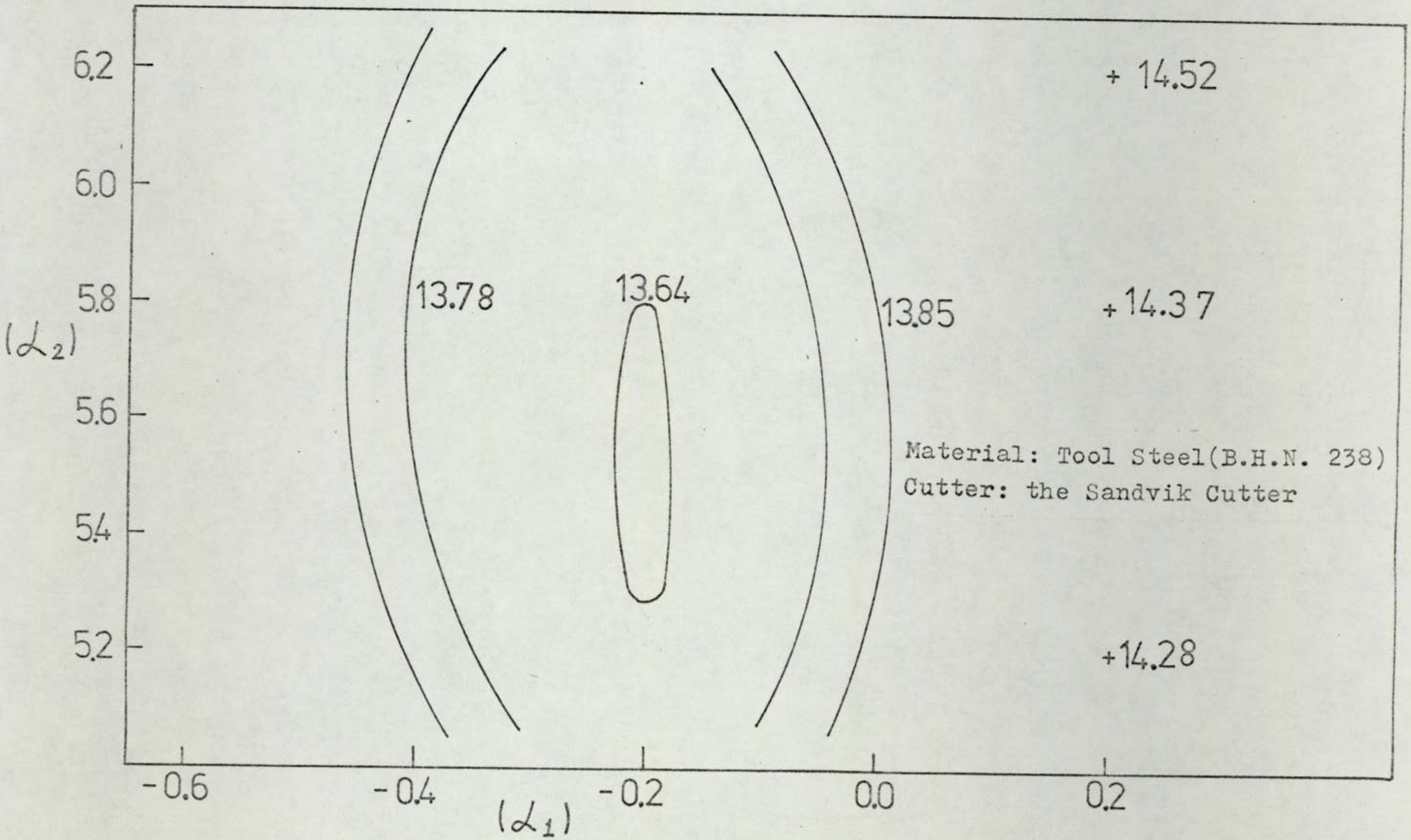


Fig.56 R.S.S. Contour Diagram in α_1-α_2 Plane

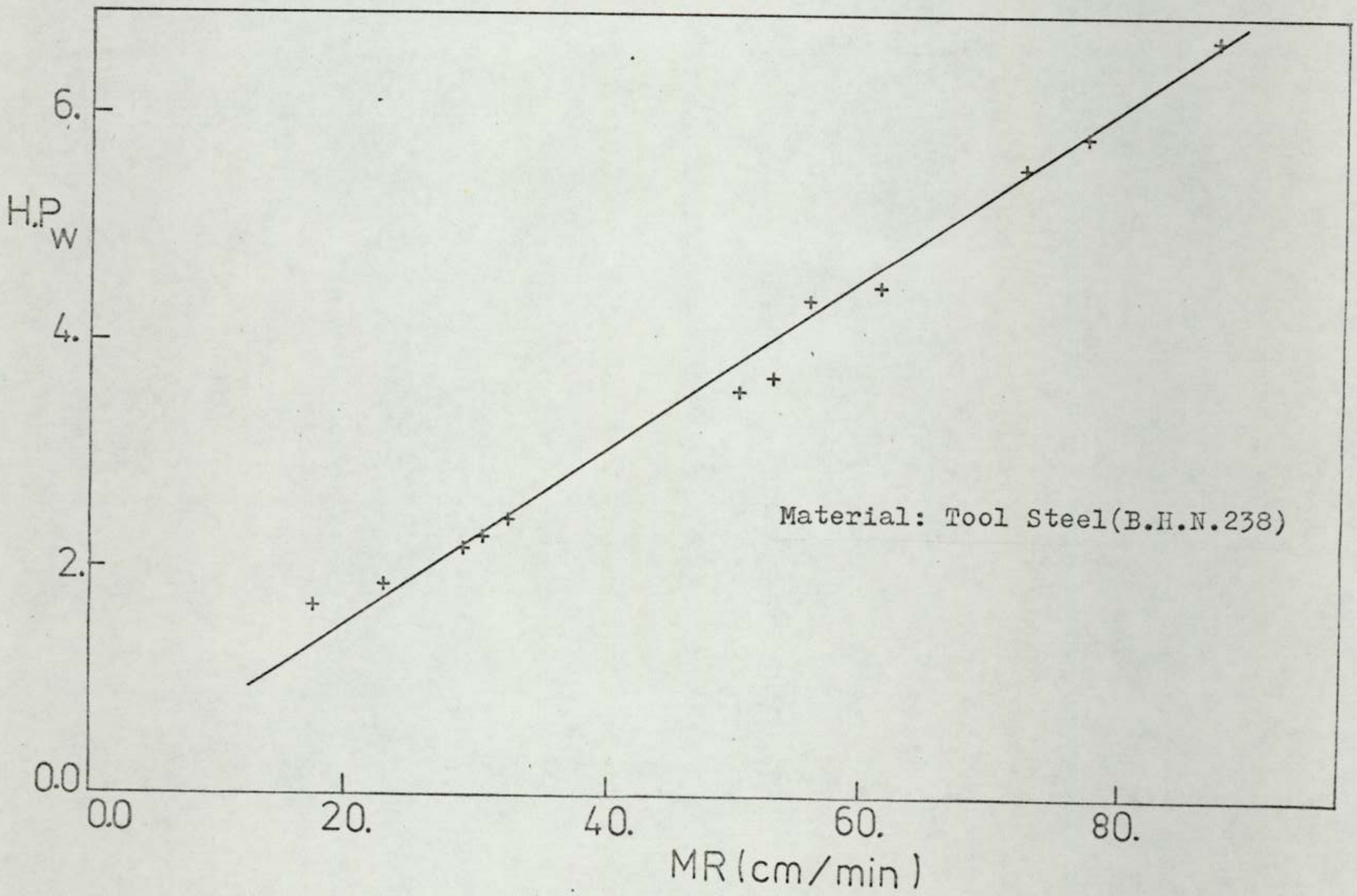


Fig.57 Power Required at the Walter Cutter in Down-Cut Milling

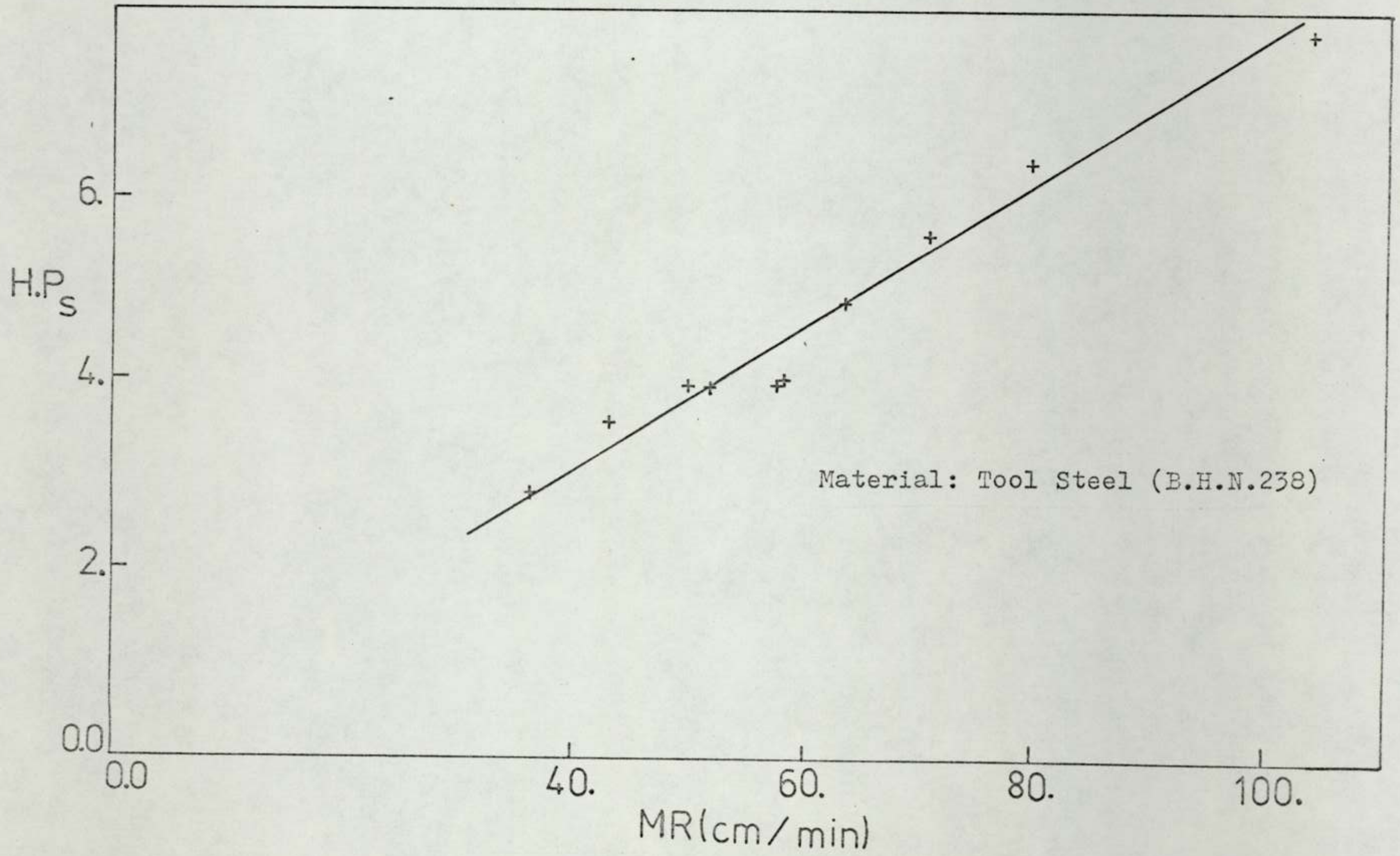


Fig.58 Power Required at the Sandvik Cutter in Down-Cut Milling

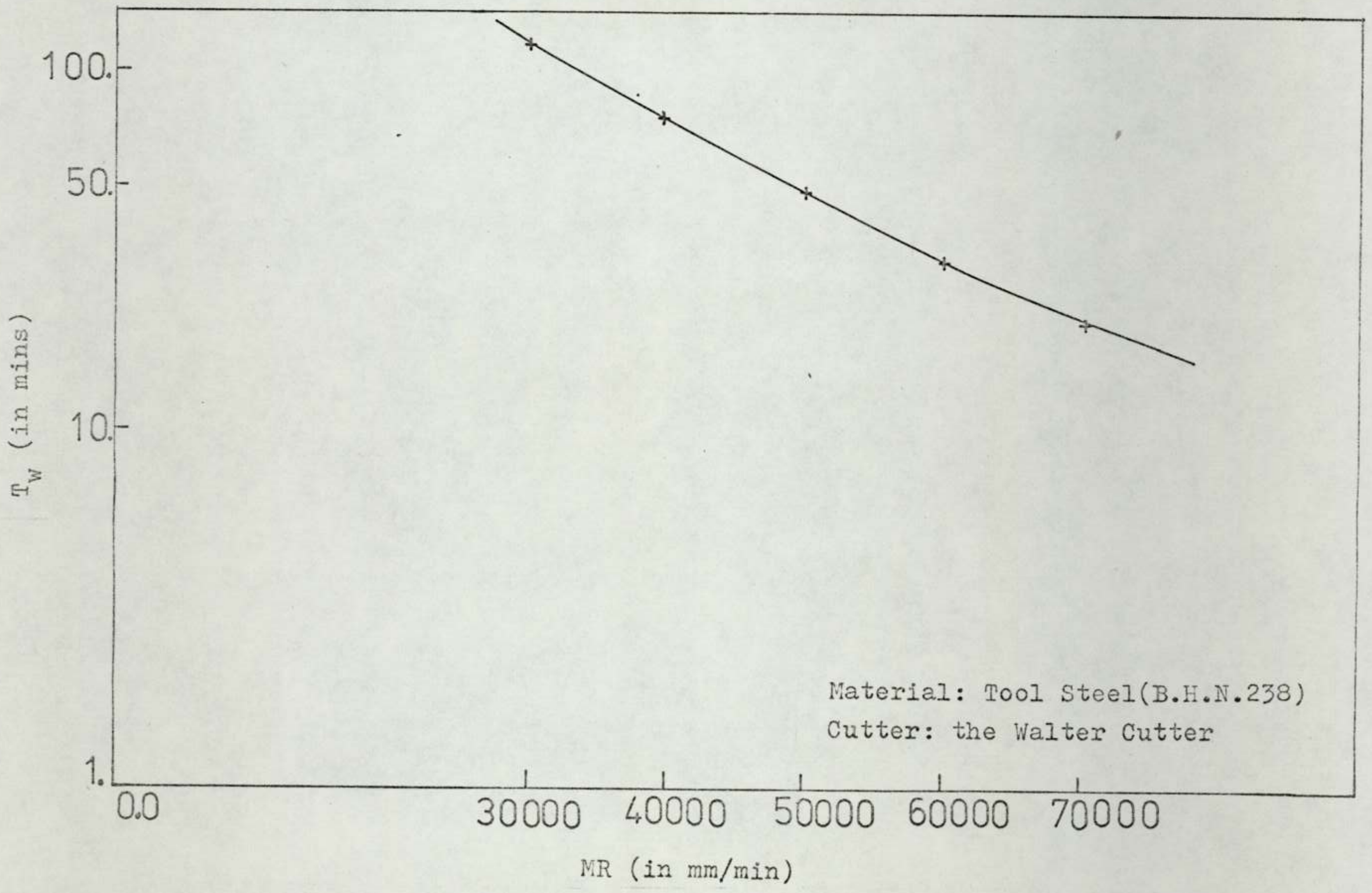


Fig.59 T_w-MR Characteristic Function in Down-Cut Milling

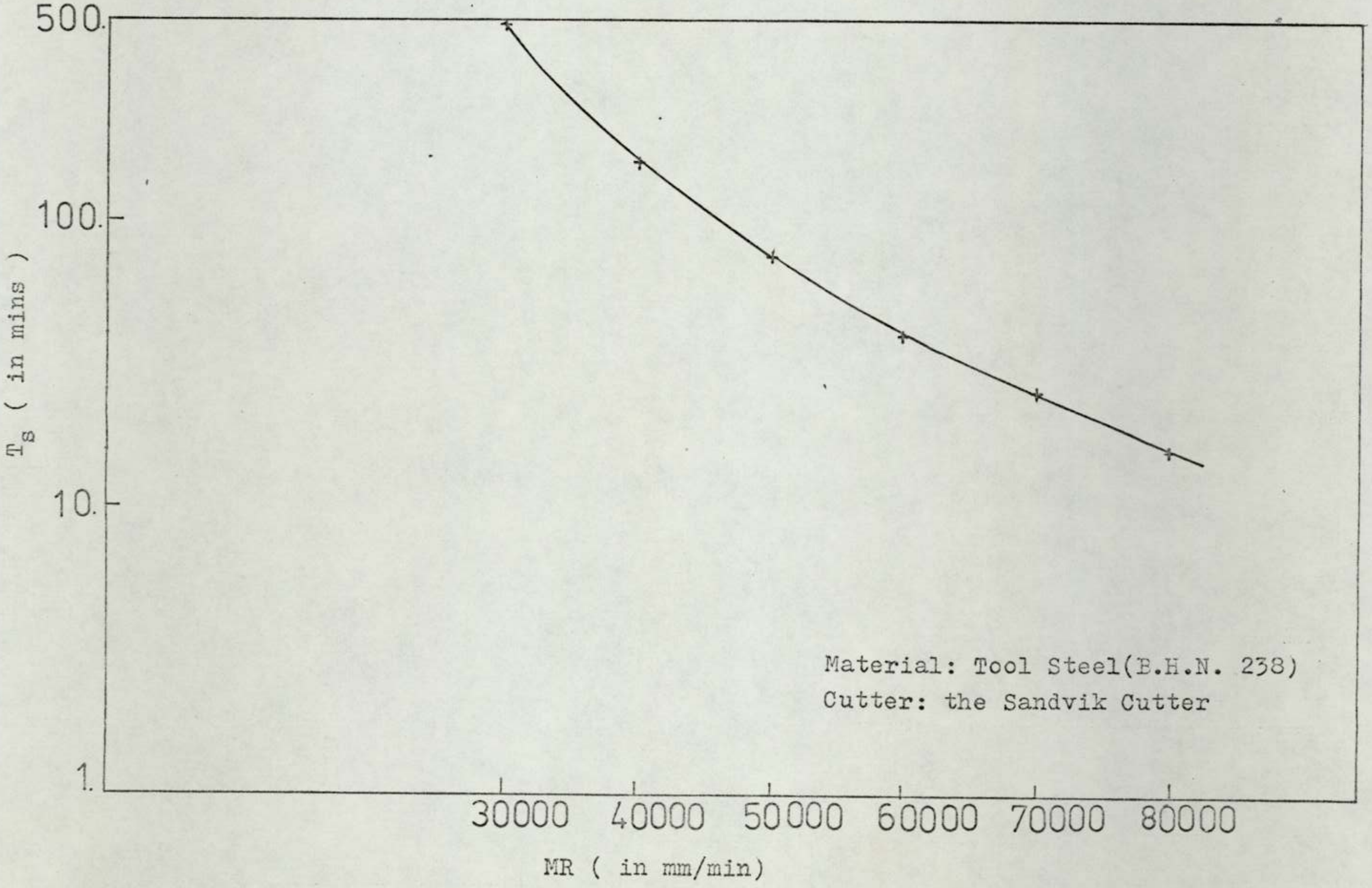


Fig.60 T_s-MR Characteristic Function in Down-Cut Milling

SOME ASPECTS OF MACHINABILITY
DATA OPTIMISATION

BY

CEMAL NECDET ORUNDAS B.Sc., M.Sc.

A thesis submitted for the
degree of Doctor of Philosophy
The University of Aston in Birmingham

December 1976

SUMMARY

Face milling is considered for this work in two main parts. Firstly, the cutting geometry of face milling was examined. As the one independent variable, the author used equivalent chip thickness which is the ratio of the area cut (which is a measure of heat generated) to the cutting edge engaged with the workpiece (which is a measure of heat transferred to the chip, to the cutter and to the workpiece) by each tooth, because cutter wear is a function of cutting temperature.

The machinability data such as cutter life, power required at the cutter, surface finish and vibrations, were obtained using two different face milling cutters (the Walter Cutter and the Sandvik cutter), two different types of tool steel material (B.H.N. 238 and B.H.N. 197 as used by G.K.N. Ltd) in down-cut and up-cut face milling.

The cutter life tests were planned and performed only as a function of cutting speed and of equivalent chip thickness in order to reduce testing time and number of workpieces required. The validity of the equivalent chip thickness was proved. It was found that the equivalent chip thickness gives a guide to the selection of the geometry of teeth commercially available. Cutter life equations were obtained using statistical techniques. The power required at the cutter was expressed only as a function of metal removal rate. The results show both feed and cutting speed affects surface quality and vibration is generally generated by cutting force not by the chatter phenomenon.

With the necessary backlash eliminator down-cut face milling showed better performance (in terms of machinability data, initial contact point at entry conditions) than up-cut face milling. Shorter cutter life was obtained in central milling than in up-cut and down-cut milling, because the width of the workpiece was relatively small according to the cutter diameter used.

Secondly, using the cutter life, metal removal equations and T - MR (T is cutter life; MR is metal removal rate) characteristic function idea, MR was expressed only as a function of T. Then the economics of face milling were examined.

Dedicated to my wife.

The Author

The Author completed his B.Sc and M.Sc. degrees in Mechanical Engineering Faculty of Istanbul Technical University in 1968.

After two years military service he worked for a further two years in industry. After successfully completing his examination, he went abroad for Ph.D studies.

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The author also wishes to thank his wife for her constant encouragement and patience with their daughter.

Thanks also go to Miss D. Drew for patiently typing this thesis.

DECLARATION

No part of this work described in this thesis has been submitted in support of an application for another degree or qualification of this or any other University or other institution of learning.

NOMENCLATURE

W	Width of workpiece (mm)
F	Table speed (m/min)
d	Depth of cut (mm)
φ_e	Engagement angle
φ_z	Angle between any two teeth in cutter
Z	Number of teeth
N	Number of revolution (r/min)
f	Feed per tooth (mm)
h	Underformed radial chip thickness at any instant (mm)
h_m	Mean value of underformed chip thickness (mm)
A_w	Characteristic cross-sectional area of cut for the Walter Cutter (mm^2)
D_w	The nominal diameter of the Walter cutter (mm)
V_w	Cutting speed of the Walter Cutter (m/min)
h_w	Equivalent chip thickness for the Walter Cutter (mm)
A_s	Characteristic cross-sectional area of cut for the Sandvik Cutter (mm^2)
D_s	The nominal diameter of the Sandvik Cutter (mm)
V_s	Cutting speed of the Sandvik Cutter (m/min)
h_s	Equivalent chip thickness for the Sandvik Cutter (mm)
T_w	Cutter life of the Walter Cutter (min)
T_s	Cutter life of the Sandvik Cutter (min)
MR	Metal removal rate
T_p	Total time to produce per piece (min)
Tr	Replacement time for all teeth
C	Total cost to produce per piece
C_o	Operator and overhead cost per unit time.

CONTENTS

CHAPTER I

Introduction

The evaluation of machinability data obtained using the properties of the cutting system (which are known to be: type of machining process, cutter, workpiece being cut, and machine tool) has always been of importance to industry especially from the point of view of economics and utilisation of machine tools.

Machinability data enables the production engineer to select for the process the correct cutter (among those commercially available), the correct process method and the correct machine tool. By using the machinability data obtained, the process selected can be controlled either directly or indirectly.

Face milling, which is one of the cutting processes, removes excess material from the plane surface of given workpieces. It is known as interrupted cutting process and widely used in industry because material can be removed in large amounts in unit time with brazed or throw-away carbide inserts. These inserts or teeth, are subject to impact during their entry into the workpiece being cut, and the chip thickness varies during cutting. Due to the great scarcity of literature available on face milling, in this project, the author analyses the geometry and properties of face milling (down-cut, up-cut and central milling) and determines the variation of the chip thickness. The characteristic feed is defined and the metal removal rate is formulated as a function of cutting speed, characteristic feed and depth of cut.

Cutting tests were planned and performed in order to obtain machinability data within industrially practical ranges. At the same time, the entry condition of each tooth was examined in order to determine the first initial contact of each tooth with the workpiece being cut.

The machinability data (which includes cutter life, power required at the cutter, surface finish produced, acceptable dimensional accuracy and vibrations generated), obtained and evaluated for down-cut, up-cut and central milling in order to compare the results using the Walter cutter and the Sandvik cutter with their different throw-away inserts, and the tool steels (B.H.N. 238 and B.H.N. 197) which were all kindly supplied by G.K.N. Ltd., Birmingham. The results were analysed in graphical and by means of mathematical equations. The equations were obtained in as simple a form as possible using statistical techniques.

Cutter life results were obtained by optical means only as a function of cutting speed and equivalent chip thickness using the mean value of the maximum flank wears. It has been known that wear is related to the cutting temperature in metal cutting. Equivalent chip thickness is calculated by the cutter specification (diameter and number of teeth), the width of the workpiece being cut, the tooth geometry and by cutting variables such as table speed, depth of cut, but excepting cutting speed.

The cutter life equations were obtained using the power transformations method, known as one statistical method, in the semi-logarithmic form. Power is measured in terms of gross and idle power. Power required at the cutter was evaluated only as a function of metal removal rate in order to obtain simple equations. The same slopes were calculated using the Sandvik cutter and the Walter cutter.

Milling processes are generally known as intermittent processes. They are not finishing processes like turning or grinding. C.L.A. (Centre line Average) measurements taken under different cutting conditions give an idea about the kind of surface finish produced. Generally, the vibrations generated by the cutting force were measured on line under different cutting conditions.

Using the machinability data obtained and having due consideration to time and cost,the economics of face milling were investigated from the T - MR characteristic function (T is the cutter life,MR is metal removal rate), optimum cutter life, metal removal rate and cutting variables such as cutting speed, table speed for the pre-selected depth of cut were obtained bearing in mind the maximum horse power available on the machine tool used.

CHAPTER II

Review of Relevant Literature

As can be seen in Figure (1) and Figure (2) the responses of any machining process can be grouped together into two main groups or indexes, namely: Technological Performance Index, and Economic Performance Index.

Previous investigations, carried out using only one or two of the responses and related to our own research, will be briefly discussed here below:-

2.1. Technological Performance Index and its Measurement.

2.1.1. Temperature

Temperature and its distribution over any local area which is exposed during the cutting process has been the subject of much attention, mostly in turning processes (1), because temperature plays an important role in influencing the rate of wear of cutting tools.

Techniques of temperature measurement in metal cutting are divided into four categories (2).

a) Thermo-electrical methods, b) Calorimetric methods, c) Radiation methods, d) Thermistor methods.

Garter spring pick-up thermocouples positioned at the back of the cutter inserts (which is one of the thermo-electrical methods mentioned above) were used in face milling processes by Wang, Wu and Iwata (3). In order to evaluate the performance of the process, the average cutting temperatures on a multi-tooth cutter were measured and recorded.

Average cutting temperatures were examined for different cutting speeds, feeds and depths of cut, and using different numbers of teeth. It was found that cutting temperatures increased as the number of teeth increased, for the same cutting conditions.

2.1.2. Chipping or Fracture of Tool

When brittle tools like cemented carbide tools and ceramic tools are used either in a continuous or in an interrupted cutting process such as the milling process, chipping can occur in association with a wear zone, because of both mechanical and thermal stresses. Also, chipping which is not associated with any wear zone can occur in a brand new cutting tool as stated by Cook(4).

He theoretically reviewed tool wear mechanisms and tool life criteria, especially in single-tool operations such as turning rather than multi-tooth operations such as milling.

Kronenberg(5) made an analysis of the initial contact of a milling cutter taking face milling as a reference process. Both geometrically and mathematically and with the aid of the graphical method, he showed and explained the location of the inital contact in terms of the geometrical parameters, such as axial and radial rake angles, corner angle, cutter diameter, position of the cutter relative to the workpiece, as well as of the machining variables, such as feed per tooth and depth of cut, but only along the plane of engagement determined by the length of the workpiece. He did not investigate the location of the first plane of engagement determined either by the width of the workpiece as in the case of up-cut face milling or by the length of the workpiece as in the case of down-cut face milling. Taylor(6) showed the necessity of introducing statistical techniques in the field of metal cutting, because of errors especially in the determination of tool life. He also pointed out that the main objective should be to prevent breakage and chipping when applying carbide tools. He tabulated the results of a two-year survey on the condition of brazed tipped carbide tools in terms of percentage worn and chipped tools, for a number of grades of carbides. The mechanism of cracking of carbide tools in face milling, using single tooth cutters, was considered by Shinozaki (7) from the probability point of view. The effect of machining variables on cracking was investigated by plotting the individual variables against the number of cracks on workpieces of constant length. The following criteria are recommended as ideal for cutting with the least probability of cracks:-

a) Minimize the temperature difference at the cutting edge, b) Lower maximum temperature as much as possible. The limitations of the investigation were in using only single-tooth cutters and face milling in central position. Kuljanic (8) showed the tool life to be a function of the number of teeth in the cutter, in face milling. He also proved statistically that the impact of the tooth entering the material does not affect the tool life when two teeth cut simultaneously. He concluded that the tool life tests for predicting the behaviour of the cutter should be carried out with more than one tooth.

The work was limited to one workpiece, one tool material, and face milling for central position of the material. An analysis of thermal strain in peripheral milling processes, using high speed and carbide end-milling cutters was presented by Yellowley and Barrow (9). They briefly pointed out that in the face milling process, workers in Germany have concluded that entry conditions are all-important, whilst Japanese and Russian workers have laid great emphasis on thermal stressing in discontinuous cutting. They found that tooth life in down-cut peripheral milling was higher than in up-cut peripheral milling. Loladze (10) outlined the problem of brittle failure of cutting tools from stress state conditions for different machining processes (turning, Planing, and certain types of milling) using photoelasticity. He theoretically calculated the thermal stresses using temperature gradients for orthogonal cutting.

2.1.3. Tool Wear, Tool-life Criteria and Tool-life Equations

The fundamental reasons behind the wear process mechanism and their applications to machining processes, basically according to time, have been the subject of investigation by many researchers (11), (12). Opitz and Konig (11) showed that different mechanisms operate in tool wear when steel is machined with carbide cutting tools, namely: diffusions reactions, abrasive wear (plastic deformation), adhesive wear (pressure welding), oxidation wear, etc. It was noticed that, at low and medium cutting speeds, tool-life depends on the wear at the flank face. Under high speed conditions, plastic deformation may occur on the rake face which determines the useful life of cutting tools. In recent years, researchers like Konig (12) have been involved with the development of improved cutting tools to obtain longer tool life. Konig (12) claimed that coated carbide tools, like TiN or TiC - coated carbide, might give tool life approximately 100-300% better than traditional carbides.

Cook (4) and Barrow (13) reviewed tool-life criteria especially in single-tool cutting operations. A tool can be used according to any one of the following criteria:-

1. Tool Failure

Tool failure is a most generally accepted criterion for tool-life. Failure can be classified as follows:

a) Chipping

b) Accelerated wear both on flank face and on rake face. Barrow (13) recommended the values discussed below, especially in turning.

1) Flank face wear

1.1) Carbide and ceramic tools can be used until the prescribed value of wear, the mean value $V_B \cong 0, 38$ mm or the maximum value $V_B \cong 0, 76$ mm, is reached on the flank face (see figure (3)).

1.2) High speed steel tools can be used until the maximum value $V_{B\ max} \cong$ 1.5 mm or complete failure is reached on the flank face.

2) Rake face wear

Carbide and ceramic tools can be used until depth of crater KT = 0.004 + 0.3s (in) is reached on the rake face; s is the feed per revolution in (mm/rev).

Barrow(13) schematically indicated that the relationship between mean value of flank wear V_B and time is in three stages: (a) an initial non-linear rapid wear rate, (b) an approximate constant wear rate, and (c) another zone of non-linear rapid wear rate, with both wear and time on a linear scale. He also pointed out that, provided the correct tool material is used for a machining process, failure by flank wear is usual; in view of this, tool-life equations are usually developed using a flank-wear criterion and, to compare tool-life data, the same criterion should be used. Opitz and Konig(11) showed that in milling the curve of the mean value of flank wear V_B plotted against milling length on a log-log scale, and the curve of the depth of crater KT plotted against cutting time on linear scales, show an approximately linear increase after a first rapid wear rate. Konig(12) obtained curves of V_B against cutting time-in logarithmic scale and KT against cutting time (in linear scale), approximately in linear form, using P25 carbide tool and P25 + TiC - 13Mo - 13Ni Coated carbide tools.

Gilbert, Boston and Siekmann(14) obtained cutter-life data and cutter-life equation for cast iron mostly using carbide brazed single tooth face milling cutters in central milling on a knee-type horizontal milling machine. The parameters and variables (namely: grade of cast iron, tool material, feed per tooth, depth of cut, width of bar, number of teeth) were changed one at a time, using a value of 0.76 mm for the steady flank wear. The limitations were that they used mostly a single tooth cutter, central milling and only one type of tool with a certain geometry.

In process measurements of tool wear obtained by sensors have been given attention, particularly on numerically controlled machine tools rather than conventional machine tools (15), (16), (17). Their investigation is out-side our scope.

2. Change of Surface Finish

Tool wear effects on surface finish. The deterioration of surface finish can determine the end of tool-life.

3. Change of Workpiece Dimensional Tolerance and Accuracy

The cutting edge might have to be replaced if the components produced are out of tolerance, because the degree of tolerance is associated with the wear of the radiused nose of the cutting edge.

4. Change of Cutting Force and Power

Cutting force and power required to cut the workpiece increase as the tool wears. The tool is replaced after a predetermined amount of increase.

5. Economic Considerations

Tools can be replaced before they are completely worn out,on the basis of an estimate of tool-life and of average tool cost. Tool-life data obtained from reliable tests can be evaluated in tabular, graphical, or mathematical form (equation).

An accurate assessment of tool-life data in mathematical form has been necessary, following the development of optimization procedures and numerically-controlled machine tools (13). When considering the validity of tool-life equations, one realizes that they are all emperical.

In the metal-cutting field, many independent parameters and variables contribute many responses as can be seen in Figure (1) and Figure (2). If the number of the independent variables chosen is large, and one of the responses can be selected first, research can be carried out on the evaluation of the effects of each one of the independent variables on the selected response by using the Analyis of Variance, a well known method in the science of Statistics$^{(18)}$. The analysis of Variance can show the significance of the independent parameters and variables influencing a machining process. Generally, when selecting the independent variables from the point of view of tool wear, either of two main different criteria can be adopted:

a) The independent variables such as surface speed, feed, depth of cut etc., are taken into consideration individually.

b) Only two independent variables are taken into consideration individually: surface speed and chip equivalent, or its reciprocal the equivalent chip thickness, which includes feed, depth of cut, tool geometry and some geometric properties.

Using the two main different criteria mentioned above, up-to now three different tool-life equations have been used$^{(13)}$ to predict the behaviour of the cutting process, especially in turning operations.

a) Taylor-type tool-life equations. Firstly, Taylor$^{(19)}$ introduced his best-known tool-life equation $V.T^{n} = K$ (1)

Where n is the slope of the logT-logV plot and K is a constant.

For turning, Kronenberg$^{(20)}$ suggested a method to obtain the following tool-life / cutting-speed relation, by keeping constant the feed, the depth of cut and the tool geometry:

$$(V \pm K_s)\, T^{n_1} = (K \pm K_s) \qquad (2)$$

where K_s is a constant (straightening factor). An extended Taylor-type equation which includes V, S, d, is used especially in turning with one type of tool geometry, as follows:

$$V.T^{\alpha}.\ s^{\beta}.\ d^{\gamma} = K \qquad (3)$$

where the exponents α, β, γ are accepted as reasonably constant.

b) Tool-life equations using the chip-equivalent concept.

Woxen$^{(21)}$ first introduced the idea of chip equivalent q which includes geometrical parameters as well as machining variables of cutting in turning; he expressed the tool-life equation as follows:

$$V = \left(\frac{T_*}{T}\right)^{\alpha} . C . \frac{q + q_o}{1 + cq_o} \qquad (4)$$

where V is the cutting speed, T is the tool-life, T_* is a predetermined tool-life, e.g. 60 mins, α is an exponent, C is a constant determined by work material and tool material referred to the time T_*, q_o is a constant, c is a constant in turning process.

Brewer and Rueda$^{(22)}$ carried out work to demonstrate the validity of the "equivalent chip thickness" h_e which is the reciprocal of q in turning, and pointed out that h_e was unfamiliar parameter in English-speaking countries. Using a high-speed steel tool, they also expressed the tool-life in turning operations using a much simpler relationship involving only two variables, cutting speed V and equivalent chip thickness h_e, instead of five variables, V, S, d, side-cutting edge angle S_c and noise radius r. Colding$^{(23)}$ derived one limited equation and one general hyperbolic tool-life equation involving the variables cutting speed, chip equivalent and tool-life, at first in turning, using a well-known dimensional analysis. The limited tool-life equation was

$$V.T^{\alpha} = Aq^m \qquad (5)$$

where α and m are reasonably constant, and A is a constant for the limited tool-life. The general hyperbolic tool-life equation was

$$\varnothing(x,y,x) = -\frac{(X-Xo)^2}{a^2} \div \frac{(Y-Yo)^2}{b^2} + \frac{(Z-Zo)^2}{c^2} = H \qquad (6)$$

where $\varnothing(x,y,x)$ is general hyperbolic tool-life function, $X = \ln q$, $Y = \ln V$, $Z = \ln T$, and a, b and c are the semiaxes of the hyperbolic tool-life surface. He also expressed the total cost Q of turning one piece:

$$Q = \frac{Wp.P}{V.s.d} \cdot \frac{T + \delta}{T} + p.T_i \qquad (7)$$

where Wp is the volume of material to be removed per part, p is the cost of machine and operator including overheads, (V.s.d) is the metal volume removed per unit time, T is the tool-life, $\delta = T_d + R/p$, T_d is the tool-replacement time, R is the average cost of regrinding the tool, T_i is the idle time.

He defined f as a productivity function:

$$f = (V.s.d) \cdot \frac{T}{T+\delta} = L \cdot \frac{V}{q} \cdot \frac{T}{T+\delta} \qquad (8)$$

where L is the engaged cutting edge of the tool and q is the chip equivalent. Then he searched to optimize the ratio $\frac{f}{L}$ called productivity.

Later Colding$^{(24), (25)}$ obtained expressions, using the chip equivalent idea, for all types of milling and grinding processes according to his own tool geometry and set-up. Then he used the general tool-life equation in second order polynominal logarithmic form for turning and plain milling processes.

$$k + ax + bx^2 + cy + dy^2 + ez^2 - z + fxy + gyz + hxz = 0 \qquad (9)$$

where k, a, b, c, d, e, f, g, h are constants, $x = \ln q$, $y = \ln V$ and $z = \ln T$.

The equation above is quite complicated and it is not easy to use since lnT also appears in the second order. The effects of cutting angles on tool-life were analysed by Akun(26) using equivalent chip thickness idea in turning. He concluded that if rake angle is increased, tool-life is increased, when the angle (side cutting-edge angle) between the work-piece and the tool is increased,tool-life is decreased in turning.

c) Tool-life Equation in Exponental Form

(Proposed by Konig-Depiereuz)

Konig and Depiereuz(27) derived a tool-life equation for the turning process using T-V and T-S logarithmic curves, obtained during actual cuts, taking non-linearity into account.

They assumed that the slopes K and i of the above curves vary as follows:

$$k = -k_V . V^m \qquad (10)$$

$$i = -i_s . s^n \qquad (11)$$

where k_V, i_s, m, n are constants.

Using actual values of T, v and s, they then obtained their tool-life equation:

$$T = e\ (-\frac{k_V}{m} V^m - \frac{i_s}{n} s^n + C) \qquad (12)$$

where C is another constant.

The limitations of this equation are that it is derived for a constant depth of cut in turning, and it does not take into account the experimental errors.

Since all tool-life experimental results include experimental errors, just like any other experimental processes, it is very difficult to obtain the values of five constants (K_V, m, i_s, n, c) by using only five experimental tool-life results (writing five simultaneous equations), especially in a multi-tool cutting process like milling. If the values of T,V and s are not rigidly related to each other, five unknown-constant values cannot be found using five simultaneous equations. This is one of the main reasons why statistical techniques have been so successful in the field of metal cutting as well as in other engineering fields.

The statistical techniques mentioned below have been used to determine the proposed mathematical form of any response of machining processes; They are 1) Response Surface Methodology, 2) Power Transformations, 3) Multiple Regressions, 4) I.C.L Statistical Package XDS.3.

1. Response Surface Methodology

Response surface methodology was first proposed by Prof. G. E. P. Box in 1951 in chemical process engineering. This statistical technique views the response as a surface. Wu(28), (29) first applied this technique to the field of metal cutting using Taylor-type first and second order equations, taking V, s,d individually as independent variables. A composite design was used. After calculating the coefficients by means of the least square method, the confidence intervals were defined. The adequacy of the postulated model was checked by means of Analysis of Variance. Confidence intervals were determined for tool-life results.

2. Power Transformations

Instead of linearizing tool-life equations, Wu, Ermer and Hill(30) used transformations of certain forms of dependent and independent variables to determine directly Taylor-type equations.

The transformations, used in tool-life equations, were in the following forms:

$$T^{\lambda} = \begin{cases} \dfrac{T^{\lambda} - 1}{\lambda (\dot{T})^{\lambda - 1}} & \text{if } \lambda \neq 0 \\ \dot{T} \ln T & \text{if } \lambda = 0 \end{cases} \qquad (13)$$

where T is the tool-life and $\dot{T}$ is the geometric mean value of tool-life observations.

For the independent variables, U_1, U_2 .... U_p, the transformations were in the forms below:-

$$U_i = \begin{cases} X_i^{\alpha i} & \text{if } \alpha_i \neq 0 \\ \ln X_i & \text{if } \alpha_i = 0 \end{cases} \qquad (14)$$

where X_i is any independent variable and α_i is any parameter.

The tool-life equations are generally written as;

$$E(T^{(\lambda)}) = \beta_o + \beta_1 U_1 + \beta_2 U_2 + \beta_3 U_3 \; ..... + \beta_p U_p \qquad (15)$$

where $E(T^{\lambda})$ is the expected value of the transformed tool-life β_o, β_1, β_3 ..... β_p are coefficients and are calculated using the method of least squares. For example if $\lambda \neq 0$ and $\alpha_i \neq 0$, the equation is written as follows:

$$E\left(\frac{T^{\lambda} - 1}{\lambda (\dot{T})^{\lambda - 1}}\right) = \beta_o + \beta_1 X_1^{\alpha 1} + \beta_2 X_2^{\alpha 2} + \beta_3 X_3^{\alpha 3} \dots + \beta_p X_p^{\alpha p} \qquad (16)$$

If $\lambda = 0$ and $\alpha_i = 0$ the equation is written as follows:

$$E(\dot{T}.\ln T) = \beta_o + \beta_1 \ln X_1 + \beta_x \ln X_2 + \beta_3 \ln X_3 \; .... + \beta_p \ln X_p \qquad (17)$$

This is a logaritmic transformation, which is a special case of the power transformations. The method of the residual sum of squares was used as the numerical criterion to indicate the best fit among the equations. An approximate percent confidence region was determined for tool-life.

3. Multiple Regression and Analysis

Some researchers (31), (32), (33) have already shown that multiple regression, one of the statistical techniques, also plays an important part in finding relationships between any one response of any machining process and a number of independent variables involved in that machining process.

In the past, instead of multiple regression, researchers used linear, curve or surface fitting methods.

Any proposed function which may be converted to linear form can be written as follows:

$$Y = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \cdots \beta_p X_p \qquad (18)$$

here Y is the estimated response and $\beta_o, \beta_1, \beta_2, \beta_3 \cdots \beta_p$ are coefficients which are determined by the method of least aquares.

Their composite effect is measured by the multiple correlation coefficient.

When the number of independent variables is large, the use of a computer may become necessary. After estimating the coefficients, the analysis of variance can be used to check the adequacy of the proposed model. Certain percentage confidence intervals for the estimated coefficients can be calculated.

4. The I.C.L. Statistical package XDS.3.

The I.C.L. 1900 series statistical mark 2 package (34) defined in the manual gives different facilities.

4.1. Independent and dependent variables are defined at the beginning of the programme. Observations are introduced in a matrix. Using the observation matrix, the package can calculate the mean, the variance and the standard deviation of each of the variables.

A cross-product matrix is calculated from the observation matrix. A covariance matrix is found using the cross-product matrix. Then a correlation matrix is determined by the covariance matrix. All these matrixes are available from the output file.

The regression analysis can be carried out on a covariance which was calculated before the regression analysis. For each analysis, a dependent variable is defined. A significance level of each or of all the independent variables is determined. Two different cases are identified.

a) Significance level $\geqslant$ 99%,using the significance level equal to or greater than 99%, each independent variable, which is written in the regression analysis, is pushed into the regression set.

b) Significance level $\langle$ 99%, using the significance level each independent variable, which is written in the regression analysis, appears when it is significant compared with the standard significance level.

Output of the Programme

Regression coefficients are calculated using the least square method. Standard error of the regression coefficient, confidence interval, student t-statistic, partial correlation coefficient, multiple correlation coefficient, error sum of squares (E.S.S) of each one of the independent variables and also E.S.S. of the dependent variable, are calculated in the analysis.

4.2. Analysis of Variance. As mentioned earlier, the analysis of Variance can be used to break down a measurement variation into additive components. The use of the analysis of Variance is shown in I.C.L. 1900 series statistical mark 2 package.

2.14. Cutting Force and Measurements

In the study of the metal cutting field, measurements and evaluation of the components of cutting force are particularly important especially from the point of view of the mechanism and of the machine tool design, as well as from the point of view of the cutting tool design. For designing of the machine tool structures and the associated mechanisms, only the maximum values of the components of the cutting force are required.

In any metal cutting process the cutting force, which is originated from a point on the interface between the cutting edge of the tool and the workpiece, is a single vector. That vector can be resolved into three mutually perpendicular components called the tangential force F_t the radical force F_r and the axial force F_a. In addition F_t and F_r can be further resolved into two components, one parallel and the other one perpendicular to the direction of feed. One example of force resolution in down face milling process supposing two teeth in engagement with the workpiece is shown in Figure (4).

Traditionally the instantaneous value of each component, especially the tangential force F_t, can be given by a function of the machining parameters, like feed and depth of cut. In face milling, for example, the value of F_t for each tooth is given by Koeningsberger$^{(35)}$ as follows:

$$F_t = P_m . d . f_i^{\,p} \qquad (19)$$

where P_m is the mean value of the specific cutting pressure, d is the depth of cut, f_i is the instantaneous value of the radical chip thickness, and the value of p lies between 0.75 and 0.9.

Especially in milling, measurements of force components F_t, F_r and F_a are difficult because they are oscillating rapidly due to the variation of chip thickness during cutting(36). A dynamometer should record the fluctuations on a time base. For peripheral milling, Figure (5) and Figure (6) show the trend of F_t and F_r in relation to the underformed chip length, both in up-cut and down-cut milling(36). Koenigsberger and Sabberwal(37), Sabberwall(38) measured the horizontal vertical and axial components of the cutting force for different machining variables and different materials, in both up-cut and down-cut peripheral milling, using a three-dimensional dynamometer.

A standard vertical milling machine was used. A hydraulic piston and cylinder arrangement was mounted at the end of the table to eliminate the backlash in the screw and nut assembly in down-cut milling.

He concluded that in down milling the cutting forces are generally higher than in up milling. In down milling the specific and mean cutting pressures are higher than in up milling. In down milling greater power will be required for the rotation of the spindle. Herderson(39) made a theoretical analysis of cutting force components in turning, milling and drilling. He explained each component of the cutting force as a function of the machining parameters and of the tool geometry. Pandley and Shan(40) described and analytical method for evaluating the cutting force components in peripheral and face milling operations using a single tooth cutter. They concluded that the cutting force components can be calculated with sufficent accuracy by describing the cutting action of the tooth by means of a shear plane model. The coefficient of friction largely depends on the tool rake angle and is virtually unaffected by the machining parameters.

2.15. Power Consumption

Because machine tools have limited horse power, the evaluation of the power required during cutting is as important as the evaluation of the cutting force components.

Gilbert, Boston and Siekmann(41) considered the power required in force milling processes using cutters having a single carbide tooth, brazed in position. They examined the unit power (horse power per volume of metal removed in the unit time) required at the cutter in relation to the machining parameters and geometrical variables, using different materials. They also pointed out that the cutting speed has very little effect on the unit horse power at the cutter. The feed per tooth has an appreciable effect on the unit power. Depth of cut has little effect on the unit horse power at the cutter. The width of the surface face-milled effects the thickness of the chip. The Brinell hardness of the material being face-milled also affects the unit horse power.

2.16. Surface Finish

Surface finish is an important parameter especially in finishing processes like turning and grinding. Feed, as a machining parameter, has been known to affect the quality of the surface. Surface roughness, both in the feed direction and in a circumferential direction, and surface waviness, which are known as properties of surface finish, can play an important role to determine the useful life of the tool. Surface roughness in C.L.A index was considered in a regression analysis of feed, noise radius of tool and cutting speed by Bhattacharyya, Gonzalez and Ham(42). In recent years the measurement of surface finish in various processes has been given closer attention, especially using laser beams(43). The discussion of this developement is out-side the scope of our research.

2.2. Economical Performance Index

One of the three machining functions (process cost, process time and profit rate), which together constitute the performance index, can be taken as an objective function. Apart from those three functions, metal removal rate may be proposed as an object function. In machining processes, different types of constraints can arise.

Machining variables can be determined according to a selected objective function, either without constraints or under constraints. The importance of being able to select the economically optimum machining conditions has long been recognized in the metal cutting field. The basic mathematical models which have been used in the analysis of the economics of machining are: Unit-time model, unit-cost model, and profit-rate model.

1. Unit-time model

The total time per piece T_p can be divided into elements as follows:

a) Non-productive time T_1.T_1 includes loading, unloading and set-up time; it is independent of machining variables.

b) Machining or feed engagement time $T_2 = T_c + T_o$,where T_c is the actual time for cutting and T_o is the time for approach and overtravel. In practice, $T_2 \cong T_c$.

c) Tool replacement time $T_3 = \frac{T_r . T_c .}{T}$

where T_r is the replacement time (time for replacing the cutting edge or edges) and T is the tool or cutter life.

Thus: $$T_p = T_1 + T_c + T_r \cdot \frac{T_c}{T} \qquad (20)$$

The reciprocal of T_p is the production rate P_p which indicates the number of pieces produced per unit time.

$$P_p = \frac{1}{T_p} \tag{21}$$

2. Unit-cost model

If C_o is the cost rate (which includes operator costs and overheads), and Y is the cost per cutting edge or edges of the tool, we have:

$C_1 = C_oT_1$ = non-productive cost.

$C_2 = C_oT_2 \cong C_oT_c$ = machining cost.

$C_3 = C_oT_3 = C_oT_r \cdot \frac{T_c}{T}$ = tool replacement cost.

$C_4 = Y \cdot \frac{T_c}{T}$ = tool cost.

The total cost per piece, C, will then be given by:

$$C = C_1 + C_2 + C_3 + C_4 = C_oT_1 + C_oT_c + C_oT_r \cdot \frac{T_c}{T} + Y \cdot \frac{T_c}{T} \tag{22}$$

3. Profit rate

The profit per unit time, Pr, can be written as follows:

$$P_r = \frac{S-C}{T_p} \tag{23}$$

where S is the selling price per piece and may be assumed to be a function of T_p, C is the total cost per piece, and T_p is the total time per piece.

It is essential that cost, time and tool-life data should be available to evaluate economic cutting conditions. But it is not always essential to express tool-life data in a mathematical form; Optimum cutting conditions can be obtained using tool-life data curves drawn using points obtained in actual tests.

As mentioned earlier, Brewer and Rueda$^{(22)}$ used a number of nomograms to determine the economic cutting speed in turning. The cutting speed was determined for a selected maximum feed under cutting force and horsepower restrictions using the equivalent chip thickness variable for different tool materials (High speed steel, carbide, ceramic) and work piece materials (cast irons, steels).

Ravignani (44) suggested graphical methods for determinining the optimum machining conditions from tool-life curves obtained from actual tests, using the relationships between the basic unit-time, the unit-cost and the profit-rate models. He extended his studies to the case of different operations successively carried out on the same workpiece. He also derived a method for determining the optimum ranges of the cutting conditions. He showed some examples in turning. Generally, his studies, need a rather high degree of simplication for practical use. Jakobsson (45) suggested a method to obtain optimum cutting conditions, based on actual tests and using T-V and V-q curves drawn on a logarithmic graph, where q is the chip equivalent. The productivity, $P = \frac{V}{q} \cdot \frac{T}{T+T_V}$, is calculated as an economic criterion to obtain values. In the above equation T_V is tool replacement time + tool cost per replacement expressed in machining time Tool-life data are more convenient (13) if expressed in mathematical form.

Brown (46) considered the selection of machining parameters when turning with a single-point tool in one pass and in two passes, using a unit-cost model. When turning in one pass with constant feed and constant depth of cut, using Taylor's well known tool-life relationship $VT^n = K$ he derived an expression for the minimum-cost tool-life.

$$T_{vm} = \frac{C_o T_3 + Y}{C_o} \cdot \left(\frac{1}{n} - 1\right) \qquad (24)$$

and for the corresponding speed V_{vm}

$$V_{vm} = \frac{K}{\left(T_e \cdot \left(\frac{1}{n} - 1\right)\right)^n} \qquad (25)$$

where $T_e = \frac{C_o T_3 + Y}{C_o}$

Similarly, with constant speed and depth of cut, using $s\,.T^{n_1} = K_1$ Taylor's tool-life equation for feed s, he obtained an expression for the minimum-cost tool-life.

$$T_{sm} = \frac{C_o T_3 + Y}{C_o} \cdot \left(\frac{1}{n_1} - 1 \right) \qquad (26)$$

and for the corresponding feed:

$$s_{sm} = \frac{K_1}{T_{sm}^{\ n_1}} \qquad (27)$$

He also derived the expressions for the cost of the two passes, which is the sum of the cost of each pass plus the cost of time required to change conditions from one pass to the next, at each pass using different cutting speeds, feeds and depths of cut. The derivations are rather complex and needs simplifying before they can be used in practice.

Taylor (6) showed the effect of speed on the unit cost model at constant feed using the relationship $VT^n = K$ in turning. He also examined the effect residual variance in the determination of the equation linking the tool-life T to the cutting speed V. In the absence of any quantitave statement regarding residual variance, he applied 95% confidence limits which produced a variation of ± 30% on the individual determinations of tool-life value, thus indicating that the work and tool material are the main sources of variability. He showed graphically the probable range of unit cost models with 95% limits. He pointed out that EN970 specification allows hardness the vary from 248 to 302 Brinell. Variations of this magnitude can cause tool-life to alter by 50%.

Ermer and Wu(47) investigated statistically the effect of experimental errors in tool-life tests on the determination of the minimum unit cost model using $VT^n = K$ (Taylor's tool-life equation) in turning. They determined a probable range of cutting speeds for minimum-cost because of uncertainty in the tool-life equation. A decision rule based on the minimum principle was used for the selection of a particular cutting speed for minimum-cost confidence interval. Ermer and Morris(48) used a different approach, a correction factor for the selection of the cutting speed for minimum cost, which takes into account the effect of experimental errors in tool-life tests. French, Milner and Weston(49) presented a computer programme for selecting the cutting parameters using only the known properties of machine tool, cutter and workpiece in turning.

They pointed out that for the numerical control of machine tool,it is necessary to determine the four facts listed below in order to obtain maximum utilization, because of high initial investment cost of machine tool: a) tool motions, b) cutting variables, c) tools required, d) sequence of operations.Throughout their investigations, the workpiece material used was steel because any research and development programme concerned with machining should include a high proportion of ferrous matals as stated by PERA reports No. 142(50). Okushima and Hitomi(51) analysed theoretically the profit per piece in turning, using a linear break-even chart and employing Taylor's tool-life equation $VT^n = K$. Wu and Ermer(52) showed the application of economic principle to the profit-rate criterion for the selection of the optimum machining conditions in turning, using Taylor's tool-life equation $VT^n = K$. Amergeo and Russell(53) analysed theoretically the selection of machining conditions based on profit-rate for a single pass turning process, using Taylor's tool-life equation

$VT^{\alpha} . s^{\beta} = K_1$. It was found that the largest possible feeds should be used when selecting cutting conditions, in order to obtain minimum-cost or maximum production-rate; in general the maximum profit-rate is not achieved under conditions affording minimum-cost or maximum production rate.

Armarego and Russell (54) also showed theoretically the use of the profit-rate criterion in single pass shaping and peripheral milling. They applied Taylor's tool-life equation to peripheral milling with a single-tooth cutter, as follows:

$$T = \frac{A}{V^{\frac{1}{n}} . (teg)^{\frac{1}{n_1}}} \qquad (28)$$

where T was the tool-life, expressed as actual cutting time of the one tooth of the cutter, V was the cutting speed, teg. was the average chip thickness (because of variations in chip thickness), and A, n, n_1 are constants. They determined the machining time from the ratio $\frac{l}{F}$, where l was the length of workpiece and F was the table speed and obtained the tool replacement time from the formula

$$T_d . \frac{T_{cs}}{T}$$

where T_d was the time required to replace the tooth of the single-tooth cutter, T_{cs} was the cutting time for the one tooth to cut workpieces, and T was described by equation (28). Wu and Tee (55) determined the optimum cutting conditions using maximum profit-rate and the cutting speed at maximum feed to meet the fixed demand. The effect of the variation of selling price per piece and operator cost on the profit rate was examined.

In single-pass turning operations with fixed feed and depth of cut, using Taylor's tool-life equation $T = \frac{K}{\left(V^{\frac{1}{n}}\right) . s^{\frac{1}{n_1}}}$, Kizhanatham and Brian(56) analysed a cost model, including the in-process inventory cost which is determined as the cost due to the waiting of the semi-finished jobs in the workshop for processing by some machine, and the penalty cost which is a cost for violating a due date clause.

Ermer(57) showed the application of geometric programming to turning operations, to obtain optimum cutting conditions for minimum unit cost under constraints such as available speeds, feeds, horsepower, surface finish. The optimum cutting conditions obtained by his method are subject to uncertainty because some coefficients of the unit cost model, such as non-productive time and coefficients of constraint, are subject to variations.

Iwata, Muratsu, Iwatsubo and Fujii(58) showed an analytical method to determine optimum cutting conditions by considering the probabilistic nature of coefficients in some constraints such as cutting force, horse power and surface finish.

Friedmann and Tipnis(59) introduced a new concept which explained the existence of a characteristic relation between metal removal rate MR and tool-life T for a given metal process. They showed that the optimum point, which determines optimum cutting conditions, must lie on the MR-T characteristic curve. Tipnis and Friedmann(60) showed the application of the above concept to circular sawing and peripheral end milling processes they obtained a MR-T curve, using the cutting speed V and the feed per tooth f as the two variables.

They also theoretically explained the use of the MR-T characteristic curve for the selection of economic cutting conditions under limited cost data, the economical development of tool-life data, the comparison of machining responses such as tool-life, surface finish, the determination of an objective function for adaptive control, and the maximisation of Metal removal rate at the desired level of surface integrity.

As can be followed from the literature survey, in the field of face milling processes little research has been done covering all aspects, especially in order to obtain mechinability data such as cutter life, power required, surface finish produced, and vibration of workpiece. The chip equivalent, which is the reciprocal of the equivalent chip thickness, was proved and used by Woxen(21) in turning. Colding(24),(25) only derived mathematical formulas for the chip equivalent in all aspects of milling processes using his own tool geometry and grinding processes. He did not use it in face milling processes. Cutter life tests have not been conducted using only two independent variables namely cutting speed and equivalent chip thickness, and no equation has been obtained using the two independent variables mentioned above. The power required at the cutter has not be obtained in terms of metal removal rate. The surface finish obtained has not been expressed in term of any machining variable. The vibration of workpiece in three directions, namely tangential, feed and axial directions, has not been measured. Surprisingly, there are few available machinability data in face milling processes. Milner(61) pointed out a similar conclusion.

CHAPTER III

Theoretical Analysis of the Technological Performance Index, the Relationship of each of its Machining Responses and Economic Index in Face Milling Processes

Face milling was chosen as a typical process in order to evaluate the performance indexes of face milling processes themselves as well as other metal cutting processes. It removes metal from a given plain surface more efficiently than the shaping process, it is widely used in industry especially with brazed or throw-away carbide inserts. For this research we were fortunate to obtain the co-operation of the GKN Ltd., Smethwick, Birmingham, a Company producing nuts, bolts and fasteners.

Surprisingly there is litte available machinability data for face milling processes. The following considerations on face milling will be limited to those cases which are of particular importance in establishing relationships such as cutter life, cutting force, power required, surface finish, and vibration produced.

3.1. On the Mechanics of Face Milling

Face milling, which is considered as interrupted cutting process and treated to be a type of milling process such as the others peripheral (slab), end, side etc., milling, is essentially similar to continuous single-point tool cutting except variation of the chip thickness and impact upon the first engagement of each tooth of the cutter with the workpiece material being machined. Three types of face milling, which are described according to set-ups and machining directions, are named as central, down-cut (climb) and up-cut (conventional) milling as shown in Figure (7).

In up-cut and down-cut milling, the eccentricity, e, determines the distance between two planes of symetry: One plane passes through the centre of the cutter, the other passes through the longitudinal axis of the workpiece. In up-cut milling, the cutter rotates against the direction of the table movement, in other words, the workpiece advances towards the cutter on the side where the teeth move against it. In down-cut milling, the cutter rotates in the direction of the table movement, in other words, the workpiece advances towards the cutter on the side where the teeth move away from it. In central milling, the centre of the cutter is on the longitudinal axis of the workpiece being machined.

In Figure (8) one typical down-cut face milling is shown, in which the width of the workpiece is W, the table speed F, the depth of cut d, the engagement angle φ_e, the angle φ_z between any two teeth. The cutter, which has diameter D and number of teeth z, rotates a number of revolutions per unit time N and a cutting speed V. In face milling, the thickness of the undeformed chip varies continuously while each tooth of the cutter cuts the workpiece. In up-cut milling, the undeformed radial chip thickness increases from a small value f_s to the maximum value f. In down-cut milling f occurs almost at the beginning of the cut and the undeformed radial chip thickness will then decrease. In central milling, the undeformed radial thickness increases to f from f_s then decreases again to f_s. The path of each tooth of the cutter relative to the workpiece is a trochoid. For the sake of simplicity it is assumed that the path generated by each tooth is circular$^{(65)}$.

In any face milling process, each tooth cuts a certain volume of metal (W.d.f). All teeth will cut a total volume of metal removed in the unit time, MR, will then be (W.d.f.z.N). The characteristics of MR are as follows:

a) The equation is the same for all face milling processes.

b) Time is not related to the tooth engagement time T_z which is a function of φ_e.

In face milling processes the expressions below are well known;

$$V = \pi.D.N. \qquad (29)$$

$$F = f.z.N. \qquad (30)$$

$$MR = W.d.f.z.N = W.d.F \qquad (31)$$

If the teeth are equally spaced along the periphery of the cutter the angle φ_z between any two teeth is written by:

$$\varphi_z = \frac{2\pi}{z} \qquad (32)$$

It may not be necessary to space teeth equally, in fact it might be desirable. Doolan, Phadke, Wu$^{(66)}$ proposed a method to design a face milling cutter with unequal tooth spacing which has a higher stability against relative vibration between the cutter and workpiece.

In up-cut milling, the unde formed radial chip thickness h at any instant can be expressed approximately according to the set-up used as shown in Figure (9) in the following:

$$h = f.\operatorname{Sin}\varphi \qquad (33)$$

The mean value of the unde formed chip thickness h_m can be written as follows:

$$h_m = \frac{1}{\varphi_e} \int_{\varphi_o}^{\varphi_t} f.\operatorname{Sin}\varphi.d\varphi \qquad (34)$$

$$h_m = \frac{f}{\varphi_e} (\operatorname{Cos}\varphi_o - \operatorname{Cos}\varphi_t) \qquad (35)$$

In down milling, the unde formed radial chip thickness h_1 at any instant can be written approximately as shown in Figure (10) in the following provided the same value f is used;

$$h_1 = f.\mathrm{Cos}\ \varphi_1 \qquad (36)$$

The mean value of the unde formed chip thickness h_{1m} can be written as follows:

$$h_{1m} = \frac{1}{\varphi_{e1}} \int_{\varphi_{o1}}^{\varphi_{t1}} f.\ \mathrm{Cos}\ \varphi_1 . d\varphi_1 \qquad (37)$$

$$h_{1m} = \frac{f}{\varphi_{e1}} \left(\mathrm{Sin}\ \varphi_{t1} - \mathrm{Sin}\ \varphi_{o1}\right) \qquad (38)$$

It can be seen that for the same f value and angles, up-cut and down-cut face milling produce chips with the same mean chip thickness value:

$$h_m = h_{1m} \qquad (39)$$

From now on, therefore only h_m will be used in notation.

Either of the two situations below can occur face milling processes

a) $$\varphi_e \leq \varphi_z \qquad (40)$$

Either one or non tooth is engaged with the workpiece at any time.

b) $$\varphi_e > \varphi_z \qquad (41)$$

One or more than one tooth could be engaged with the workpiece at any time. The number of teeth engaged with the workpiece, z_e, depends both upon φ_e and z. The value of φ_e also depends upon the relative position of the cutter with respect to the workpiece. φ_e increases, when the workpiece is displayed from the centre-line position towards the down-cut or the up-cut position, that is to increase the value of φ_e. The value of z_e is written as follows:

$$z_e = \frac{\varphi_e}{\varphi_z} \tag{42}$$

or

$$z_e = \varphi_e . z/2\pi \tag{43}$$

For example, if $z_e = 1.6$, it will indicate that for 40% of the time only one tooth cuts and for the remaining 60% two teeth cut. The author proposes that for any set-up regardless of type of face milling, the metal removal rate, MR, may be also expressed in the other way apart from the equation (31) using the mean value of unde formed chip thickness h_m and the engagement angle φ_e ideas as follows:

$$MR = h_m . d . \frac{D}{2} . \varphi_e . z . N \tag{44}$$

or

$$MR = h_m . d . V . \frac{\varphi_e}{\varphi_z} \tag{45}$$

The value of MR depends upon h_m, which is a function of f and the geometry of set-up, d, V, φ_e and φ_z. In MR, the term which in this research the author called the "characteristic feed" f_c is defined as follows:

$$f_c = \frac{\varphi_e}{\varphi_z} . h_m \tag{46}$$

When φ_e is smaller than φ_z it shows only one or non tooth is engaged with the workpiece at a time and non-cutting time exist between any two teeth, the ratio $\frac{\varphi_e}{\varphi_z}$, is smaller than 1, determines non-cutting time, hence f_c becomes smaller than h_m. If φ_e is equal to φ_z it also showns only one tooth is engaged with the workpiece at any time but non-cutting time does not exist between any two teeth, the ratio $\frac{\varphi_e}{\varphi_z}$ is equal to 1, hence f_c becomes equal to h_m. When φ_e is bigger than φ_z, it shows one or more than one tooth is engaged with the workpiece at any time, the ratio $\frac{\varphi_e}{\varphi_z}$ is bigger than 1, hence f_c, which becomes bigger h_m, determines the complete motion of one tooth plus the partial motions of one or more teeth, which will engage the workpiece while the first tooth completes cutting.

Metal removal rate, MR can be calculated by using one of the formulas given below:

$$MR = W.d.F = f_c.d.V \qquad (47)$$

The product $f_c.d$ determines the area A_c which will be called "the characteristic cross-sectional area of cut";

$$A_c = f_c.d \qquad (48)$$

For example when φ_e is bigger than φ_z, A_c is the total area cut by one tooth while passing across W.

f_c and A_c are related to the mean value of chip thickness. They can give better understnading than f itself in order to evaluate responses of face milling. Because f is varied during cutting.

3.2. Equivalent Chip Thickness Idea and its Derivation in Face Milling

All energy, which is required to remove excess metal from a given surface, is converted into heat, mostly in frictional heat and in shear plane(67). The sum of energy in a metal cutting process is expanded in several forms listed below:

a) Shear energy alone the shear plane.

b) Friction energy among chip, tool and workpiece.

c) Surface energy due to the formation of a new surface area.

d) Momentum energy.

The temperature at a specific point on the tool can be determined in terms of the quantity of heat generated during cutting and the quantity of heat taken out of the specific point. Every temperature can be related to a particular value of wear on the tool. Referring to face milling, Kuljanic(8) stated that the heat generated rate Q_z can be determined as follows:

$$Q_z = K_s.A.V.z \qquad (49)$$

where K_s is specific cutting pressure, A is chip cross-sectional area, V is speed of face milling cutter and z is number of teeth in face milling cutter.

The heat generated is transfered to chips removed, the tool, the workpiece, the surrounding air by radiation, convection and to cooling fluid if it is used. Woxen(21) assumed that the heat is chiefly carried to the workpiece because of a low heat conducting coefficient and the cross-section of the tool being relatively small, the difference in mean temperature between the nose of the tool and the workpiece greater than between the nose of the tool and chip, the surrounding air and cooling fluid which carry off heat indirectly chiefly from the workpiece and a large volume of the workpiece in relation to chip. Woxen(21) stated that the contact surface between the tool and the workpiece is a measure of the heat carried off. He first proposed the engaged cutting-edge of tool to constitute a measure for the contact surface and in doing so for the heat transport in turning. Woxen showed that in turning actual area of cut $A = s.d.$ (where s is feed and d is depth of cut) is a measure of the heat quantity generated with cutting speed and the engaged cutting-edge length of the tool L is a measure of the heat quantity carried off by chip, tool and workpiece. The relation which is called the chip equivalent q was first used by Woxen$^{(21)}$ and it was expressed by the ratio of the engaged cutting-edge length of the tool L to the area of cut A in turning as seen in Figure (11).

$$q = \frac{L}{A} \qquad (50)$$

The reciprocal of q, which is called equivalent chip thickness h_e, was used by Barrow$^{(13)}$, Brewer and Rueda$^{(22)}$ in turning.

$$h_e = \frac{1}{q} \qquad (51)$$

In this research the idea of equivalent chip thickness and its application, which have not been searched yet in face milling, will be used in order to investigate face milling processes.

Because dimensionally equivalent chip thickness is easier to understand and it can play a useful part in helping researchers to a deeper appreciation of face milling rather than feed f itself,because of the variation of f during cutting. Two different face milling cutter, the Walter cutter and Sandvik cutter (with their indexable right hand P25 grade throwaway inserts) which are widely used in industry, were used throughout this project. The angles for both Walter cutter and Sandvik cutter are shown in Figure (12), Figure (13) respectively.

By using the idea of equivalent chip thickness, in face milling two quantities are considered; area, which is a measure of the heat quantity generated with cutting speed, is calculated as characteristic cross-section area of cut Because the heat is generated while one tooth or more teeth pass across the width of workpiece W depending upon the set-up. Therefore characteristic cross-section area of cut is taken into account as a measure of the heat generated with cutting speed. Length, which is a measure of the heat generated carried out by chip, tool and workpiece, is calculated as cutting-edge of one tooth of the cutter engaged with the workpiece. Because cutting-edge of each tooth of the cutter engaged with the workpiece has the same value while the cutter pass across the width of workpiece W.

Equivalent chip thickness is the ratio of these two quantities mentioned above.

Two situations are developed; one is for Walter cutter, the other is for Sandvik cutter.

3.2.1. Derivation of an Equivalent Chip Thickness Expression for the Walter Cutter in Face Milling.

Characteristic cross-section area of cut A_W for Walter cutter is calculated from the ratio of metal removal rate MR to cutting speed as follows:

$$A_W = \frac{MR}{V_W} \qquad (52)$$

Metal removal rate is also calculated from either the equation (31) or the equation (47) obtained in section 3.1. For the simplicity the equation (31) is used. Hence A_W is written as follows:

$$A_W = \frac{W.d.F.}{V_W} \qquad (53)$$

or
$$A_W = \frac{W.d.f.z}{D_W} \tag{54}$$

Where W is the width of the workpiece, d is the depth of cut, f is feed per tooth, z is the number of teeth and D_W is nominal diameter of the cutter as shown in Figure (12). The cutting edge of tooth engaged with the workpiece L_W is written using the tool geometry parameters as shown in Figure (12), in the following:

$$L_W = l_W + \frac{d}{\sin\theta_W . \cos\delta_W} \tag{55}$$

where l_W is the horizontal length of insert, θ_W is the approach angle, δ_W is the positive axial rake angle, d is the depth of cut. The values are: l_W = 1mm, $\theta_W = 42^{o}$, $\delta_W = +8^{o}$. These values were taken from one of Walter Current Technical Informations$^{(68)}$ and were checked under the Nikon Shadow projector in the Metrology Laboratory of the Production Engineering Department of the University of Aston.

Hence in face milling the equivalent chip thickness h_W for the Walter Cutter can be written as follows:

$$h_W = \frac{A_W}{L_W} \tag{56}$$

$$h_W = \frac{W.d.f.z/\pi D_W}{l_W + \frac{d}{\sin\theta_W . \cos\delta_W}} \tag{57}$$

As can be seen from equation (57) the effects of seven geometrical parameters and machining variables, W, f, z, D_W, l_W, θ_W, and δ_W on h_W are significant. If the values of W, f, z and θ_W are increased, h_W will be increased. If D_W, l_W, δ_W are increased, h_W will be decreased. The effect of d on h_W is not very significant. Only big variations in d will affect on h_w. The equation (56) is valid for all types of face milling. The value of h_w is not related to cutting speed.

3.2.2. Derivation of an Equivalent Chip Thickness Expression for the Sandvik Cutter in Face Milling

Characteristic cross-section area of cut A_s for Sandvik Cutter is calculated from the ratio of metal removal rate MR to cutting speed as follows:

$$A_s = \frac{MR}{V_s} \qquad (58)$$

$$A_s = \frac{W.d.f.z}{\pi .D_s} \qquad (59)$$

D_s is the nominal diameter of the cutter as shown in Figure (13). These two formulas are not the same (formulas (54) and (59)), because diameters of cutters are not the same value.

Two situations can arise according to cutting-edge of tooth engaging the workpiece as seen in Figure (13).

a) $$d < l_a \qquad (60)$$

where d is depth of cut, l_a is vertical length as seen in Figure (13). In this situation engaged cutting-edge of tooth L_{s1} can be expressed by:

$$L_{s1} = l_s + \frac{\left(l_\theta + \frac{d}{\mathrm{Sin}\phi} - l_\theta \cdot \frac{\mathrm{Sin}\,\theta_s}{\mathrm{Sin}\,\phi}\right)}{\mathrm{Cos}\,\delta_s} \qquad (61)$$

where l_s and l_θ are the length of tooth, θ_s and ϕ are the angles of corners, δ_s is the negative axial rake angle. These values were taken from the Sandvik Catalogue$^{(69)}$ and also were checked under the Nikon Shadow Projector in the Metrology laboratory of the Production Engineering Department.

The values are: $l_s = 1.4$ mm, $l_\theta = 1$ mm, $\theta_s = 30^\circ$, $\emptyset = 60^\circ$, $\delta_s = -7^\circ$

b) $$d > l_a \qquad (62)$$

In this situation engaged cutting-edge of tooth can be written as;

$$L_{s2} = l_s + \frac{\left[l_\theta + l_\emptyset + \frac{d}{\mathrm{Sin}\lambda_s} - (l_\emptyset . \frac{\mathrm{Sin}\theta_s}{\mathrm{Sin}\,\emptyset}) \frac{\mathrm{Sin}\emptyset}{\mathrm{Sin}\lambda_s} \right]}{\mathrm{Cos}\,\delta_s}, \qquad (63)$$

where $l_\emptyset$ is another length of tooth, λ_s is the approach angle as seen in Figure (13). The other values are $l_\emptyset = 1.4$ mm, $\lambda_s = 75^\circ$.

Hence the equivalent chip thickness h_{s1} for situation (a) can be written as:

$$h_{s1} = \frac{W.d.f.z/\pi .D_s}{l_s + \frac{\left(l_\theta + \frac{d}{\mathrm{Sin}\emptyset} - l_\theta . \frac{\mathrm{Sin}\,\theta_s}{\mathrm{Sin}\,\emptyset} \right)}{\mathrm{Cos}\,\delta_s}} \qquad (64)$$

The equivalent chip thickness h_{s2} for situation (b) can be written as:

$$h_{s2} = \frac{W.d.f.z/\pi .D_s}{l_s + \frac{\left[l_\theta + l_\emptyset + \frac{d}{\mathrm{Sin}\lambda_s} - (l_\emptyset + l_\theta . \frac{\mathrm{Sin}\theta_s}{\mathrm{Sin}\emptyset}) \frac{\mathrm{Sin}\emptyset}{\mathrm{Sin}\,\lambda_s} \right]}{\mathrm{Cos}\,\delta_s}} \qquad (65)$$

As can be seen from equation (64) and equation (65), the effects of eleven geometrical parameters and machining variables, W, f, z, D_s, l_s, l_θ, $l_\emptyset$, θ_s, $\emptyset$, λ_s, δ_s, on h_{s1} and h_{s2} are significant. If the values of W, f, z are increased h_w will be increased. When the values of l_s, l_θ, $l_\emptyset$, δ_s are increased, h_{s1} and h_{s2} will be decreased. δ_s has a negative value but it does not effect on the result. The effect of d on h_{s1} and h_{s2} are not very significant. Only big variations in d will affect on h_{s1} and h_{s2}. The equations for h_{s1} and h_{s2} are valid for all types of face milling. The value of h_{s1} and h_{s2} are not related to cutting speed. The equivalent chip thickness formula takes into account all lengths of one insert engaged with the workpiece during cutting and cutting angles of inserts, machining variables (feed per tooth f and depth of cut d but not cutting speed V), cutter specifications (diameter, number of teeth z, and axial rake angle), and width of workpiece W. By using the equivalent chip thickness, the many independent variables, which determine the cutter life, are reduced to only two independent variables, namely, cutting speed and equivalent chip thicknesses. Feed per tooth itself, due to variation during face milling, cannot be one of the independent variables. It is obvious that in metal cutting tests when the number of independent variables is reduced big savings can be achieved both in the time consumed and in the number of workpieces required.

The equivalent chip thickness can also give useful information about the selection of inserts geometry, cutters and machining variables except cutting speed, which selection is among the duties of the Production Engineer.

3.3. Chipping Mechanism in Face Milling

Generally the chipping mechanism, which limits the use of brittle cutting tools like carbide and ceramic tools especially in interrupted cutting processes such as face milling, can easily occur because of the two reasons below: These two reasons can act either together or separetely.

a) Chipping, which can be the consequence of mechanical stresses produced by cutting force, can be related to entry conditions, when the contact point between the tool and the workpiece occur along the cutting edge of the tool even as soon as the cutting process starts. Cook (4) pointed out that chipping is not associated with any wear zone and can occur in brand new cutting tool.

b) Chipping can be the consequence of both mechanical and thermal stresses, after a certain cutting time, not only under severe cutting conditions but also under medium cutting conditions.

As it was mentioned in Chapter II, Kronenberg(5) made an analysis from the geometrical point of view of the initial contact point only along the length of the workpiece between the face milling cutter and the workpiece. Shinozaki(7) examined cracks, which are caused by both mechanical and thermal stresses, almost perpendicular to the cutting edge on both the rake face and the flank face from probabilistic point of view. The analysis of this part is mainly related to entry conditions. The equations derived by Kronenberg(5) used here are given below: The intersection angly i' between rake face of tool and plan of engagement is given as follows:

$$tg\, i' = \frac{tg\,\delta \,.\, \mathrm{Cos}\, r}{\mathrm{Sin}\,(r-\varepsilon)} \qquad (66)$$

where δ is the axial rake angle, r is the radial angle and ε is the engagement angle which changes continuously according to set-up.

Slope of transient surface of metal being machined produced by approach angle of tool is given below:

$$\text{Slope of transient surface} = \frac{tg\ (\text{approach angle})}{\mathrm{Cos}\,\varepsilon} \qquad (67)$$

Using the value of i' and the value of slope of transient surface, the location of initial contact point can be determined, according to the engagement plane described, cutter angles and machining variables. When initial contact point is not on the cutting edge or edges of the tool used, chipping cannot occur, but if initial contact point is on the cutting edge or edges, chipping can occur.

3.4. Definition of Face Milling Cutter life

Face milling cutter life is defined as the time between two replacement operations or two regrinding operations of all teeth in the cutter.

This is the total time, which is obtained by adding the cutting times that are spent to cut the individual workpieces until the below-mentioned criterion occurs. In this research two different criteria are used, namely i) chipping of some of the teeth and ii) 0.635 mm (0.025in) arithmetic mean value of maximum widths of wears measured on the flank faces of all teeth. Which ever occurs first, it determines the end of cutter life. Chipping on cutting edges may occur first, especially when using carbide tools. When chipping on cutting edges of some teeth occur, the cutter may still cut the workpiece for a very short time; afterwards the number of cutting edges chipped increases rapidly and all teeth are replaced.

In this investigation, chipping takes place under different conditions especially up-cut face milling. According to the second criterion,when the aritmetic mean of the maximum widths of wears measured on the flank faces reaches the value 0.635 mm (0.025 in), all teeth are replaced. Only the aritmetic mean value can determine the concept of cutter wear, because the maximum width of flank wear varies from one tooth to another since all teeth are not in the same position even if they are checked by dial gauge before cutting begins. It is also assumed that each tooth of a cutter cuts an equal chip, a condition unlikely to occur in practice.

The cutting time of one pass, t, is given by the ratio of the length to cut the given material, to the feed rate or table speed F, as seen in Figure (14):

$$t = \frac{1}{F} \qquad (68)$$

3.4.1. Cutter Life Relationship in Face Milling

Cutter life is only expressed as a function of the cutting speed and of the equivalent chip thickness in this research.

After experimental results, cutter life as the dependent variable, cutting speed and equivalent chip thickness as the independent variables are taken, and the relationship among these variables is established to obtain the proposed equation. In this research two different types of cutter life equations are predicted, the coefficients of the independent variables are calculated, the adequacy of the predicted model is checked and the confidence intervals, within the certain percentage, are determined.

3.4.1a) The first proposed model of cutter life is the logaritmic form of the Konig-Depiereux type equation$^{(27)}$:

$$\hat{y} = \dot{T}\ln T = b_o + b_1 V^{\alpha_1} + b_2 h_f^{\alpha_2} \qquad (69)$$

where $\hat{y}$ is the predicted value of cutter life on a logaritmic scale, V is the cutting speed, h_f is the equivalent chip thickness (for the Walter Cutter and Sandvik Cutter, h_f is taken into account as h_w and h_s respectively), α_1 and α_2 are the power parameters, and b_o, b_1 and b_2 are the least-squares estimates. The uncertainty of the least-squares estimates b_o, b_1 and b_2 as indicated by certain percent confidence intervals.

The coefficients b_o, b_1, b_2 in the equation (69) are estimated by the method of least squares as:

$$B = (XT.X)^{-1}XT.y \qquad (70)$$

where B is the vector of the values of b_o, b_1 and b_2, X is the matrix of independent variables, XT is the transpose of X, $(XT.X)^{-1}$ is the inverse of (XT.X), y is the vector of observed cutter life, i.e., y = $\dot{T}.\ln T$,

where $\dot{T}$ is the geometric mean value of the observed cutter lives. The residual sum of squares (R.S.S.) is calculated as the numerical criterion to determine the best fit of the cutter life model:

$$\text{R.S.S.} = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{71}$$

where y_i is the i^{th} observed value of cutter life, $\hat{y}_i$ is the i^{th} predicted value of cutter life, n_o is the number of observations.

The experimental error is estimated by the error variance S^2;

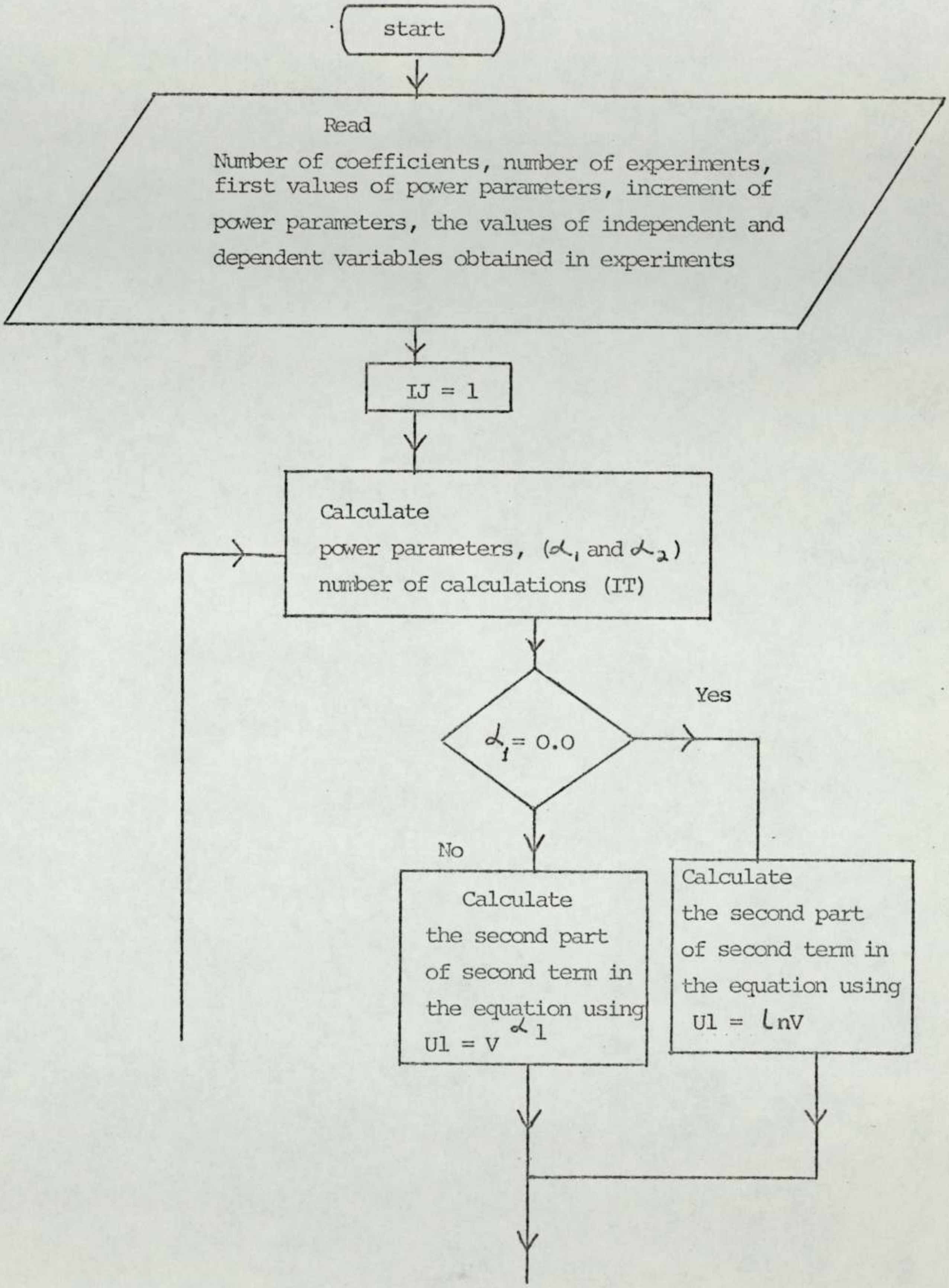
$$S^2 = \frac{\text{R.S.S.}}{n_o - p} \tag{72}$$

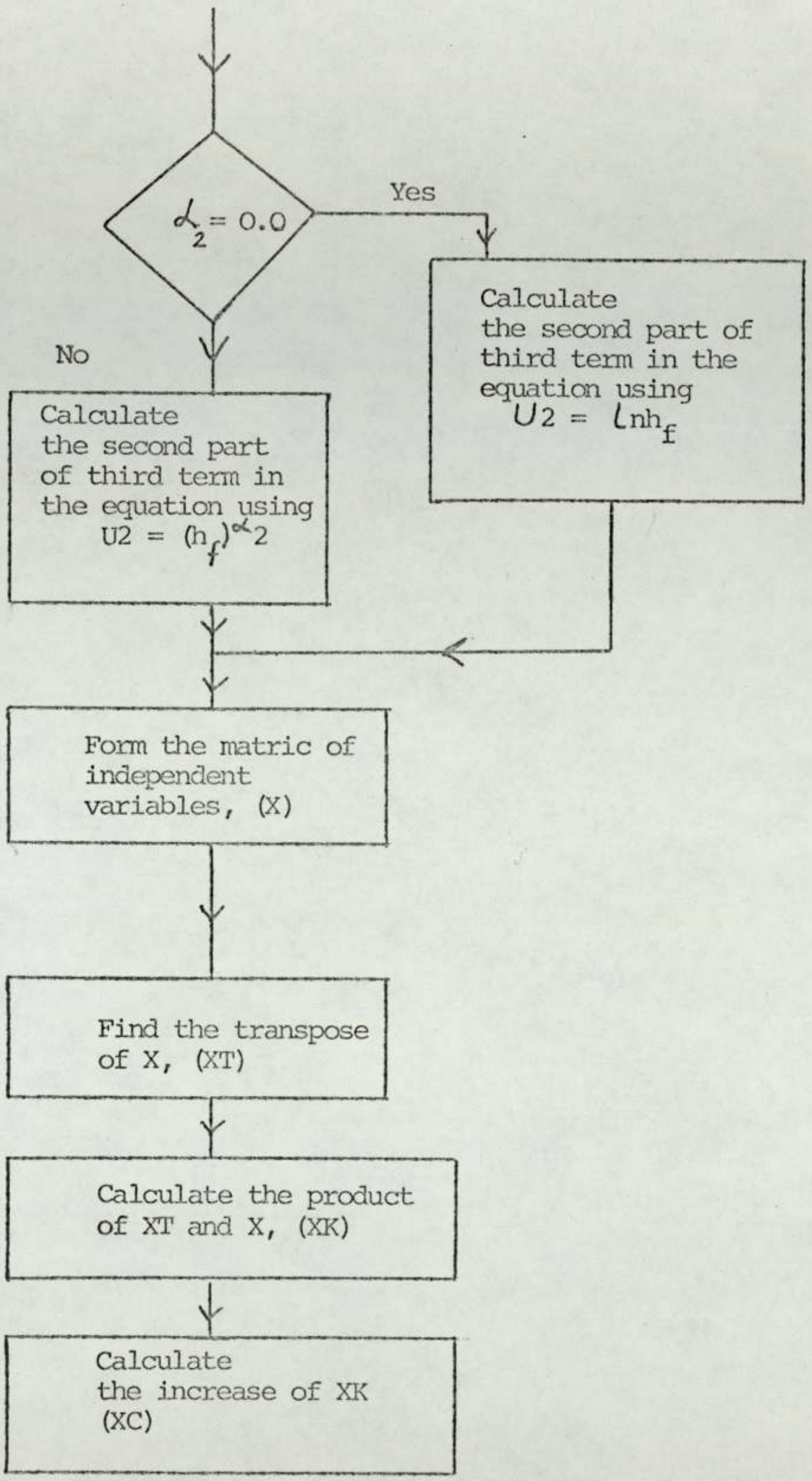
where p is the number of coefficients. The confidence interval (CI) for any coefficients b_i, under the assumption of spherical normality, is given by;

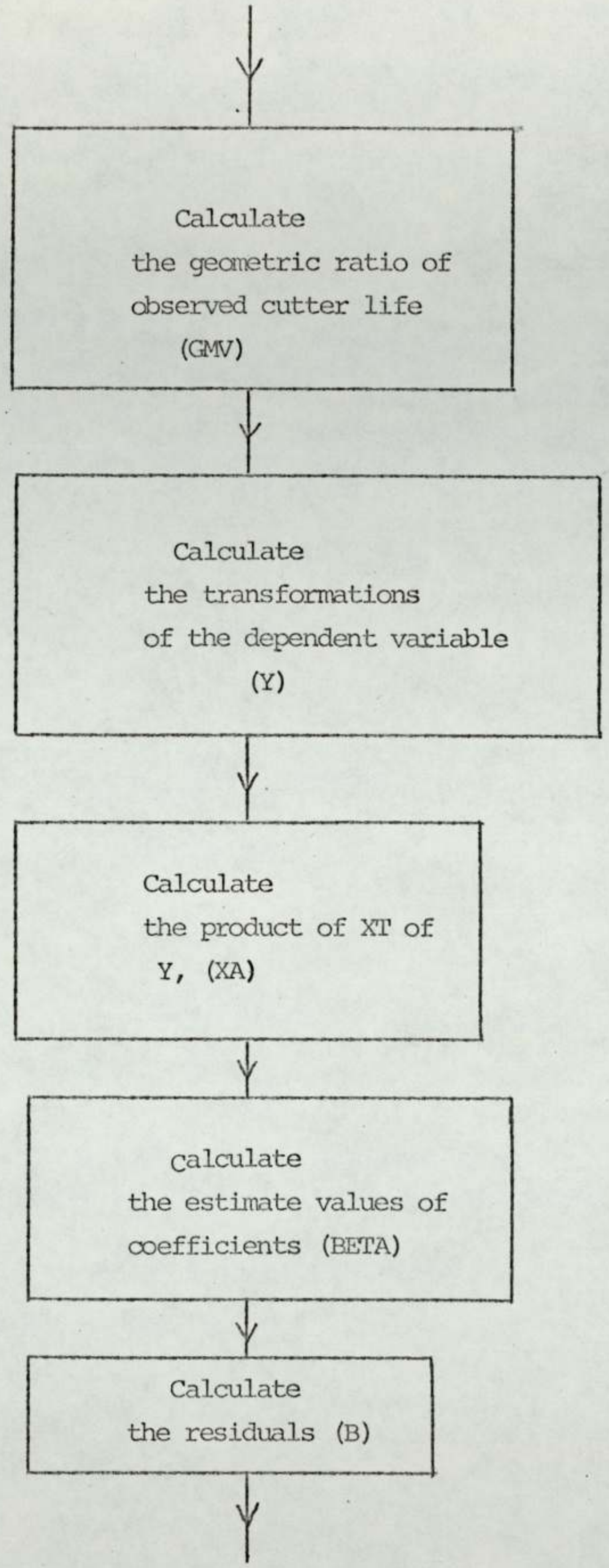
$$CI(b_i) = b_i \pm t_{v;\xi/2} \cdot \sqrt{S^2 . d_{ii}} \tag{73}$$

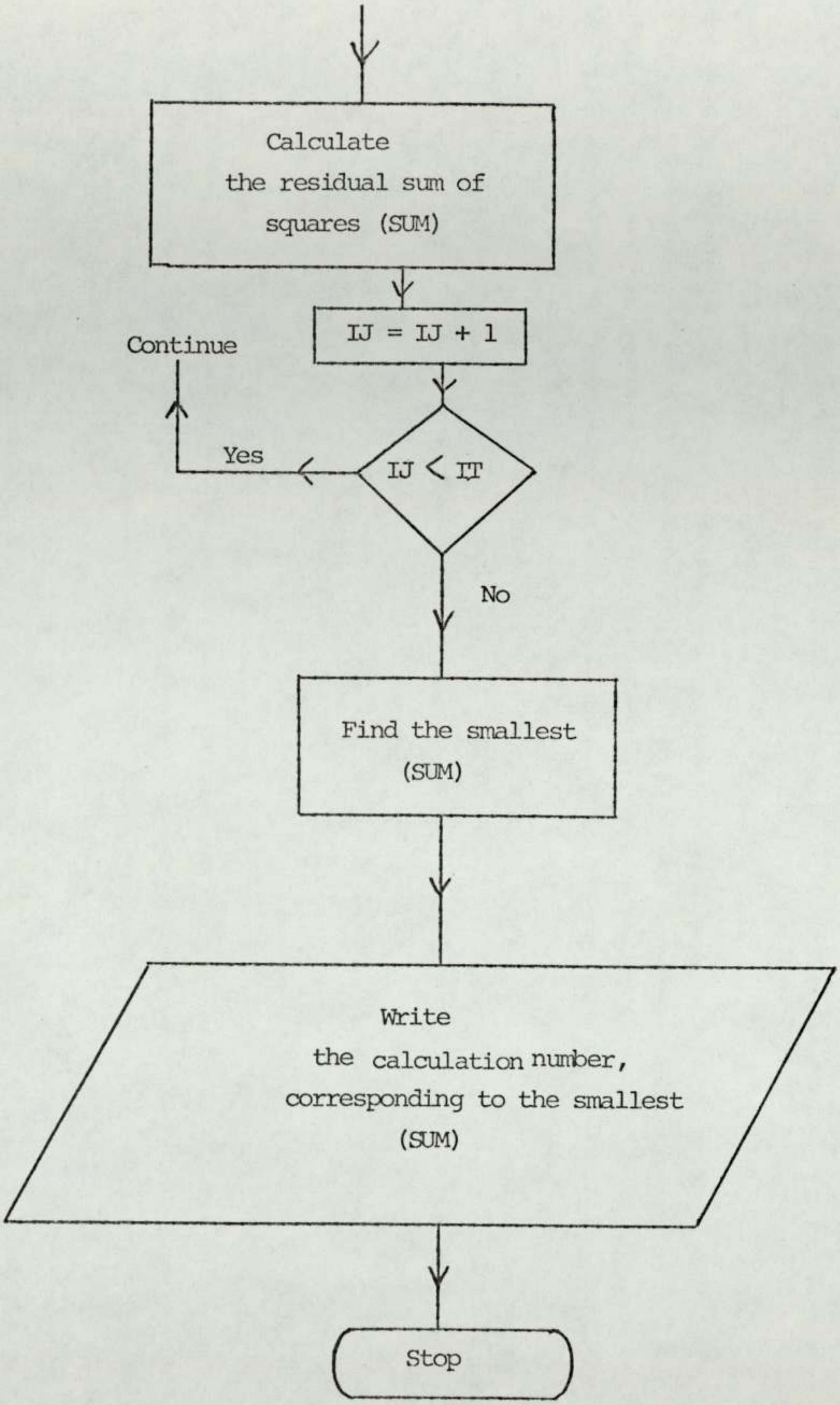
where $t_{v;\xi/2}$ is the Student's t-distribution (with v the degree of freedom and ξ the level of significance), and d_{ii} is the element of the i^{th} row and i^{th} column of the inverse of (XT.X).

The computer program was written to calculate the coefficients of the first proposed cutter life equation (69). The flow chart of the program is given below:


start
Read
Number of coefficients, number of experiments, first values of power parameters, increment of power parameters, the values of independent and dependent variables obtained in experiments
IJ = 1
Calculate
power parameters, (α_1 and α_2)
number of calculations (IT)
$\alpha_1 = 0.0$
Yes
No
Calculate
the second part of second term in the equation using
$U1 = V^{\alpha 1}$
Calculate
the second part of second term in the equation using
$U1 = \ln V$


$\alpha_2 = 0.0$
Yes
No
Calculate the second part of third term in the equation using $U2 = \ln h_f$
Calculate the second part of third term in the equation using $U2 = (h_f)^{\alpha 2}$
Form the matric of independent variables, (X)
Find the transpose of X, (XT)
Calculate the product of XT and X, (XK)
Calculate the increase of XK (XC)


Calculate
the geometric ratio of
observed cutter life
(GMV)
Calculate
the transformations
of the dependent variable
(Y)
Calculate
the product of XT of
Y, (XA)
Calculate
the estimate values of
coefficients (BETA)
Calculate
the residuals (B)


Calculate the residual sum of squares (SUM)
IJ = IJ + 1
Continue
Yes
IJ < IT
No
Find the smallest (SUM)
Write the calculation number, corresponding to the smallest (SUM)
Stop

When $\alpha_1 = 0$ and $\alpha_2 = 0$, the equation is written;

$$\dot{T}\ lnT = b_o + b_1\ lnV = B_2\ lnh_f \qquad (74)$$

This is a logaritmic transformation which is similar to Taylor's type of tool-life equation.

The computer programme can also give the comparison between the linear logaritmic transformation and any other transformation in term of R.S.S.

3.4.1b) The Second proposed model of cutter life is the second-order equation in a logarithmic form;

$$\ln T = b_o + b_1 \ln V + b_2 \ln h_f + b_3\ (\ln V)^2 + b_4\ (\ln h_f)^2 + b_5\ \ln V.\ln h_f \qquad (75)$$

where T is the predicted value of cutter life on a logarithmic scale, V is the cutting speed on a logarithmic scale, h_f is the equivalent chip thickness on a logarithmic scale (for the Walter Cutter, $h_f = h_w$, for the Sandvik Cutter, $h_f = h_s$) and b_o, b_1, b_2, b_3, b_4 and b_5 are the least-squares estimated coefficients. To calculate the coefficients, statistical package$^{(34)}$ was used.

3.5. Power Relationships in Face Milling

In face milling, the power required (in H.P) at the cutter can be given, when one or more than one tooth is engaged with the workpiece, by the expression:

$$H.P = \frac{\Sigma F_t . V}{4500} \qquad (76)$$

where ΣF_t is the total tangential force (in kg) and V is the cutting speed (in $\frac{m}{min}$).

When only one tooth is engaged with the workpiece, the value of F_t is given by Koeningsberger(35) as:

$$F_t = k_s.d.h^p \tag{77}$$

where k_s is the specific cutting pressure, d is the depth of cut, h is the instantaneous value of the radial chip thickness, and the value of p lies between 0.75 and 0.9. For instance, in up-cut milling, h can be given by equation (33) as;

$$h = f.\ \mathrm{Sin}\ \varphi$$

Hence $F_t = k_s.d.(f.\mathrm{Sin}\ \varphi)^p$ (78)

The maximum value of F_t, $F_{t\ max}$, occurs when $\varphi = 90^o$.

$$F_{t\ max} = k_s.d.f^p \tag{79}$$

The ratio of $\frac{F_t}{F_{t\ max}}$ is written as;

$$\frac{F_t}{F_{t\ max}} = (\mathrm{Sin}\ \varphi)^p \tag{80}$$

Power, P, may be written as;

$$P = k_s.d.(f.\mathrm{Sin}\ \varphi)^p.V \tag{81}$$

The value of P is changed according to the value of φ under one cutting condition.

In this research, average total tangential force $\sum F_t$ is proposed as follows:

$$Ft = K_s.d.h_m.\frac{\varphi_e}{\varphi_z} \qquad (82)$$

or

$$Ft = K_s.d.f_c \qquad (83)$$

where h_m is the mean value of the undeformed chip thickness as calculated equation (35), φ_e is the engagement angle, and φ_z is the angle between any two teeth as calculated equation (32).

Hence power required at the cutter can be given as

$$P = k_s.A_c.V \qquad (84)$$

or

$$P = k_s.MR \qquad (85)$$

k_s can be changed with the equivalent chip thickness.

3.6. Surface Finish Relationship in Face Milling

Surface finish obtained can be expressed in terms of different measurements taken. In this research,(C.L.A.) index is taken as a measurement of surface finish in order to compare surface profiles obtained in different cutting tests. In any machining process, it is known that feed is an important independent variable on surface finish. In some situations, cutting speed may be the other independent variable like in face milling, because surface finish is produced when the cutter across all over workpiece. Surface finish model is proposed as:

$$S.F = K_1.V^{k_2}.f^{k_3} \qquad (86)$$

or when logarithms of both sides are taken, the following expression is written;

$$\ln S.F = \ln K_1 + K_2.\ln V + K_3.\ln F \qquad (87)$$

$\ln K_1$, K_2 and K_3 are calculated using the method of least squares.

3.7. Vibrations Relationships in Face Milling

Vibrations, in milling process, may occur due to a number of causes$^{(70)}$. Mainly two reasons can be recognized.

a) Vibrations due to the geometry of milling process,

b) Self excited vibrations. Vibrations due to the geometry of process are known as forced vibrations. Those may come out from two main reasons in face milling.

ai) Variation of the chip thickness, because cutting force F_t is changed with the chip thickness as given in equation (78).

aii) Impact due to interrupted cutting.

b) Self-excited vibrations.

Chip removing machine tools belong to a group of dynamical systems in which a slight disturbance of the steady-state motion may generate internal forces which depend on the velocity of the disturbance. Cutter and workpiece perform a relative motion,then the cutting system becomes dynamically unstable$^{(70)}$. That is called Chatter which can be detected either by its noise or surface finish marks.

In this research, vibrations generated are considered as forced vibrations. Chatter marks on any surface finish produced that have not been observed. Peak-to-peak amplitude of vibrations in feed and axial directions in down-cut milling, in feed and tangential directions in up-cut milling are taken into account rather than frequencies of vibrations.

The maximum peak-to-peak vibration amplitude model is proposed by the following expression.

$$\mathrm{VIB.AMP} = D_1 . V^{D_2} . (s_{max})^{D_3} \qquad (88)$$

where S max is the maximum area being cut, S max = d.f.

When logarithms of both sides are taken, the following expression is written;

$$\ln \mathrm{VIB.AMP} = \ln D_1 + D_2 . \ln V + D_3 . \ln s_{max} \qquad (89)$$

Ln, D_1, D_2 and D_3 are estimated using the least-squares method.

3.8. Economics of Face Milling

Generally in metal cutting field, producing a batch of components to the acceptable dimensional accuracy and surface finish is to make decisions the right choice of machine tool among available machine tools, cutting tools, method of the process, the use of cutting fluid, machining conditions such as cutting speed, feed and depth of cut. The approaches, to make such decisions have been known as economics of machining, can be achieved in two ways. One is a mathematical solution, the other is a graphical solution. In some cases mathematical solution can be much more suitable when cost, time information as well as sufficiently accurate tool-life data are available about the process. In some cases graphical and mathematical solutions together can give a reliable answer in machine shop practice.

The concept of T-MR characteristic functions can give another application to machining economics (59), (60). At any given constant tool-life value, it is possible to obtain several different metal removal rates, depending on the combination of its variables and vice versa.

In this research, more or less the same cutter life results were obtained in the validity tests of equivalent chip thicknesses both using Sandvik cutter and Walter cutter. But metal removal rates were different (Test No. 6 and 7 - using Walter cutter in down-cut milling. Test No. 5 and 6 - using Sandvik cutter in down-cut milling). It was proved that the T -MR characteristic function could give the best possible combinations of metal removal rates and tool life$^{(59)}$.

3.8.1. Unit-time model

In face milling, the total time to produce per piece, Tp, can be written as;

$$T_p = T_{LU} + T_{set\text{-}up} + T_{ar} + K.\ \frac{MV}{MR} + K.\ \frac{MV}{MR} \cdot \frac{T_r}{T} \qquad (90)$$

where T_{LU} is loading and unloading time, $T_{set\text{-}up}$ is set-up time, T_{ar} is approach and returning time of the cutter. These three times are independents from machining variables. It is also very difficult to give their exact values in machine shop practice. Their values partially depend upon the behaviour of the operator which uses the machine tool. Their controls can be possible either in bonus production system or using the robot. The total of $(T_{LU} + T_{set\text{-}up} + T_{ar})$ is simplified as T_1. MV is the volume of the metal to be removed, MR is the metal removal rate, K is the constant coefficient which is determined by the position of the cutter relative to the workpiece as seen in Figure (14).

$$K = \frac{l}{l_p} \qquad (91)$$

where l is the length which can be calculated using the geometry of cutting, l_p is the length of the workpiece being cut.

By introducing K, MR is considered as unique variable during cutting. T_r is the replacement time for all teeth. T is the cutter life.

$$T_p = T_1 = K.MV \quad (\frac{T + T_r}{MR.T}) \qquad (92)$$

T_1, K, MV and Tr are independent values from machining variables. To obtain extreme values of T_p in terms of machining variables, $F_1 = \frac{MR.T}{T+T_r}$ function, which is the reciprocal of the part of the second term in equation (92), should be searched. For the minimum value of T_p, the function F_1 should reach the maximum value. F_1 is a function of MR and T.

$$F_1 = F_1(MR,T) \qquad (93)$$

It may be possible to obtain the characteristic function, T = T(MR), which is the best combination of metal removal rates and cutter life values$^{(59)}$.

For the existence of T-MR characteristic function, in the other words, to obtain the function T = T(MR), their Jacobian should vanish$^{(71)}$ as follows:

$$J = \frac{\partial (MR,T)}{\partial (V,h_f)} = \begin{vmatrix} \frac{\partial MR}{\partial V} & \frac{\partial MR}{\partial h_f} \\ \frac{\partial T}{\partial V} & \frac{\partial T}{h_f} \end{vmatrix} = 0 \qquad (94)$$

MR can be expressed by a function of d, h_f and V as seen in equations (57), (64) and (65).

$$MR = MR(d, V, h_f) \qquad (95)$$

In this expression d can be taken into account as one chosen parameter depending upon the maximum available cutting force, horsepower and test results obtained. Therefore, MR can be written as;

$$MR = MR(V, h_f) \qquad (96)$$

Cutter life T can also be expressed in a function of V and h_f;

$$T = T(V, h_f) \qquad (97)$$

Using equation (94), T = T(MR) can be obtained. For the maximum value of F_1, the first derivation of F_1, $\frac{dF_1}{dMR}$ should vanish.

$$\frac{dF_1}{dMR} = \frac{T}{T+T_r} + MR \ \frac{T_r}{(T+T_r)^2} \ . \frac{dT}{dMR} = 0 \qquad (98)$$

or

$$T(T + T_r) + MR.T_r. \frac{dT}{dMR} = 0 \qquad (99)$$

Hence optimum cutter life T and metal removal rate MR can be obtained.

3.8.2. Unit-cost model.

In face milling, the total cost to produce per piece C can be written as follows;

$$C = Co.T_1 + Co.K.\ \frac{MV}{MR} + Co.K.\ \frac{MV}{MR}.\ \frac{T_r}{T} + Y.K.\ \frac{MV}{MR} \cdot \frac{1}{T} \qquad (100)$$

where Co is the operator and overhead cost per unit time, Y is the total cost of cutting edges of the cutter

or $$C = Co.T_1 + Co.K.\ \frac{MV}{MR} \left(1 + \frac{T_r + Y/Co}{T} \right) \qquad (101)$$

Co, T_1, K, MV, Tr and Y are independent values from machining variables. To obtain the extreme values of C, the function $F_2 = \frac{MR.T}{T + Tr + Y/Co}$ should be searched. For the minimum value of C, the function F_2 should reach the maximum value. The functions F_1 and F_2 are similar functions except the term (Y/Co). By following the similar procedure as unit-time model the first derivation of F_2 to MR should be zero.

$$\frac{dF_2}{dMR} = \frac{T}{T + Tr + Y/Co} + MR \frac{(Tr + Y/Co)}{(T + Tr + Y/Co)^2} \cdot \frac{dT}{dMR} = 0$$

or

$$T(T + Tr + Y/Co) + MR(Tr + Y/Co).\frac{dT}{dMR} = 0 \qquad (102)$$

The optimum cutter life T and metal removal rate for the minimum value of C can be determined.

3.8.3. Profit-Rate.

The profit per unit time, Pr, can be written in face milling as;

$$Pr = \frac{S - C}{T_p} \qquad (103)$$

where S is the selling price per piece, C is the cost per piece, T_p is the time to produce the piece. The equation (103) is also a function of C and T_p, therefore only of MR and T. But the value of S is not always the fixed value.

In this research C and T_p will be considered in order to obtain optimum machining variables.

CHAPTER IV

Experimental Equipment, Workpiece Materials, plan of Experimental Work Technique and Procedure

4.1. Experimental Equipment

4.1.1. The Machine Tool

The conventional horizontal Knee-type milling machine manufactured by Cincinnati, which has been used for teaching purposes and research work for some years in the Production Department, was used in this project in such a manner to achieve face milling processes. It was coupled with 15 H.P electric motor. Additional balancing or flywheel mass was constructed on the milling spindle in order to reduce torsional vibrations. The machine tool was attached to the calibrated meter which reads directly horsepower consumption up to 20 H.P. and the tachometer which shows a number of revolution of the spindle per minute up to 2000 r/min. Before the research was started, the tachometer readings were checked with another tachometer during cutting. It was noticed that the actual readings were not corresponding to the numbers written on the machine tool. The table speeds or feed rates were calculated using three methods : Firstly X-Y plotter; secondly stopwatch; and finally time counter in order to measure times for the fixed distances during cutting. It was also found that actual table speeds or feed rates calculated did not correspond with the numbers written on the machine tool.

Actual number of revolutions per minute N used in the research, followed a very close geometric progression. They are given below (in r/min);

198, 238, 300, 378, 460, 580, 680, 860

Actual table speeds or feed rates F used in the research also followed a very close geometric progression. They are given below (in m/min):

0.356, 0.447, 0.559, 0.686, 0.864, 1.092, 1.354, 1.666

The machine tool was stopped from time to to time to obtain necessary measurements. According to up-cut or down-cut face milling backlash eliminator was adjusted at each time to eliminate the backlash in the screw and nut assembly of the table. General view of the machine tool with the equipment are shown in Figure (15).

4.1.2. The set-up

Each workpiece being machined was mounted on the big plain block and clamped using screws in such a manner to simulate a vice and to ensure enough rigidity. The view of the set-up is seen in Figure (16).

4.1.3. The Cutters

Throughout the research two different cutters with their indexable throwaway inserts were used. Both were medium grades P25, and recommended for light and rough machining of steels. They were mounted on the horizontal plain knee-type milline machine by means of arbors.

i) The Walter milling cutter, type Wendelnovex F244, nominal diameter D_W = 101.6 mm, with 8 indexable inserts, grade P25, axial rake angle $\delta_W = +8^\circ$, the approach angle $\theta_W = 42^\circ$, radial rake angle = -16°, face relief angle = 5°.

   The geometry of the cutter and one of the inserts is shown in Figure (12). General view of this cutter with one workpiece and the top view of one of the inserts are shown in Figure (17) and in Figure (18) respectively.

ii) The Sandvik milling cutter, type T-Max 265.1, nominal diameter D_s = 100 mm, with 8 indexable inserts, grade P25, axial rake angle $\delta_s = -7^{\circ}$, the approach angle $\lambda_s = 75^{\circ}$, radial rake angle = -5°, face relief angle = 5°, the geometry of the cutter and one of the inserts is shown in Figure (13) General view of this cutter, one workpiece and the top view of one of the inserts are seen in Figure (19) and in Figure (20) respectively.

4.1.4. Wear Measurements

The travelling microscope, which has a magnification of times 5, was mounted and adjusted on the table of the milling machine in order to measure maximum flank wear $V_{B\ max}$ on the flank face of each tooth of a cutter. The microscope is seen in Figure (16). From time to time cutting process was stopped. When the clear wear picture of each tooth was observed through the microscope with the aid of electric light, the measurement of $V_{B\ max}$ was taken. For each situation, eight measurements were recorded, because of eight teeth on a cutter used. Then arithmetic mean value of eight measurements was obtained with the corresponding cutting time in order to determine wear-cutting time progress. The cutter life criterion, which was used in this investigation, was either 0.635 mm (0.025 in) arithmetic mean value of maximum flank wears or chipping of some teeth and which ever occurs first, it takes into account.

4.1.5. Power Measurements

The calibrated meter was already attached to the milling machine in order to measure directly idle power and power consumed during cutting in unit of horse power. According to wear progress with cutting time, horse power readings were taken and recorded when two teeth were engaged with the workpiece. The meter is seen in Figure (16).

4.1.6. Surface Finish Measurements

Talysurf device was used to measure average surface roughness (C.L.A) of the surface finish produced. A pointed stylus detected the surface for a fixed distance, then centre line average meter indicated (C.L.A) readings according to cutting conditions. It is shown in Figure (21).

From time to time the graph of the surface was obtained from the graph recorder. The Talylin device was also used to measure the waviness of the surface.

4.1.7. Vibration Measurements

Two identical vibration analysers with their magnetic pick-ups were used in order to measure peak-to-peak vibration amplitutes and frequencies in two different directions when two teeth were engaged with the workpiece under cutting conditions. By using the storage oscilloscope, vibration photographs were taken. The positions of vibration pick-ups is shown in Figure (16).

4.1.8. Workpiece Materials

Two different types of tool steel, which were provided by GKN Ltd., were tested. The company uses these types of materials in its production. Their compositions are given below:

i) Tool steel (B.H.N. 238)

C	1.69%
Si	0.29%

Mn	0.12%
Cr	11.82%
V	0.14%
Mo	0.65%

The mean value of Brinnel hardness number is 238. Materials were annealed. Widths of workpieces were varied according to cutting conditions between 25.4 mm and 46 mm, lengths were between 150 mm and 200 mm and heights were between 40 mm and 90 mm.

ii) Tool Steel (B.H.N.197)

C	1.53%
Si	0.35%
Mn	0.25%
Cr	11.91%
V	0.17%
Mo	0.75%

The mean value of Brinnel hardness number (B.H.N.) is 197. Materials were annealed. Widths of workpieces were varied according to cutting conditions between 37 mm and 44 mm, lengths were between 150 mm and 200 mm and heights were 90 mm.

4.2. Plan of Experimental Works

As it was mentioned before there is little published machinability data available on face milling processes. Limited knowledge in the range of cutting speed V, feed per tooth f, depth of cut d exists.

Using carbide tools in face milling, the range of cutter life T, horse-power required, surface finish produced, vibration, which are normally dependent variables, did not exist. There was also lack of knowledge in literature about equivalent chip thickness,which is a function of geometrical parameters of one of the inserts and machining variables, f, d except V, is used as one independent variable in this investigation in order to obtain machinability data. Also the range of equivalent chip thicknesses used was unknown. In this research in investigation of each machining response and its mathematical form as less as possible, the number of independent variables are used. That achievement reduces experimental time consumed as well as a number of workpieces required in order to obtain machinability data.

4.2.1. Planning Cutter Life Tests

In the research, cutter life tests were planned and performanced using the Walter Cutter and the Sandvik Cutter, annealed Tool Steel materials B.H.N. 238 and B.H.N. 197 types in down-cut and up-cut face milling. Before planning cutter life tests, the working region, which can be thought around optimum cutting conditions, may be determined for cutter life, cutting speed and equivalent chip thickness. In this research a typical domain for cutter life was considered between 10 and 70 minutes. This procedure identifies the working region in the cutter life domain but it doesn't determine the ranges in the cutting conditions domain (as cutting speed and equivalent chip thickness). A convenient criterion, which can be used for identification of cutting conditions domain in face milling, can be metal removal rate MR, provided W is constant. High level MR is always desirable until power limitation is taken into account.

Because there is a relationship between MR to be cut and power required at the cutter. In this research two types of face milling were planned and tested namely down-cut and up-cut milling. All tests were conducted dry. Central face milling was performed under cutting speed of 182.21 m/min and equivalent chip thickness of 0.133 mm. Two teeth of the cutter were chipped at the 0.412 mm average maximum flank wear which was lower than the chosen cutter life criterion of 0.635 mm. In this research the linear distance between any two teeth for both cutters was bigger than the width of the workpiece being machined in most cases. At least one tooth was always engaged with the workpiece in any type of milling. Generally carbide tools are particularly weak under thermal stress. The characteristic repetitions of heating and cooling of one tooth during one rotation of the cutter are important. These repetitions should be balanced, especially the width of workpieces is small like width of workpieces used in this research. When down-cut or up-cut milling were positioned, the contact time of any tooth with the workpiece was increased.

Therefore down-cut or up-cut milling can give longer cutter life when width of workpieces are small. Kronenberg(5) approached the problem from impact problem of view. He also tested five different face milling using the narrow workpiece (19 mm) in order to reduce tool wear due to cutting, in comparison with the wear due to impact. He found that both in up-cut and down-cut face milling, tool wear due to impact were smaller than tool wear in central milling.

4.2.1a. Planning of Cutter Life Tests for Annealed Tool Steel (mean B.H.N. 238) using Walter Cutter in down-cut milling

As it was mentioned before due to lack of knowledge in literature, two pilot tests were peformed at the beginning in order to plan cutting tests. Cutting conditions of first pilot test were chosen as follows, a number of revolution per minute N available on the machine tool was selected to be 198 r/min, it gave a cutting speed of 63.19 m/min. Feed rate or table speed F available on the machine tool was selected to be 0.356 m/min, the width of each workpiece W, which was sent by the company, was 25.4 mm (1 in), depth of cut d was chosen 2.54 mm (0.100in). Using the specification of Walter Cutter the value of equivalent chip thickness h_w was obtained to be 0.075 mm from the equation (57).

Cutter life was obtained to be 143.2 mins. That value was out of typical domain of cutter life and the value of MR was 22.968 cm^3/min. The cutting conditions of second pilot test was chosen as follows; a number of revolution per minute N available on the machine tool was selected to be 238 r/min which was higher than previous N. It gave a cutting speed of 75.96 m/min.

Feed rate F available on the machine tool was selected to be o.447 m/min which was higher than previous F. Depth of cut d was selected to be 1.52 mm which was lower than previous d. This time the value of equivalent chip thickness h_w was selected to be 0.116 mm which was as twice as previous h_w. Using the equation (57) the width of each workpiece was calculated to be 42.7 mm.

Cutter life for these cutting conditions was obtained to be 120.8 mins. That value was still out of typical domain of cutter life and the value of MR was 29.012 cm^3/min. It was decided to increase cutting speed V which meant to increase a number of revolutions N. The next value of N available on the machine tool was 300 r/min. It gave a cutting speed of 95.75 m/min.

According to the value of N, F was increased to the value of 0.559 m/min in order to keep the value of f at the same level as previous f.

This time the value of h_w was kept constant that was the value of 0.116 mm as the previous value. The value of W was selected to be 45.7 mm (1.8in) and depth of cut d was calculated to be 1.26 mm (0.050 in) from the equation (57). Using these cutting conditions, the cutter life was obtained to be 61.8mins which was in the typical domain of cutter life. Hence the lower limits of cutting speed and equivalent chip thicknesses were determined according to available material, machining variables and the cutter specifications. Under these cutting conditions the value of MR was calculated to be 32.188 cm^3/min.

Three more levels of cutting speeds were selected, according to the values of N available on the machine tool. One more level of h_w was chosen to be 0.143 mm, this being different to 0.116 mm the previous one.

After determining of the levels of both cutting speeds and equivalent chip thicknesses, two tests were conducted to prove the validity of equivalent chip thickness. For both tests the same low cutting speed and the same low equivalent chip thickness, which were 120.65 m/min and 0.116 mm respectively, were used provided W, f and d values were changed. On the first test W was chosen to be 38.1 mm, $d=2.79$ mm and $F=0.685$ m/min respectively.

On the second tests W was increased to 45.72 mm by 17% and d was decreased to 0.77 mm by 72% F was increased to 0.863 m/min by 21%. Metal removal rates were 72.81 cm^3/min and 30.38 cm^3/min respectively. Planning of cutting tests and cutter life results are shown in Table (1).

4.2.1b. Planning of Cutter Life Tests for Annealed Tool Steel (mean B.H.N. 238) Using the Sandvik Cutter in down-cut milling

At this time, planning of cutting tests became easier than previous planning of cutting tests because of experience obtained. Three levels of cutting speed V_s=118.75, 144.51 and 182.21 m/min and three levels of equivalent chip thicknesses h_s=0.083, 0.122 and 0.133 mm were selected according to available width of material and machining variables. Specially two values of equivalent chip thickness were chosen close to each other in order to compare cutter life test results which can also give idea about the validity of equivalent chip thickness. First cutting conditions were chosen as follows; a number of revolution per minute N available on the machine tool was selected to be 378 r/min, it gave a cutting speed of 118.75 m/min. Feed rate or table speed available on the machine tool was chosen to be 0.559 m/min, and d was selected to be 1.65 mm and available W was taken to be 40 mm. All these variables gave the value of 0.083 mm of the equivalent chip thickness using the equation (64). Cutter life value was obtained to be 51.6 min. This value was in the typical domain of cutter life.

Two tests were conducted to prove the validity of equivalent chip thicknesses at the same cutting speed of 144.51 m/min. and at the same equivalent chip thickness of 1.122 mm. To obtain this value of equivalent chip thickness from the equation (65), first cutting conditions were chosen as follows; W = 43.2 mm; F = 0.864 m/min; and d = 1.905 mm.

In order to obtain the 0.122 mm value of equivalent chip thickness, F was increased to 1.092 m/min, d was reduced to 1.27 mm. Then using the first equation (64) the value of W was calculated to be 42 mm.

Metal removal rates were 58.25 and 71.03 cm^3/min. Another test under the conditions of V_s of 182.21 m/min and h_s of 0.133 was repeated twice to compare cutter life results. Planning of cutting tests and results are shown in table (2).

In addition to these tests two more tests were performed. The first test was in up-cut milling in order to compare the cutter life results with the cutter life obtained in down-cut milling under the conditions of V_s of 182.21 m/min, and h_s of 0.133 mm. Cutter life result was obtained to be 7.8 mins which was smaller than the cutter life obtained in down-cut milling. Second test was tried under the conditions of V_s of 182.21 m/min, and h_s of 0.133 mm in central milling.

Two of the inserts were chipped at 0.412 mm flank wear. Hence the test was not completed. Another test was planned under the conditions of cutting speed of 182.21 m/min, feed rate of 1.666 m/min, depth of cut of 2.03 mm, W of 57 mm, MR of 192.772 cm^3/min. The test was a failure, some cutting edges were broken, because of power required was exceeded maximum available power on the machine. Chips obtained in these tests are seen in Figure (22).

4.2.1c. Planning of Cutter Life Tests for Annealed Tool Steel (mean B.H.N. 197) Using Sandvik Cutter in Up-cut milling.

B.H.N. of second type of tool steel materials, which were sent by the company, were lower than first type of materials received.

Obviously in order to compare dependent variable (s) some independent parameters and variables should be kept constant. At the beginning, one of the major aims of the project, was to compare cutter life results both in down-cut and in up-cut milling. Unfortunatley, the same type of materials were not obtained from the company. The values of cutting speeds and equivalent chip thicknesses were kept the same as down-cut milling using available widths of materials. At the beginning $(3)^2$ experiments were planned and carried out. Three tests under low-speed conditions and two tests in medium-speed conditions were not completed.

Because two or three cutting edges of the cutter were chipping simultaneously, then three more tests were planned and carried out using a higher cutting speed until power available on the machine tool reached to the limit in order to obtain the cutter life equation. One test under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm was repeated twice.

The reasons for chipping will be investigated and explained in Chapter V. Another test was carried out in down-cut milling to compare the cutter life result with the cutter-life result obtained in up-cut milling.

Planning of cutting tests and results are shown in table (3).

4.2.1d. Planning of Cutter Life Tests for Annealed Tool Steel (mean B.H.N.197) Using Walter Cutter in Up-cut Milling.

In order to compare tests results three levels of cutting speeds and three levels of equivalent chip thicknesses were planned. Planning of tests are shown in table (4). This time, eight of nine tests were failures. These were like those of Sandvik Cutter life tests in up-cut milling, that is, cutting edges were chipping on the first or second cut pass. Obviously cutter wear was not associated with any wear zone. The reasons for chipping will be investigated and explained in chapter V.

4.3. Planning of Power Tests

Tests of power were not planned, because planning of cutter life tests also gave an opportunity to obtain different values of metal removal rate, MR, and power measurements. In this research during every cutter life test under planned cutting conditions three measurements of power were taken, when any two teeth were engaged with workpiece. First, measurements were taken around average maximum flank wear of 0.2 mm, the second measurement around 0.4 mm and the final one around 0.6 mm.

4.4. Planning of Surface Finish Tests.

Special tests of surface finish were not planned, because milling process is generally recognized as intermittent process and many cases milling is not final process like turning or grinding. Only surface roughnesses in C.L.A. index were measured while cutter life tests were being performed. Surface waviness measurements were taken, but in each case over a fixed distance at different positions, different wavinesses of the surface profile were obtained.

4.5. Planning of Vibration Tests

Vibration measurements in two directions were taken according to a type of milling. Vibration in the third direction was also taken in order to compare measurements. It is known that tool wear is affected by vibrations. In order to avoid the point mentioned above all vibration measurements were recorded and photographed, as shown in Figure (16), when cutter wear had the same level in all set-ups. These were taken when two teeth of the cutter were engaged with the workpiece.

Vibrations under each cutting conditions were stored to the osciloscope in order to take their photographs. Horizontal scale which represent the frequency of vibration, was 5 m sec per division. Vertical line which represent amplitude of vibration, was 0.1 m volt per division.

4.6. Technique and Procedure of Tests.

At the beginning of each cutting test, the positions of all new brand teeth of each cutter were measured in the axial direction using a dial gauge to make sure that all teeth were the same position. Maximum allowable height was ± 0.0127 mm. Each workpiece was held rigidly. Cutting variables such as a number of revolution, table speed or feed rate, depth of cut etc., were fixed according to the cutting test condition. From time to time cutting was stopped and maximum flank wear of each tooth was measured and recorded where ever it occured. Typical crater wear for both Sandvik Cutter and Walter Cutter are shown in Figure (23) and Figure (24) respectively. Typical flank wear for both the Sandvik Cutter and the Walter Cutter are also seen in Figure (25) and Figure (26) respectively. The arithmetic mean value of eight maximum wears was calculated. The total cutting time was also calculated as the product of the number of passes and the cutting time per pass calculated by equation (68). Normally four times the above mentioned procedure was repeated in order to observe a wear-cutting time progress. The points obtained were joined with each other by straight lines. When either some cutting edges were chipped or the 0.635 mm arithmetic mean value of flank wears was reached roughly, machining was stopped. Then the end of the cutter life was obtained from wear-cutting time progress under each cutting condition chosen. The first point on wear-cutting time graph was determined after short cutting time. From time to time the 0.635 mm arithmetic mean value was exceeded to trace the progress of wear. That was noticed after a certain time some cutting edges were chipped. One of the cutter life criteria, which was the 0.635 mm arithmetic mean value, determined correctly the end of each cutter life test. All tests were conducted dry, because cutting fluid cools cutting edges when they are free, after cutting they are healed. These cooling and heating repetitions make worse effect on cutter life than cutting is conducted to be dry.

Typical examples of chips obtained during cutter life tests using the Sandvik cutter, annealed tool steel (B.H.N. 238) and the Walter Cutter in down-cut milling are seen in Figure (27) and Figure (28) respectively.

Three gross power measurements were recorded when any two teeth were engaged with the workpiece being cut. It was noticed that power was increased due to wear progress. To obtain power required at the cutter, idle horse power plus power required to drive the table were substracted from each gross power value. The arithmetic mean value of three calculated power was obtained as power required at the cutter.

Surface finish roughnes (in C.L.A. index) measurements were recorded around 0.4 mm flank wear. When the teeth were brand new, rough surface finish was produced. Due to wear progress surface finish produced was better, toward the end of each cutter life test surface finish was rough. These were observed for both the Sandvik Cutter and the Walter Cutter. When the cutter acrossed the workpiece completely, ten measurements (in C.L.A. index) were taken in direction of table movement. Then the arithmetic mean value of ten readings was calculated under each cutting test condition.

Vibration measurements were obtained in two different directions in each case. In the other direction vibration amplitude and frequency were not high values. In down-cut milling, measurements were taken in feed and axial direction and in up-cut milling in feed and tangential direction.

Typical examples of vibrations taken for both the Sandvik cutter and the Walter cutter are seen in Figure (29) and Figure (30) respectively. All reading were obtained around 0.4 mm flank wear.

CHAPTER V

Experimental Results, Discussion of Results and Relevant Relationships

5.1. Experimental Results and Discussion of Results

One of the aims of this research was to prove the validity of equivalent chip thickness in face milling. That was achieved in two ways; first proof was to use the same cutting speed and the same equivalent chip thickness but to change the relevant variables of equivalent chip thickness. In down-cut milling, using the Walter cutter under the conditions of the cutting speed of 120.65 m/min and the equivalent chip thickness of 0.116 mm, the values of cutter life were obtained to be 39.0 mins and 38.2 mins. Their wear-cutting time progresses are seen in Figure (31). Also using the Sandvik cutter under the conditions of the cutting speed of 144.51 m/min and the equivalent chip thickness of 0.122 mm, the values of cutter life were obtained to be 20.4 mins and 18.9 mins. Their wear-cutting time progresses are drawn in Figure (32).

The results obtained were acceptable, because in any machining test, ± 10% variation is always allowable. Second proof was to choose two close values of equivalent chip thickness and to trace cutter life results in different cutting speeds. These were achieved selecting equivalent chip thickness values of 0.122 mm and 0.133 mm using the Sandvik cutter and two different workpiece materials in both down-cut and up-cut milling. The wear-cutting time progresses obtained using the Walter cutter, tool steel (B.H.N. 238) in down-cut milling are shown in Figure (33), Figure (34), Figure (35), Figure (36) and Figure (37).

The wear-cutting progresses obtained using the Sandvik cutter, tool steel (B.H.N. 238) in down-cut milling are seen in Figure (38), Figure (39) and Figure (40). Cutter life results, which were obtained using the Walter cutter and the Sandvik cutter in down-cut milling, versus cutting speeds are seen in semilog. scale Figure (41) and Figure (42) respectively.

Some cutting tests were repeated twice under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm using the Sandvik cutter and two different workpiece materials (namely tool steel B.H.N. 238 and 197) in both down-cut and up-cut milling. Cutter life results were obtained to be 9.10, 8.20, 11.49 and 11.17 mins respectively. Their wear progresses are shown in Figure (43) and Figure (44).

In central milling, one test was planned using the Sandvik cutter under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm, but the test was not completed, because two teeth were chipped around the 0.412 mm flank wear. W was 46.4 mm which was bigger than the linear distance between any two teeth in the Sandvik cutter. The wear progress is shown in Figure (45). Under the same cutting conditions, up-cut and down-cut milling were performed successfully. When width of workpiece is small, down-cut or up-cut milling can give longer cutter life because of better partial balance of heating and cooling repetitions of each tooth. One up-cut milling was tested under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm using tool steel (B.H.N. 238) and the Sandvik cutter to compare the cutter life result with the cutter life result obtained in down-cut milling under the same conditions. The cutter life was obtained to be 7.8 mins which was lower than the cutter life results of 9.10 and 8.20 mins obtained in down-cut milling. The wear-cutting time progress is seen in Figure (45).

One down-cut milling test was also performed under the conditions of V_s of 182.21 m/min and h_s of 0.133 mm using tool steel (B.H.N. 197) and the Sandvik cutter. The cutter life was obtained to be 13.9 mins which was bigger than the cutter life results of 11.49 and 11.17 mins obtained in up-cut milling. The wear-cutting time progress is shown in Figure (46).

Using the Sandvik cutter and tool steel (B.H.N. 197), up-cut milling tests were a failure at very short time or 0.3 mm flank wear under low and medium cutting speed conditions. The other tests under high speed conditions were performed until around 0.5 mm flank wear. Their wear-cutting time progresses are shown in Figure (47), Figure (48) and Figure (49). Using the Walter cutter and tool steel (B.H.N. 197) only one test was performed until around 0.5 mm flank wear which was smaller than the cutter life criterion used in down-cut milling tests. The wear-cutting time progress is seen in Figure (50).

By examining cutter life results it was noticed that cutting speed was one of the significant independent variable in cutter life results especially under high-speed conditions. Generally when cutting speed was increased cutter life decreased. Equivalent chip thickness played a significant role under low-speed conditions. When equivalent chip thickness was increased by means of W, f and d, cutter life decreased.

Equivalent chip thickness values of the cutters being commercially available gives ideas about which cutter can provide longer cutting time. Under the same cutting variables (at the same cutting speeds, table speeds or feed rates, depth of cuts, widths of workpieces, number of teeth) the smaller equivalent chip thickness values were calculated, when the Sandvik cutter was used. Hence the longer cutter life results were obtained,because under the same cutting variables in each test the same amount of heat was generated but bigger value of each cutting edge engaged with the workpiece being cut (due to bigger lengths values of each cutting edge),which is a measure of the contact surface, was obtained,when the Sandvik cutter was used. In the other words heat generated was transfered in bigger value to chips, the cutter and the workpiece being cut by using the Sandvik cutter in each test.

Longer cutter life results were obtained in down-cut milling with comparing cutter life results of down-cut milling to up-cut milling. Under the same cutting conditions, cutter workpiece material.

5.2. Chipping Mechanism

The reasons for failure, which was occured by chipping of some cutting edges, at very short cutting time for both the Sandvik cutter and the Walter cutter in up-cut milling tests were thought to be related to cutting force and mechanical stresses caused by entry conditions along the width of the workpiece being cut, AB, for both the Sandvik cutter and the Walter cutter as seen in Figure (51) and Figure (52) respectively. Because the initial contact point between AB and each tooth always occurs along the cutting edge of each tooth. Some examples are seen in Figure (51) and Figure (52) . It is known that failure caused by both mechanical and thermal stresses normally occurs after certain cutting time; not very short cutting time. Shinozaki (7) pointed out thermal cracks after certain cutting time in face milling.

The location of the initial point can be determined applying equations (66) and (67) derived by Kronenberg (5) to both the Sandvik cutter and the Walter cutter. The intersection angle i' between rake face of one tooth and plane of engagement can be calculated as follows:

a) For the Sandvik cutter;the angle of the engagement plane ε changes continuously according to progress of cutting. If for example $\varepsilon = -47^{\circ}$, thus the values of i', θ'_s, ϕ' and λ_s can be calculated using the formulas (66) and (67);

$$\mathrm{tg}\, i' = \frac{\mathrm{tg}\,\delta_s . \cos r}{\sin(r-\varepsilon)}$$

$$\mathrm{tg}\, i' = \frac{\mathrm{tg}\,(-7) . \cos(-5)}{\sin[-5-(-47)]} \qquad (104)$$

Hence the angle, $i' = -10^{\circ}$

The cutting edge angles, θ'_s, ϕ' and λ'_s

$$\mathrm{tg}\,\theta'_s = \frac{\mathrm{tg}\,\theta_s}{\cos\varepsilon}$$

$$\mathrm{tg}\,\theta'_s = \frac{\mathrm{tg}\,30}{\cos(-47)} \qquad (105)$$

$$\theta'_s = 40^{\circ}$$

and

$$\mathrm{tg}\,\phi' = \frac{\mathrm{tg}\,\phi}{\cos\varepsilon}$$

$$\mathrm{tg}\,\phi' = \frac{\mathrm{tg}\,60}{\cos(-47)} \qquad (106)$$

$$\phi' = 68^{\circ}.5$$

and

$$\mathrm{tg}\,\lambda'_s = \frac{\mathrm{tg}\,\lambda_s}{\cos\varepsilon}$$

$$\mathrm{tg}\,\lambda'_s = \frac{\mathrm{tg}\,75}{\cos(-47)} \qquad (107)$$

$$\lambda'_s = 80^{\circ}$$

b) For the Walter cutter;the angle of the engagement plane ϵ again changes continuously according to the progress of cutting.

$$tg\ i' = \frac{tg\ \delta_W . \mathrm{Cos}\ r}{\mathrm{Sin}(r - \epsilon)}$$

If for example $\epsilon = -\ 47^{\circ}$

$$tg\ i' = \frac{tg\ (8) . \mathrm{Cos}(-16)}{\mathrm{Sin}\ [-5-(-47)]}$$

$$i' = 11^{\circ}.4$$

The cutting edge angle, θ'_W

$$tg\ \theta'_W = \frac{tg\ \theta_W}{\mathrm{Cos}\ \epsilon}$$

$$tg\ \theta'_W = \frac{tg\ 42}{\mathrm{Cos}(-47)} \qquad (108)$$

$$\theta'_W = 53^{\circ}$$

Initial contact points in both cases are along the cutting edges as seen in Figure (53) and Figure (54). Surface finish was also examined over a certain area after cutting. On surface finish the traces of the broken cutting edges were seen.

However in down-cut milling, the initial contact points for both the Sandvik cutter and the Walter cutter were away from the cutting edges and toward the inside of the edges. Plan of engagement was always occured along the length of the workpiece, l, in down-cut milling.

5.3. Cutter life Relationships

The computer programme was written to calculate the coefficients of the proposed cutter life model given by the equation (69) for both the Walter cutter life data and the Sandvik cutter life data given in Table (1) and Table (2). The flow chart of the Computer programme written is given in Chapter III. The programme and the results for both the Walter cutter life data and the Sandvik cutter life data are seen in Appendix I. Their R.S.S. contour diagrams in $\alpha_1 - \alpha_2$ plane are also shown in Figure (55) and Figure (56). An example of a R.S.S. value, coefficients and confidence interval of coefficients are given in Appendix II.

The cutter life equation, using the Walter cutter life data, was obtained as;

$$31.836 \ln T_W = 226.568 - 2.066\, V_W^{0.8} - 857.419\, 10^2 h_W^{4.0}$$

or

$$\ln T_W = 7.177 - 0.065\, V_W^{0.8} - 2693.237 h_W^{4.0} \qquad (109)$$

R.S.S., which was the minimum value, was calculated to be 0.411. The error variance S^2 was obtained to be 0.046 using the equation (72). The 95 percent confidence interval for b_o, $CI(b_o)$ is given as;

$$CI(b_o) = b_o \pm t_{v;\, \xi/2} \cdot \sqrt{S^2 \cdot d_{ii}}$$

$t_{v;\, \xi/2}$ was taken to be 2.262 from a statistic table

$$CI(b_o) = 7.117 \pm 2.262 \cdot \sqrt{(0.046)(1.525)}$$

$$CI(b_o) = \left\{ \begin{array}{l} 7.716 \\ \\ 6.518 \end{array} \right.$$

for b_1 ;

$$CI(b_1) = -0.065 \pm 2.262 \cdot \sqrt{(0.046)(0.00076)}$$

$$CI(b_1) = \begin{cases} -0.052 \\ -0.078 \end{cases}$$

for b_2 ;

$$CI(b_2) = -2693.237 \pm 2.262 \sqrt{(0.046)(467.57\ 10^4)}$$

$$CI(b_2) = \begin{cases} -1644.190 \\ -3742.284 \end{cases}$$

Two more cutter life equations can be written using the upper and lower limits of coefficients calculated above. If the upper limit of $CI(b_o)$ is used for b_o, the lower limits of $CI(b_1)$ and $CI(b_2)$ are chosen for b_1 and b_2 and vice versa.

$$\ln T_w = 7.716 - 0.078V_w^{0.8} - 3742.284h_w^{4.0} \qquad (110)$$

and

$$\ln T_w = 6.518 - 0.052V_w^{0.8} - 1644.190h_w^{4.0} \qquad (111)$$

Logarithmic transformations of both sides, which is similar to Taylor type tool-life equations, were also obtained in the results.

$$31.835\ \ln T_w = 420.399 - 79.199\ \ln V_w - 30.512\ \ln h_w$$

or

$$\ln T_w = 13.206 - 2.488\ \ln V_w - 0.958\ \ln h_w \qquad (112)$$

R.S.S was calculated to be 0.885 which is bigger than the value of R.S.S. obtained in the equation (109).

The second proposed cutter life equation which is in the second order model, was obtained using the statistical package Mark $2^{(34)}$. The computer programme and results are seen in Appendix III. The multiple correlation coefficient was calculated to be 0.990

$$\ln T_w = 45.391 - 12.994 \ln V_w + 6.846 \ln h_w$$

$$+ 0.346 (\ln V_w)^2 - 1.6 (\ln h_w)^2 - 3.354 \ln V_w . \ln h_w \qquad (113)$$

R.S.S. was calculated to be 0.228.

The first proposed cutter life equation, using the Sandvik cutter life results, was obtained as;

$$18.195 \ln T_s = -220.96 + 757.52 V_s^{-0.2} - 645.871\ 10^3 h_s^{5.6}$$

or

$$\ln T_s = -12.14 + 41.63 V_s^{-0.2} - 35\ 10^3 h_s^{5.6} \qquad (114)$$

R.S.S., which was the minimum value, was calculated to be 0.041. The error variance S^2 was obtained to be 0.005 using the equation (72). The 95 percent confidence interval for b_o, $CI(b_o)$ is calculated as;

$$CI(b_o) = -12.14 \pm 2.306 \sqrt{(0.005)(80.674)}$$

$$CI(b_o) = \begin{cases} -10.68 \\ -13.60 \end{cases}$$

for b_1

$$CI(b_1) = 41.63 \pm 2.306 \sqrt{(0.005)(585.580)}$$

$$CI(b_1) = \begin{cases} 45.58 \\ 37.68 \end{cases}$$

for b_2

$$CI(b_2) = -35\ 10^3 \pm 2.306 \sqrt{(0.005)(44.64\ 10^8)}$$

$$CI(b_2) = \begin{cases} -24.1\ 10^3 \\ -45.9\ 10^3 \end{cases}$$

Hence two more cutter life equations can be written using the upper and lower limits of coefficients calculated above.

$$\ln T_s = -10.68 + 37.68\ V_s^{-0.2} - 45.9\ 10^3 h_s^{5.6} \qquad (115)$$

and

$$\ln T_s = -13.60 + 45.58\ V_s^{-0.2} - 24.1\ 10^3 h_s^{5.6} \qquad (116)$$

Logarithmic transformations of both sides, which is similar to Taylor type tool-life equation, were also obtained in the results;

$$18.195\ \ln T_s = 303.143 - 56.354\ \ln T_s - 14.534\ \ln h_s$$

or

$$\ln T_s = 16.661 - 3.097\ \ln V_s - 0.799\ \ln h_s \qquad (117)$$

R.S.S. was calculated to be 0.060 which is bigger than the value of R.S.S. obtained in the equation (114).

The second proposed cutter life equation, which is in the second order logarithmic model, was also obtained. The coefficients of the proposed equation and the miltiple correlation coefficient were calculated using the Statistical package Mark 2(34). The computer programme written and the coefficients obtained are seen in Appendix IV. The multiple correlation coefficient was calculated to be 0.930

The cutter life relationship is given;

$$\ln T_s = -122.597 + 62.440 \ln V_s + 19.933 \ln h_s - 6.387 (\ln V_s)^2 + 5.437 (\ln h_s)^2 + 0.857 \ln V_s . \ln h_s \quad (118)$$

5.4. Power Relationships

Powers required at any cutter in different cutting conditions were measured and evaluated in a function of metal removal rate, because metal removal rate can be easily calculated. The results in each test were obtained subtracting idle horse power and power required to move the table from the gross horse power. The results are given in Table (5) and Table (6),(7),Figure (57) and Figure (58) for both the Walter cutter and the Sandvik cutter using tool steel (B.H.N. 238 and 197), in down-cut milling and up-cut milling respectively.

As can be seen by examining the results, there is not much difference between power required at the Walter cutter and power required at the Sandvik cutter in down-cut milling under different cutting conditions. For the Sandvik cutter less power is required at the spindle in up-cut milling than down-cut milling.

The power relation equations, which are in the first order logarithmic models, were obtained. The coefficients were calculated the least square method using the Statistical package. One example of the computer programmes written and results are seen in Appendix V.

The equation using the Walter cutter, tool steel (B.H.N. 238) and and in down-cut milling was obtained.

$$H.P._W = 0.0816 + 0.0738 \text{ MR} \quad (119)$$

The correlation coefficient was calculated to be 0.995

It is known that when MR is 0.0, horse power consumption is zero. Hence the equation above can be written as;

$$H.P._W \cong 0.075\ MR \qquad (120)$$

The equation using the Sandvik cutter, tool steel (B.H.N. 238) in down-cut milling was obtained;

$$H.P._S = 0.178 + 0.0738\ MR \qquad (121)$$

The correlation coefficient was calculated to be 0.982 For the same reason the equation can be written as;

$$H.P._S \cong 0.075\ MR \qquad (122)$$

Both equations have the same slopes.

5.5. Surface Finish Relationships

Surface finish results are given in Table (8), Table (9) and Table (10) . Cutting speed plays a significant role on surface finish. Better surface finish results were obtained using the Sandvik cutter in down-cut milling and rough surface finish were produced in up-cut milling.

The coefficients of the surface finish equations were calculated by the least square method using the Statistical package Mark 2(34) in first order logarithmic models.

The equation , using the Walter cutter in down-cut milling is written as;

$$\ln S.F_W = 4.326 - 1.013\ \ln V_W + 0.064\ \ln h_W \qquad (123)$$

The multiple correlation coefficient was calculated to be 0.660, the equation, using the Sandvik cutter in down-cut milling, is written as;

$$\ln S.F_s = 1.27 - 0.741 \ln V_s - 0.853 \ln h_s \qquad (124)$$

The multiple correlation coefficient was calculated to be 0.733.

5.6. Vibration Relationship

Vibration amplitutes results from peak to peak (P.T.P.) are given under different cutting conditions in Table (11), Table (12) and Table (13). It was found that cutting speed and maximum area being cut were significant variables on vibration amplitude produced. The results obtained also show that vibrations are generated by cutting force components applied to the cutting system. There is not much difference between vibration amplitutes produced by the Walter cutter and the Sandvik cutter in down-cut milling, but less vibrations were produced during the up-cut milling.

The relevant vibration equations were obtained. The coefficients of the equations were calculated by the least square method using the Statistical package Mark 2$^{(34)}$ in the first order logarithmic model.

The equation using the Walter cutter in down-cut milling is written as;

$$\ln VIB.AMP_w = 4.636 - 0.174 \ln V_w + 0.537(s_{max_w}) \qquad (125)$$

where (s_{max_w}) is the maximum area being cut which is equal to d.f. The multiple correlation coefficient was calculated to be 0.848.

The equation using the Sandvik cutter in down-cut milling is written as;

$$\ln VIB.AMP_s = 7.426 - 0.682 \ln V_s + 0.898 (s_{max_w}) \qquad (126)$$

where (s_{max_w}) is the maximum area. The multiple correlation coefficient was calculated to be 0.895.

CHAPTER VI

Economics of Face Milling and Applications

Basically two models are considered, namely unit-time model and unit-cost model in this research. The use of profit-rate can be difficult, because selling price of each piece is not normally fixed at the beginning of the process in practice.

1) Unit-time model.

The total time to produce one piece T_p was written in Chapter III as;

$$T_p = T_1 + K.\ MV. \left(\frac{T + T_r}{MR.T} \right) \qquad (127)$$

where T_1 is the total, K is the constant, MV is the volume of metal to be removed, T_r is the replacement time of teeth, T is the cutter life, MR is the metal removal rate.

To obtain the minimum values of T_p, which is the aim of industry, the reciprocal of the second term of the equation above $F_1 = \frac{MR.T}{T + T_r}$, which is called time function in this research, should be maximum. Then the equation, which will give the optimum cutter life value, was obtained in Chapter III as;

$$T(T + T_r) + MR.\ T_r.\frac{dT}{dMR} = 0 \qquad (128)$$

The first derivation of T to MR can be obtained using the T - MR characteristic function.

a) Determination of optimum cutting conditions using the Walter cutter, tool steel material (B.H.N. 238) in down-cut milling.

The cutter life equation was obtained using power transformations in the form as;

$$\ln T_w = b_o + b_1 . \frac{V_w^{\alpha_1}}{1000^{\alpha_1}} + b_2 \, h_w^{\alpha_2} \qquad (129)$$

where $b_o = 7.117$, $b_1 = -0.065$, $\alpha_1 = 0.8$, $b_2 = -2693.23$, $\alpha_2 = 4.0$, V_w in $\frac{mm}{min}$ and h_w in mm.

Metal removal rate, MR, was written in Chapter III as follows;

$$h_w = \frac{MR/V_w}{l_w + \frac{d}{\sin \theta_w . \cos \delta_w}}$$

or

$$MR = \left(l_w + \frac{d}{\sin \theta_w . \cos \delta_w} \right) . h_w . V_w \qquad (130)$$

where V_w in $\frac{mm}{min}$, h_w in mm, and l_w in mm.

In this research, depth of cut d is taken into account as any parameter, not a variable. In calculation, any value is given to depth of cut bearing in mind horse power limitation of the machine tool used. Therefore the first term of the equation above

$$l_w + \frac{d}{\sin \theta_w . \cos \delta_w}$$ is calculated as any

parameter. Hence MR is expressed only as a function of h_w and V_w. For the existence of the MR - T characteristic function, their Jacobian should vanish as follows:

$$J = \begin{vmatrix} \frac{\partial MR}{\partial h_w} & \frac{\partial MR}{\partial V_w} \\ \\ \frac{\partial T_w}{\partial h_w} & \frac{\partial T_w}{\partial V_w} \end{vmatrix} = 0 \qquad (131)$$

The partial differentiations, $\frac{\partial MR}{\partial V_w}$, $\frac{\partial MR}{\partial h_w}$, $\frac{\partial T_w}{\partial V_w}$ and $\frac{\partial T_w}{\partial h_w}$ can be obtained using the equations (129) and (130) respectively.

$$\frac{\partial MR}{\partial V_w} = a_1.h_w , \frac{\partial MR}{\partial h_w} = a_1.V_w$$

$$\frac{\partial T_w}{\partial V_w} = b_1.\alpha_1.\frac{V_w^{\alpha_1 - 1}}{1000^{\alpha_1}} . T$$

$$\frac{\partial T_w}{\partial V_w} = b_2.\alpha_2.h_w^{\alpha_2 - 1} . T$$

where $a_1 = l_w + \frac{d}{\text{Sin } \Theta_w . \text{Cos} \delta_w}$

By using the formulas above in equation (131) the following expression is obtained ;

$$\frac{b_1 \alpha_1}{1000^{\alpha_1}} . V_w^{\alpha_1} = b_2.\alpha_2.h_w^{\alpha_2} \qquad (132)$$

The equation above gives the relationship between V_w and h_w. This is also the T - MR curve in V_w - h_w plane and an exponential form. Using the equations (130) and (132) we obtain;

$$h_w^{\alpha_2} = \frac{b_1.\alpha_1.V_w^{\alpha_1}}{b_2.\alpha_2.1000^{\alpha_1}} \qquad (133)$$

and

$$h_w^{\alpha_2} = \left(\frac{MR}{a_1}\right)^{\alpha_2} \frac{1}{V_w^{\alpha_2}} \qquad (134)$$

The relationship between V_w and MR can be obtained as;

$$\frac{b_1}{b_2} \cdot \frac{\alpha_1}{\alpha_2} \cdot \frac{V_w^{\alpha_1}}{1000^{\alpha_1}} = \left(\frac{MR}{a_1}\right)^{\alpha_2} \cdot \frac{1}{V_w^{\alpha_2}}$$

or

$$\left(\frac{1}{1000^{\alpha_1}} \cdot \frac{b_1}{b_2} \cdot \frac{\alpha_1}{\alpha_2}\right)^{\frac{\alpha_1}{\alpha_1+\alpha_2}} \cdot V_w^{\alpha_1} = \left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 . \alpha_2}{\alpha_1+\alpha_2}}$$

Using the cutter life equation (129) T_w can be written only as a function of V_w

$$\ln T_w = b_o + \frac{b_1}{1000^{\alpha_1}} \left(1 + \frac{\alpha_1}{\alpha_2}\right) V_w^{\alpha_1} \qquad (135)$$

Hence the relationship between T_w and MR can be obtained as follows;

$$\ln T_w = b_o + \frac{b_1}{1000^{\alpha_1}} \cdot \left(1 + \frac{\alpha_1}{\alpha_2}\right)\left(1000^{\alpha_1} \cdot \frac{b_2 \alpha_2}{b_1 \alpha_1}\right)^{\frac{1}{\alpha_1+\alpha_2}} \cdot \left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 \alpha_2}{\alpha_1+\alpha_2}}$$

This is the MR - T_w characteristic equation. By using the values of parameters, the equation can be written as follows;

$$\ln T_w = 7.117 - 0.006 \left(\frac{MR}{a_1}\right)^{0.667} \qquad (136)$$

That is the unique equation, because the ratio $\frac{MR}{a_1}$ is equal to $h_w . V_w$, the value of the equation is not related to the value of d. The curve of the equation above is given in Figure (59).

To obtain equation (128), the first derivation of T_w to MR is calculated

$$\frac{dT_w}{dMR} = \frac{b_1}{1000^{\alpha_1}} \left(1 + \frac{\alpha_1}{\alpha_2}\right) \left(1000^{\alpha_1} . \frac{b_2 - \alpha_2}{b_1 \cdot \alpha_1}\right)^{\frac{\alpha_1}{\alpha_1 + \alpha_2}} . \frac{\alpha_1 . \alpha_2}{\alpha_1 + \alpha_2} . \left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 . \alpha_2}{\alpha_1 + \alpha_2}} . \frac{T}{MR} \qquad (137)$$

Using equation (137) obtained, the equation, which will give the optimum value of the cutter life, is written as follows:

$$(T_w + T_r) + T_r \, (\ln T_w - b_o) \frac{\alpha_1 . \alpha_2}{\alpha_1 + \alpha_2} = 0 \qquad (138)$$

The solution of the equation above depends on the values of T_r, b_o, α_1 and α_2.

Two different values of the replacement time of teeth, T_r, are considered as 15 and 30 mins, which are acceptable values in industry.

i) $T_r = 15$ mins

The equation (138) is written as:

$$T_w + 15 + 15 \, (\ln T_w - 7.117) \; 0.667 = 0$$

T_w was calculated to be 24 mins which is the optimum cutter life value in this situation. The value of MR was obtained to be 65217.02 $\frac{mm^3}{min}$ using T_w of 24 mins and considering the value of d to be 1.905 mm (o.075 in).

The optimum values of cutting speed V_w and equivalent chip thickness h_w were calculated to be 134.62 m/min and 0.125 mm respectively. Table speed F can be calculated according to the value W of the workpiece being cut.

ii) $T_r = 30$ mins.

$$T_w + 30 + 30\ (\ln T_w - 7.117)\ 0.667 = 0$$

T_w was calculated to be 39 mins which is the optimum cutter life value in this situation.

As can be seen when T_r is increased cutter life should be used longer.

The value of MR was calculated to be 53538.77 $\frac{mm^3}{min}$, provided d was considered to be 1.905 mm. The optimum values of V_w and h_w were obtained to be 114.19 m/min and 0.121 mm respectively. Table speed F can be calculated according to the value of W being used.

As can be observed when cutter life is used longer, the value of MR should be decreased.

b) Determination of optimum cutting conditions using the Sandvik cutter, tool steel material (B.H.N.238) in down-cut milling.

The cutter life equation was obtained using the power transformations method as:

$$\ln T_s = b_o + b_1 \frac{V_s^{\alpha_1}}{1000^{\alpha_1}} + b_2\, h_s^{\alpha_2} \qquad (139)$$

where $b_o = -12.144$, $b_1 = 41.634$, $b_2 = -35497.19$

$\alpha_1 = -0.2$, $\alpha_2 = 5.6$, V_s in $\frac{mm}{min}$ and h_s in mm

Metal removal rate, MR was written in Chapter III as follows:

$$h_s = \frac{MR/V_s}{a_2}$$

$$\text{where } a_2 = \begin{cases} l_s + \dfrac{l_\theta + \dfrac{d}{\operatorname{Sin}\phi} - l_\theta \cdot \dfrac{\operatorname{Sin}\theta_s}{\operatorname{Sin}\phi}}{\operatorname{Cos}\delta_s}, & \text{if } d < la \\[2ex] l_s + \dfrac{\left[l_\theta + l_\phi + \dfrac{d}{\operatorname{Sin}\lambda_s} - \left(l_\phi + l_\theta \dfrac{\operatorname{Sin}\theta_s}{\operatorname{Sin}\phi}\right) \cdot \dfrac{\operatorname{Sin}\phi}{\operatorname{Sin}\lambda_s} \right]}{\operatorname{Cos}\delta_s} \\ \text{if } d > la \end{cases}$$

Depth of cut d is taken as any parameter, in calculation any value is given to d according to horse power available on the machine tool used. The same formulas, which were obtained and used to determine optimum cutting conditions using the Walter cutter in down-cut milling, can be also used in this section.

MR is only a function of h_s and V_s

$$MR = MR(h_s, V_s)$$

For the existence of MR - T characteristic function, their Jacobian should vanish. By doing the procedure, the following expression is obtained:

$$\frac{b_1 \cdot \alpha_1}{1000^{\alpha_1}} V_s^{\alpha_1} = b_2 \cdot \alpha_2 \cdot h_s^{\alpha_2}$$

The equation above is the MR - T curve in V_s - h_s plane.

The MR - T relationship is also obtained as;

$$\ln T_s = b_o + \frac{b_1}{1000^{\alpha_1}} \left(1 + \frac{\alpha_1}{\alpha_2}\right) \left(1000^{\alpha_1} \cdot \frac{b_2 \cdot \alpha_2}{b_1 \cdot \alpha_1}\right)^{\frac{\alpha_1}{\alpha_1+\alpha_2}} \left(\frac{MR}{a_2}\right)^{\frac{\alpha_1 \cdot \alpha_2}{\alpha_1+\alpha_2}}$$

By using the values of parameters the MR - T_s curve is written as:

$$\ln T_s = -12.144 + 115.96 \left(\frac{MR}{a_2}\right)^{-0.207} \tag{140}$$

The Curve of the equation is given in Figure (60).

The equation, which will give the optimum cutting conditions, can be written as;

$$T_s + T_r + T_r (\ln T_s - b_o) \frac{\alpha_1 \cdot \alpha_2}{\alpha_1 + \alpha_2} = 0 \tag{141}$$

Two different values of the tool replacement time T_r are considered as 15 and 30 mins.

i) $T_r = 15$ mins

$$T_s + 15 + 15\ (\ln T_s + 12.144) - 0.207 = 0$$

T_s was calculated to be 33 mins which is the optimum cutter life value in this situation. The value of MR was obtained to be 64036.16 mm^3/min using T_s of 27 mins provided d was considered to be 1.905 mm (0.075 in).

The optimum values of cutting speed V_s and equivalent chip thickness h_s were calculated to be 111.43 m/min and 0.139 mm respectively. Table speed F can be calculated according to the value of W being used.

ii) $T_r = 30$ mins.

$$T_s + 30 + 30\ (\ln T_s + 12.144) - 0.207 = 0$$

T_w was calculated to be 72 mins which is the optimum cutter life value in this situation. When T_r is increased, cutter life should be used longer.

The value of MR was calculated to be 50622.06 mm^3/min. The optimum values of V_s and h_s were calculated to be 87.36 m/min and 0.140 mm. Table speed F can be calculated according to the value of W being used

2. Unit-cost model

The total cost to produce one piece C was written in Chapter III as;

$$C = C_o.T_1 + C_o.K.\ \frac{MV}{MR}\ (1 + \frac{T_r + Y/C_o}{T})$$

where C_o is the operator and overhead cost per unit time, T_1 is the total idle time including set-up time, K is the constant which is calculated by $\frac{1}{l_p}$ as seen in Figure (14), MV is the metal volume to be removed, MR is the metal removal rate, T_r is the replacement time of teeth, Y is the total cost of cutting edges of the cutter.

To obtain the minimum values of C, the reciprocal of the second term of the equation above $F_2 = \frac{MR.T}{(T + T_r + \frac{Y}{C_o})}$ which is called cost function in this research, should be maximum. Then the equation, which will give the optimum cutter life value was obtained in Chapter III as;

$$T(T + T_r + \frac{Y}{C_o}) + MR(T_r + \frac{Y}{C_o}) \frac{dT}{dMR} = 0$$

where the first derivation of T to MR can be obtained using the T - MR characteristic equation as done in the previous section.

a) Determination of optimum cutting conditions using the Walter cutter, tool steel (B.H.N. 238) in down-cut milling. In the previous section (unit-time model) the relationship between T and MR was obtained as below:

$$\ln T_w = b_o + \frac{b_1}{1000^{\alpha_1}} \left(1 + \frac{\alpha_1}{\alpha_2}\right)\left(1000^{\alpha_1} . \frac{b_2 \cdot \alpha_2}{b_1 \cdot \alpha_1}\right)^{\frac{\alpha_1}{\alpha_1+\alpha_2}} \left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 . \alpha_2}{\alpha_1+\alpha_2}}$$

The first derivation of T_w to MR was calculated as;

$$\frac{dT_w}{dMR} = \frac{b_1}{1000^{\alpha_1}} \left(1 + \frac{\alpha_1}{\alpha_2}\right)\left(1000^{\alpha_1} . \frac{b_2 \cdot \alpha_2}{b_1 \cdot \alpha_1}\right)^{\frac{\alpha_1}{\alpha_1+\alpha_2}} \left(\frac{\alpha_1 . \alpha_2}{\alpha_1+\alpha_2}\right) \cdot \left(\frac{MR}{a_1}\right)^{\frac{\alpha_1 . \alpha_2}{\alpha_1+\alpha_2}} \cdot$$

$$\cdot \frac{T}{MR} \qquad (142)$$

Using equation (142), to obtain the optimum cutter life value, the equation below should be solved.

$$\left(T_w + T_r + \frac{Y}{C_o}\right) + \left(T_r + \frac{Y}{C_o}\right) \quad (\ln T_w - b_o)\frac{\alpha_1 \cdot \alpha_2}{\alpha_1 + \alpha_2} = 0, \quad (143)$$

The solution of the equation above is related to the values of C_o, T_r, Y, b_o, α_1 and α_2

The following information was obtained from G.K.N. Ltd.

C_o = £4.20/hour = 7 pence/min

Y = 176 pence

By using the values of the parameters, the equation (143) is written as;

$$(T_w + T_r + 25) + (T_r + 25)(\ln T_w - 7.117).\ 0.667 = 0$$

Two different values of T_r are considered as 15 mins and 30 mins.

i) T_r = 15 mins

$$(T_w + 15 + 25) + (15 + 25)(\ln T_w - 7.117).\ 0.667 = 0$$

T_w was calculated to be 47 mins which is the optimum cutter life value in this situation. This result shows that the optimum tool life for minimum unit cost is larger than for minimum unit time. The optimum tool life for minimum unit time was already calculated to be 21 mins. in the previous section. The MR value for the 47 mins optimum cutter life value was obtained to be 50220.08 mm^3/min, d was considered to be 1.905 mm (0.075 in). The optimum cutting speed V_w and equivalent chip thickness h_w were calculated to be 106.55 m/min and 0.119 mm respectively. Table speed F can be calculated corresponding to the value of W being used.

ii) T_r = 30 mins

$$(T_w + 30 + 25) + (30 + 25)(\ln T_w - 7.117)0.667 = 0$$

T_W was calculated to be 58 mins which is the optimum cutter life value in this situation. The value of MR for the 58 mins optimum cutter life value was calculated to be 45449.79 mm^3/min and d was considered to be 1.905 mm (0.075 in). Corresponding optimum V_s and h_s were calculated to be 98.04 m/min, 0.117 mm respectively. Table speed F can be calculated according to the value of W being

b) Determination of optimum cutting conditions using the Sandvik cutter, tool steel material (B.H.N. 238) in down-cut milling. The same formulas obtained in the previous sections will be used in this section in order to calculate optimum cutting conditions. The values of C_o and Y are taken to be 7 pence/min and 176 pence respectively as previous values.

The equation, which will determine optimum tool life, is written below by using the parameters of the Sandvik cutter life equation. Two different values of T_r are considered as 15 mins and 30 mins.

i) T_r = 15 mins

$$(T_s + 15 + 25) + (15 + 25)(\ln T_s + 12.14) - 0.207 = 0$$

T_s was calculated to be 98 mins which is the optimum cutter life value in this situation. The value of MR for this 98 mins optimum cutter life value was calculated to be 46139.99 mm^3/min, d was considered to be 1.905 mm (0.075 in). The optimum values of V_s and h_s were calculated to be 79.77 m/min and 0.141 mm respectively. Table speed F can be calculated according to the value of W being cut.

ii) T_r = 30 min.

$$(T_s + 30 + 25) + (30 + 25)(\ln T_s + 12.14) - 0.207 = 0$$

T_s was calculated to be 140 mins which is the optimum cutter life value in this situation. The value of MR for the 140 mins optimum cutter life was calculated to be 41669.06 mm^3/min and d was considered to be 1.905 mm (0.075 in). The optimum values of V_s and h_s were calculated to be 71.65 m/min and 0.142 mm respectively. Table speed F can be calculated according to the value of W being cut.

T_r on optimum cutting conditions is significant. When T_r takes longer time, the cutter should be used longer time. Longer cutter life leads smaller metal removal rate, hence cutting speed and the other variables should be decreased and vice versa. The effect of Y on optimum cutting conditions is also significant. When the cost of teeth used is high, the cutter should be used in production for longer time. C_o is also another significant parameter. When C_o is increased, the cutter should be used for shorter time. The Sandvik cutter in both unit time and unit-cost gives the higher optimum cutter life than the Walter cutter because of the effect of the coefficients. The optimum cutter life value for minimum cost is higher than for minimum time.

Generally low cutting speed, high table speed and high depth of cut should be selected to obtain optimum cutting conditions in face milling bearing in mind maximum power available on the machine tool.

Optimum cutting speed for minimum time and minimum cost under the situation of the Sandvik cutter is selected to be smaller value than under the situation of the Walter cutter.

Under the situation of the Sandvik cutter, optimum equivalent chip thickness and using the result of equivalent chip thickness, table speed is selected higher value than under the situation of the Walter cutter for minimum time and minimum cost.

CHAPTER VII

Conclusions and Future Work

7.1. Conclusions

7.1.1. The selection of the cutter diameter should be related to the width of the workpiece being cut.

A maximum of 1.5 times the workpiece width is rather a good choice because in order to balance cooling and heating repetations of each tool and reduce impact effect of each tooth entering the workpiece, the number of teeth, which will be contacting the workpiece, should be as high as possible at any time. When the width of workpiece is relatively small, the down-cut or up-cut milling position* increases the number of teeth compared with central milling.

7.1.2. Metal removal rate was found to be a function of cutting speed, characteristic feed (which is determined by average chip thickness and the engagement angle), depth of cut, and also from the product of width of workpiece, table speed and depth of cut. Then equivalent chip thickness was formulated in each situation.

7.1.3. In order to evaluate machinability data, and at the same time to save tests and amount of workpiece material required, the number of independent variables was selected as small as possible.

7.1.4. The cutter wear hardly affects horse power consumption, surface finish produced, and vibration generated. Generally, mean value of measurements was taken to determine dependent variables above.

---

* i.e. Offset of workpiece to left and right side of cutter centre line

7.1.5. In the life evaluation of a multi-tooth cutter, the number of wear measurements should be on at least half the number of teeth used, because each tooth does not remove the same amount of material from the workpiece being cut.

7.1.6. The maximum width of wear land on each flank face is a better measurement than the mean value of the width of flank wear, in order to determine the useful life of the cutter. This is because after a certain cutting time, the maximum flank wear leads to the complete failure of the cutting edge. Measuring the maximum wear on each tooth takes a shorter time than measuring the mean value.

7.1.7. In down-cut milling, 0.625 mm (0.025 in) for the arithmetic mean value of maximum widths of flank wears was found a more acceptable value than 0.762 mm (0.030 in). This is because of widespread variation amoung the wear values of different teeth on the cutter. But in up-cut milling, only the 0.5 mm arithmetic mean value of maximum widths of flank wears was reached.

7.1.8. Down-cut milling gives a better performance than up-cut or central milling, especially when the width of the workpiece is relatively small. When the cost of each tooth is considered, down-cut milling can be prefered because it gives longer cutter life, provided a backlash eliminator is used. The first initial contact point of each tooth with the workpiece is always away from the cutting edge in down-cut milling, but occurs on the cutting edge in up-cut milling. Hence when a brittle cutting edge like a carbide cutting edge is used, chipping can easily occur in up-cut milling.

In this situation the cutter which has negative axial rake gives more strength than the cutter which has positive axial rake. In up-cut milling, more overall power is required, because more power is required in the direction of feed to produce the movement of the workpiece, but less power is required at the cutter itself.

Down-cut milling also produces better surface finish than up-cut milling. With the backlash eliminator, the same level of amplitude of vibration is generated on the workpiece being cut in down-cut milling when using different face milling cutters.

Less amplitude of vibration is generated on the workpiece being cut in up-cut milling.

7.1.9. In planning of cutting tests, firstly the selection of levels of cutting variables such as number of revolution table speed etc., is made.

A typical range of cutter life which can be selected is from 10 to 70 mins, and metal removal rate can give some indication to the production engineer to enable him to choose the levels of cutting variables.

7.2.0. Equivalent chip thickness can also give some guidance in the selection of tooth shape amoung commercially available tooth shapes. The cutting edge which gives the longer engaged cutting edge with the workpiece should be prefered from the cutter life point of view. This is because the heat generated during cutting is easily transfered to the chips, to the cutter and to the workpiece being cut, through the engaged cutting edges. In such a situation, a smaller equivalent chip thickness value is obtained.

7.2.1. In up-cut milling, cutting edges of inserts, which have negative axial rake values, in the Sandvik Cutter showed greater strength than cutting edges of inserts, which have positive axial rake values, in the Walter Cutter.

7.2.2. The exponential form of cutter life equation gives a better fit than the first-degree logarithmic polynominal equation.

7.2.3. By using the T - MR characteristic function, the optimum cutting conditions were obtained. Different optimum values were calculated when using unit-time and unit-cost equations. Generally, one should select low values for the cutting speed, and high values for table speed, and depth of cut, always bearing in mind the horse power limitations of the machine tool and the grade of teeth selected. The replacement time of teeth, the cost of each tooth, operator and overhead cost are significant parameters like the coefficients of the cutter life determined by workpiece material, tooth material, cutting variables etc., in the selection of cutter life, metal removal rate, and cutting variables.

7.2. Future Work

7.2.1. Cutting Tests.

Further cutting tests should be performed taking different values of the equivalent chip thickness as an independent variable with different values of the cutting speeds in the typical domain of cutter life and metal removal rate to be made better appreciation of equivalent chip thickness idea.

7.2.2. Different workpiece materials.

Different types of workpiece materials which are used in industry, mostly ferrous metals with different hardness and geometrical properties, should be tested.

7.2.3. Different cutters.

Different cutters and inserts which are commercially available with different diameters and numbers of teeth should be used on various milling machine tools having different dynamic characteristics.

7.2.4. Cutting force and measurements of cutting force components.

Three dimensional dynamometers, also capable of recording fluctuations on a time basis, should be used in order to complete the machinability data. The relationship between the tangential force and the characteristic feed, which is determined by the average chip thickness and the engagement angle between the cutter and the workpiece being cut, will be obtained in much more simple mathematical form.

APPENDIX I

```
      TRACE 2
      END



      TRACE 1
      TRACE 2
      MASTER TOMRIS
C     ********************************
C   POVER TRANSFORMATIONS FOR WALTER CUTTER
C     ********************************
C
      DIMENSION VC(50),ECT(50),CT(50),X(15,15),XT(15,15),XC(20,20),
     1A1(2000),A2(2000),BL(2000),XA(20,20),XI(20,20),
     2Y(100),BETA(10,10),U1(100),U(10),B(2000),A(100),SUM(2000),U2(100),
     3ALF1(150),ALF2(150),WKSPACE(10),XK(20,20)
C     *******     INPUT DATA     *********
      READ(1,1) N
      READ(1,1) NOB
      READ(1,2) A1L,A1I,A2L,A2I
      READ(1,3) NCA1,NCA2
      DO  10  I=1,NOB
      READ(1,4) VC(I),ECT(I),CT(I)
 10   CONTINUE
      READ(1,160)(WKSPACE(I),I=1,10)
 160  FORMAT(10A8)
C     *******     FORMATS FOR INPUTS     *********
  1   FORMAT(I0)
 2    FORMAT(4F0.0)
  3   FORMAT(2I0)
  4   FORMAT(3F0.0)
C    ******  ******   ***********
      WRITE(2,198)
 198  FORMAT(//,40X,24H NUMBER OF CALCULATIONS /)
      IT=NCA1*NCA2
      WRITE(2,199) IT
 199  FORMAT(I50)
      DO 15 N5=1,IT
      SUM(N5)=0.0
  15  CONTINUE
      DO 16 M1=1,N
      DO 16 M2=1,N
      XC(M1,M2)=0.0
 16   CONTINUE
      DO 17 N1=1,N
      XA(N1,1)=0.0
  17  CONTINUE
      DO 18 N3=1,N
      BETA(N3,1)=0.0
  18  CONTINUE
      DO 19 N4=1,NOB
      A(N4)=0.0
 19   CONTINUE
      DO 80 I=1,N
      DO 80 J=1,N
      XK(I,J)=0.0
  80  CONTINUE
C    ******     ******     ********
      IJ=1
      VN1=0.0
      DO  21  I1=1,NCA1
```

```
      VN1=VN1+A1I
      ALF1(I1)=A1L+VN1
      VN2=0.0
      DO  20  I2=1,NCA2
      VN2=VN2+A2I
      ALF2(I2)=A2L+VN2
      WRITE(2,500)
500   FORMAT(//,36X,27H ESTIMATE VALUES OF POWERS /)
      WRITE(2,51) ALF1(I1),ALF2(I2)
51    FORMAT(F40.5,F15.5)
      WRITE(2,190)
190   FORMAT(///,30X,37H THE MATRIX OF INDEPENDENT VARIABLES /)
      IF(ALF1(I1).EQ.0.0)  GO TO 700
      DO 650 I=1,NOB
      U1(I)=VC(I)**ALF1(I1)
650   CONTINUE
      GO TO 660
700   DO 652 I=1,NOB
      U1(I)=ALOG(VC(I))
652   CONTINUE
660   IF(ALF2(I2).EQ.0.0) GO TO 701
      DO 654 I=1,NOB
      U2(I)=ECT(I)**ALF2(I2)
654   CONTINUE
      GO TO 670
701   DO 671 I=1,NOB
      U2(I)=ALOG(ECT(I))
671   CONTINUE
670   DO 23 I=1,NOB
      X(I,1)=1,0
      X(I,2)=U1(I)
      X(I,3)=U2(I)
      WRITE(2,191) X(I,1),X(I,2),X(I,3)
191   FORMAT(F35,1,2F14.4)
23    CONTINUE
      WRITE(2,192)
192   FORMAT(//,30X,29H THE TRANSPOSE OF THE MATRIX /)
      DO 24 J=1,N
      DO 24 I=1,NOB
      XT(J,I)=X(I,J)
 24   CONTINUE
      WRITE(2,193)((XT(J,I),I=1,NOB),J=1,N)
193   FORMAT(F15.3,11F9.3)
      WRITE(2,188)
188   FORMAT(//,30X,31H MULTIPLICATION OF TWO MATRIXS /)
      DO 25 I=1,N
      DO 25 J=1,N
      XK(I,J)=0.0
      DO 25 K=1,NOB
      XK(I,J)=XK(I,J)+XT(I,K)*X(K,J)
 25   CONTINUE
      WRITE(2,189) ((XK(I,J),J=1,N),I=1,N)
189   FORMAT(F30.5,2F25.5)
C     *******    *******    ******
      WRITE(2,165)
165   FORMAT(//,35X,18H INVERSE OF MATRIX/)
      IFAIL=0
      CALL F01AAF(XK,20,N,XC,20,WKSPACE,IFAIL)
      IF(IFAIL.EQ.0) GO TO 170
      WRITE(2,150)
150   FORMAT(1H0,18H FAILURE IN F01AAF)
      STOP
```

```
  170  DO 155 I=1,N
       WRITE(2,156)(XC(I,J),J=1,N)
  156  FORMAT(F30.5,2F25.5)
  155  CONTINUE
C      *****     *****     *****     *****
       WRITE(2,194)
  194  FORMAT(//,30X,41H GEOMETRIC RATIO OF OBSERVED CUTTER LIFE /)
       CAR=1.0
       DO  50  I=1,NOB
       CAR=CAR*CT(I)
   50  CONTINUE
       AN=1.0/NOB
       GMV=CAR**AN
       WRITE(2,195) GMV
  195  FORMAT(F55.4)
       WRITE(2,205)
  205  FORMAT(//,30X,43H TRANSFORMATIONS OF THE DEPENDENT VARIABLE /)
       DO 33 M=1,NOB
       Y(M)=GMV*ALOG(CT(M))
       WRITE(2,206) Y(M)
  206  FORMAT(F55,5)
   33  CONTINUE
       WRITE(2,300)
  300  FORMAT(//,40X,21H SECOND PART OF BETA /)
       DO 34 I=1,N
       XA(I,1)=0.0
       DO 34 J=1,NOB
       XA(I,1)=XA(I,1)+XT(I,J)*Y(J)
   34  CONTINUE
       WRITE(2,301) (XA(I,1),I=1,N)
  301  FORMAT(F55.5)
       WRITE(2,207)
  207  FORMAT(//,30X,34H ESTIMATE VALUES OF COEFFICIENCIES /)
       DO 35 I=1,N
       II=0
       BETA(I,1)=0.0
       DO 35 J=1,N
       II=II+1
       BETA(I,1)=BETA(I,1)+XC(I,J)*XA(II,1)
   35  CONTINUE
       WRITE(2,208) (BETA(I,1),I=1,N)
  208  FORMAT(F55.5)
       IF(ALF1(I1).EQ.0.0) GO TO 800
       DO 750  K1=1,NOB
       U1(K1)=VC(K1)**ALF1(I1)
  750  CONTINUE
       GO TO 760
  800  DO 752  K1=1,NOB
       U1(K1)=ALOG(VC(K1))
  752  CONTINUE
  760  IF(ALF2(I2).EQ.0.0) GO TO 801
       DO 754 K1=1,NOB
       U2(K1)=ECT(K1)**ALF2(I2)
  754  CONTINUE
       GO TO 770
  801  DO 771 K1=1,NOB
       U2(K1)=ALOG(ECT(K1))
  771  CONTINUE
  770  WRITE(2,209)
  209  FORMAT(//,40X,15H THE RESIDUALS /)
       DO 40 L=1,NOB
       U(1)=1.0
```

```
      U(2)=U1(L)
      U(3)=U2(L)
      A(L)=0.0
      DO 41 I=1,N
      A(L)=A(L)+U(I)*BETA(I,1)
 41   CONTINUE
  40  CONTINUE
      DO 45 L=1,NOB
      B(L)=Y(L)-A(L)
      WRITE(2,210) B(L)
 210  FORMAT(F55.5)
  45  CONTINUE
      WRITE(2,211)
 211  FORMAT(//,30X,26H RESIDUALS SUM OF SQUARES /)
      SUM(IJ)=0.0
      DO  42  M=1,NOB
      SUM(IJ)=SUM(IJ)+B(M)*B(M)
  42  CONTINUE
      WRITE(2,212) SUM(IJ)
 212  FORMAT(F50.5)
      WRITE(2,225)
 225  FORMAT(/,30X,26H *****       *****       *****/)
      IJ=IJ+1
      IF(IJ.GT.IT) GO TO 501
   20 CONTINUE
  21  CONTINUE
C    ******      ******      ********
  501 WRITE(2,213)
 213  FORMAT(//,40X,18H THE SMALLEST SUM /)
      COMP=3000000.0
      DO 72 MC=1,IT
      IF(SUM(MC).GT.COMP) GO TO 72
      COMP=SUM(MC)
      IP=MC
  72  CONTINUE
      WRITE(2,214) IP,SUM(IP)
 214  FORMAT(I30,F25.5)
      STOP
      END
```

```
                 1.0        46.2617        0.0000
                 1.0        46.2617        0.0002
                 1.0        46.2617        0.0002
                 1.0        46.2617        0.0004
                 1.0        54.1288        0.0002
                 1.0        54.1288        0.0004
                 1.0        65.1572        0.0002
                 1.0        65.1572        0.0004


                 THE TRANSPOSE OF THE MATRIX

   1.000    1.000    1.000    1.000    1.000    1.000    1.000    1.000    1.000    1.000    1.000    1.000
  27.575   31.950   38.451   38.451   46.262   46.262   46.262   46.262   54.129   54.129   65.157   65.157
   0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000


                 MULTIPLICATION OF TWO MATRIXS

        12.00000               560.04653               0.00279
       560.04653             27649.55556               0.13743
         0.00279                 0.13743               0.00000


                    INVERSE OF MATRIX

         1.52518                -0.03053             -73.77131
        -0.03053                 0.00076             -21.74650
       -73.77131               -21.74650         4675695.65613


                 GEOMETRIC RATIO OF OBSERVED CUTTER LIFE

                         51.8555


                 TRANSFORMATIONS OF THE DEPENDENT VARIABLE

                        158.03904
                        152.62564
                        131.20645
                        118.83855
                        136.32610
                        116.63125
                        115.97142
                         89.45869
                         96.00101
                         68.67045
                         75.15892
                         62.84562


                      SECOND PART OF BETA

                       1322.03155
                      57975.05057
                          0.27215


                 ESTIMATE VALUES OF COEFFICIENCIES

                        226.56768
                         -2.06628
                     -65741.88409
```

```
                THE RESIDUALS

                      -8,65775
                       7,59778
                      -0,30549
                       7,57581
                       5,64105
                       1,17780
                       0,51798
                      -5,68556
                      -3,19696
                      -9,99854
                      -1,25119
                       6,76490

       RESIDUALS SUM OF SQUARES

                416,63728

       *****       *****       *****


              ESTIMATE VALUES OF POWERS

         0,80000         4,20000


       THE MATRIX OF INDEPENDENT VARIABLES

          1.0         27.5752         0.0000
          1,0         31,9498         0,0001
          1,0         38.4515         0.0001
          1,0         38.4515         0.0003
          1,0         46.2617         0,0000
          1,0         46.2617         0,0001
          1,0         46.2617         0,0001
          1,0         46.2617         0,0003
          1.0         54,1288         0,0001
          1,0         54,1288         0,0003
          1,0         65.1572         0,0001
          1,0         65.1572         0.0003

       THE TRANSPOSE OF THE MATRIX

 1.000   1.000   1,000   1,000   1,000   1,000   1,000   1,000   1,000   1,000   1,000   1,000
27,575  31,950  38,451  38,451  46,262  46,262  46,262  46,262  54,129  54,129  65,157  65,157
 0,000   0.000   0,000   0,000   0,000   0,000   0,000   0,000   0,000   0,000   0,000   0,000

       MULTIPLICATION OF TWO MATRIXS

      12.00000            560,04653            0,00186
     560.04653          27649,55536            0,09163
       0,00186              0,09163            0,00000

              INVERSE OF MATRIX

       1.52446             -0,03066           -66,54159
      -0.03066              0,00076           -31,45084
     -66,54159            -31,45084       9896955,89148
```

```
TRANSFORMATIONS OF THE DEPENDENT VARIABLE

                 158,03904
                 152,62364
                 131,28645
                 118,83855
                 136,32610
                 116,65125
                 115,97142
                  89,43869
                  96,00101
                  68,87043
                  75,15892
                  62,84582

            SECOND PART OF BETA

                1322,03155
               57975,05057
                   0,41061

ESTIMATE VALUES OF COEFFICIENCIES

                 227,14126
                  -2,06433
              -58953,33894

            THE RESIDUALS

                  -9,04638
                   7,86026
                  -0,05563
                   7,44713
                   5,06266
                   1,41250
                   0,75267
                  -5,82940
                  -2,97754
                 -10,15746
                  -1,05319
                   6,58437

RESIDUALS SUM OF SQUARES

            417,76046

*****       *****       *****


          ESTIMATE VALUES OF POWERS

  0,80000           4,00000


THE MATRIX OF INDEPENDENT VARIABLES

  1,0          27,5752          0,0000
  1,0          31.9498          0,0002
  1,0          38,4513          0,0002
  1,0          38,4513          0,0004
```

```
                        0,36914
                       12,04165

     RESIDUALS SUM OF SQUARES

               592.74297

     *****     *****     *****


               THE SMALLEST SUM

 77                   416,65728
```

```
                    THE RESIDUALS

                         1.87118
                        -0.04770
                        -1.81470
                        -0.23659
                         0.64009
                        -0.74952
                         0.32947
                        -1.68162
                         0.27344
                         1.65539
                        -0.23945

          RESIDUALS SUM OF SQUARES

                    13.65302

          *****     *****     *****


                ESTIMATE VALUES OF POWERS

          -0.20000          5.60000


          THE MATRIX OF INDEPENDENT VARIABLES

           1.0         0.3847        0.0000
           1.0         0.3847        0.0000
           1.0         0.3847        0.0000
           1.0         0.3698        0.0000
           1.0         0.3698        0.0000
           1.0         0.3698        0.0000
           1.0         0.3698        0.0000
           1.0         0.3531        0.0000
           1.0         0.3531        0.0000
           1.0         0.3531        0.0000
           1.0         0.3531        0.0000

          THE TRANSPOSE OF THE MATRIX

1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
0.3847   0.3847   0.3847   0.3698   0.3698   0.3698   0.3698   0.3531   0.3531   0.3531   0.3531
0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000   0.0000

          MULTIPLICATION OF TWO MATRIXS

      11.000000               4.045713                0.000085
       4.045713               1.489716                0.000030
       0.000083               0.000030                0.000000

                INVERSE OF MATRIX

      80.674022            -216.891422            -107808.273121
    -216.891422             585.580850             201691.023125
 -107808.273059          201691.022957         4463814190.936687
```

```
GEOMETRIC RATIO OF OBSERVED CUTTER LIFE

                18,1950

TRANSFORMATIONS OF THE DEPENDENT VARIABLE

                71,75256
                65,40335
                60,62962
                58,42145
                54,86780
                53,47819
                51,55045
                44,27971
                41,80444
                40,17966
                38,28482


          SECOND PART OF BETA

               580,65203
               214,92392
                 0,00417

ESTIMATE VALUES OF COEFFICIENCIES

              -220,95961
               757,52531
           -643871,45654


          THE RESIDUALS

                 1,89646
                -0,08382
                -1,78641
                -0,21486
                 0,60042
                -0,78919
                 0,55421
                -1,66392
                 0,22974
                 1,67610
                -0,21874

RESIDUALS SUM OF SQUARES

          13,62858

*****     *****     *****


          ESTIMATE VALUES OF POWERS

 -0,20000          5,80000


THE MATRIX OF INDEPENDENT VARIABLES
```

```
   GEOMETRIC RATIO OF OBSERVED CUTTER LIFE

                    18,1950

   TRANSFORMATIONS OF THE DEPENDENT VARIABLE

                   71,75256
                   65,40335
                   60,62962
                   58,42145
                   54,86780
                   53,47819
                   51,55045
                   44,27971
                   41,80444
                   40,17966
                   38,28482

              SECOND PART OF BETA

                  580,65203
                31289,23508
                    0,00023

  ESTIMATE VALUES OF COEFFICIENCIES

                  127,04155
                   -1,26423
            -10343948,85546

              THE RESIDUALS

                    2,73910
                    0,27026
                   -1.04993
                   -0,77098
                   -0,44426
                   -1,83387
                   -0,30806
                   -1.14507
                    0,26004
                    2,08880
                    0,19396

  RESIDUALS SUM OF SQUARES

              18,70728

  *****       *****       *****


              THE SMALLEST SUM

23                13,62838
```

APPENDIX II

APPENDIX II

A Calculation of R.S.S. Value using the Walter Milling Cutter Life Results in Down-Cut Milling

The proposed cutter life model was as follows:

$$\dot{T}\ln T = b_o + b_1 V^{\alpha_1} + b_2 h_f^{\alpha_2}$$

For the Walter cutter h_f is taken into account as h_w, Hence;

$$\dot{T}\ln T_w = b_o + b_1 V_w^{\alpha_1} + b_2 h_w^{\alpha_2}$$

The coefficients b_o, b_1 and b_2 are estimated by the method of least squares in the matrix form as;

$$B = (X'X)^{-1}X'y$$

where x is the matrix of independent variables

X' is the transpose of X

$(X'X)^{-1}$ is the inverse of $(X'X)$

y is the vector of cutter life observations,

i.e., $y = \dot{T}.\ln T$

The matrix of independent variables X is formed using the values of V, h_w, α_1 and α_2. For example, if $\alpha_1 = 0.4$, $\alpha_2 = 0.6$, V and h_w are taken from the table (1), and X is written as follows:

$$X = \begin{vmatrix} 1.0 & 5.251 & 0.211 \\ 1.0 & 5.652 & 0.275 \\ 1.0 & 6.201 & 0.275 \\ 1.0 & 6.201 & 0.311 \\ 1.0 & 6.802 & 0.151 \\ 1.0 & 6.802 & 0.275 \\ 1.0 & 6.802 & 0.275 \\ 1.0 & 6.802 & 0.311 \\ 1.0 & 7.357 & 0.275 \\ 1.0 & 7.357 & 0.311 \\ 1.0 & 8.072 & 0.275 \\ 1.0 & 8.072 & 0.311 \end{vmatrix}$$

The inverse of the product of X and X' is obtained from the computer programme as follows:

$$(X'X)^{-1} = \begin{vmatrix} 6.72329 & -0.69750 & -7.04160 \\ -0.69750 & 0.13407 & -0.78002 \\ -7.04160 & -0.78002 & 45.45204 \end{vmatrix}$$

The geometric mean value of observed cutter life values T is calculated as follows:

$$\dot{T} = (T_1 \cdot T_2 \cdot T_3 \quad \ldots\ldots T_n)^{\frac{1}{n}}$$

$$\dot{T} = 31.835$$

$$y = \dot{T} \ln T_W = \begin{vmatrix} 158.039 \\ 152.623 \\ 131.286 \\ 118.838 \\ 136.326 \\ 116.631 \\ 115.971 \\ 89.438 \\ 96.001 \\ 68.870 \\ 75.158 \\ 62.845 \end{vmatrix}$$

Hence the matrix of the independent variables B is obtained as

$$B = \begin{vmatrix} 372.939 \\ -29.286 \\ -236.582 \end{vmatrix}$$

The value of the residual sum of squares (R.S.S.) is calculated to be 730.382 for this example.

Hence the predicted cutter life equation is written;

$$31.382. \ \ln T_w = 372.939 - 29.286 V_w^{0.4} - 236.582 h_w^{0.6}$$

or

$$\ln T_w = 11.714 - 0.920 V_w^{0.4} - 7.432 h_w^{0.6}$$

The 95 percent confidence interval (CI) for the coefficients under the assumption of spherical normality, is given by;

$$CI(b_i) = b_i \pm t_{v;\,\xi/2}\sqrt{(S^2 . d_{ii})}$$

where $t_{v;\,\xi/2}$ is Student's t - distribution with v degree of freedom which is equal to $(n_o - p)$, ξ the level of significance and d_{ii} is the element of i^{th} row and i^{th} column of the inverse of (X'X). The estimate of the error variance S^2 is calculated;

$$S^2 = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n_o - p}$$

where y_i is the i^{th} observed cutter life and $\hat{y}_i$ predicted cutter life, n_o is the number of observations, and p is the number of coefficients.

For this example S^2 is calculated as;

$$S^2 = \frac{730.382/(31.835)^2}{(12 - 3)}$$

$$S^2 = 0.08$$

For the statistical tables at $v = 9$ and $\xi = 0.05$, $t\ ;\ 0.025$, is obtained to be 2.262. Hence the 95% confidence interval for b_o is

$$CI(b_o) = 11.714 \pm (2.262) \sqrt{(0.08)(6.723)}$$

$$= 11.714 \pm 1.659$$

$$CI(b_o) = \begin{cases} 13.373 \\ 10.055 \end{cases}$$

for b_1 is

$$CI(b_1) = -0.920 \pm (2.262) \sqrt{(0.08)(0.134)}$$

$$= -0.920 \pm 0.234$$

$$CI(b_1) = \begin{cases} -1.154 \\ -0.686 \end{cases}$$

for b_2 is

$$CI(b_2) = -7.432 \pm (2.262) \sqrt{(0.08)(45.452)}$$

$$= -7432 \pm 4.313$$

$$CI(b_2) = \begin{cases} -11.745 \\ -3.119 \end{cases}$$

Two more cutter life equations can be written using lower and upper limits of coefficients obtained as follows;

$$\ln T_w = 10.55 - 1.154 V_w^{0.4} - 11.745 h_w^{0.6}$$

and

$$\ln T_w = 13.373 - 0.686 V_w^{0.4} - 3.119 h_w^{0.6}$$

APPENDIX III

DEPARTMENT

C | Statement Number | FORTRAN STATEMENT

1 2 5 6 7 10 15 20 25 30 35 40 45 50 55 60 65 70

```
JØB▽:EPP8057,REGWAL,JD(JT▽100,MZ▽20K)
UASTATSXDS3▽▽PAGE,LINES▽1000
WALLIFLP
ØBSERVATIØN▽MATRIX       MATRX1
CØL▽NAMES                MATRX1
▽▽VARILVVARECTVASQLVVASQLEVAMLVELNCULI
MATRIX                   MATRX1
  RØW001  4.146  -2.590  17.189   6.708  -10.738   4.964
  RØW002  4.330  -2.154  18.749   4.640   -9.327   4.794
  RØW003  4.562  -2.154  20.812   4.640   -9.827   4.124
  RØW004  4.562  -1.945  20.812   3.783   -8.873   3.733
  RØW005  4.793  -3.147  22.973   9.904  -15.084   4.282
  RØW006  4.793  -2.154  22.973   4.640  -10.324   3.664
  RØW007  4.793  -2.154  22.973   4.640  -10.324   3.643
  RØW008  4.793  -1.945  22.973   3.783   -9.322   2.809
  RØW009  4.989  -2.154  24.890   4.640  -10.746   3.016
  RØW010  4.989  -1.945  24.890   3.783   -9.704   2.163
  RØW011  5.221  -2.154  27.259   4.640  -11.246   2.361
  RØW012  5.221  -1.945  27.259   3.783  -10.155   1.974
END OF DATA
CRØSS PRODUCT            MATRX1
CØVARIANCE               MATRX1
CØRRELATIØN              MATRX1
```

CCF

DEPARTMENT

C | Statement Number | FORTRAN STATEMENT

```
PRINT OBSERVATIONS        MATRX1  LP
PRINT MEANS               MATRX1  LP
PRINT MEANS               MATRX1  LP   S
PRINT CØRRELATION         MATRX1  LP
REGRESSIØN ANALYSIS       MATRX1        CØVA
DEPENDENT VARIABLE        LNCULI
INDEPENDENT VARIABLES AT SIG LEVEL  99.00
  VARILVVARECTVASQLVVASQLEVAMLVE
PRINT REGRESSION LP
DEPENDENT VARIABLE        LNCULI
INDEPENDENT VARIABLES AT SIG LEVEL  99.00
  VARILVVARECT
PRINT REGRESSION LP
GETØFF
****
```

CC/F

```
                    13/47/57    22/07/76     ICL  1900 STATISTICAL ANALYSIS     XDS3/22
REGRESSION ANALYSIS      COVA     MATRX1    CUT OFF PARAMETER  .100000E- 5
DEPENDENT VARIABLE     LNCULI       DEGREES OF FREEDOM                6
INDEPENDENT VARIABLES AT SIGNIFICANT LEVEL       99.00 %
  VARILV  VARECT  VASQLV  VASQLE  VAMLVE
   VARIABLES      IN THE REGRESSION SET

 VAR      REGRESSION        STANDARD        CONFIDENCE   T STAT  PART     MULTIPLE           E S S
 NAME       COEFF            ERROR           INTERVAL                CORR  CORRELATION
VARILV -    12.9947108     .101370E  2                    1.28  -0.46  0.987           .286528E  0
VARECT       6.8463338     .642788E  1                    1.07   0.40  0.988           .267452E  0
VASQLV       0.3467439     .840642E  0                    0.41   0.17  0.989           .231303E  0
VASQLE -     1.6002637     .576856E  0                    2.77  -0.75  0.976           .513417E  0
VAMLVE -     3.3558364     .120615E  1                    2.78  -0.75  0.976           .514770E  0
   VARIABLES NOT IN THE REGRESSION SET
 VAR
 NAME                                                  T STAT  PART     MULTIPLE           E S S
                                                               CORR  CORRELATION
E.S.S.            .224925E  0
RESIDUAL ERROR   .193617E  0
MULT CORR         0.990
INTERCEPT TERM           45.3913390
```

APPENDIX IV

NAME

DEPARTMENT

Pa

FORTRAN STATEMENT

```
JOB▽:EPP8057, REGSAN, JD(JT▽100, MZ▽30K)
UASTATSXDS3▽▽PAGE, LINES▽1000
SANLIFLP
OBSERVATION MATRIX        MATRIX
COL NAMES                 MATRIX
  VARILVVARECTVASQLV VASQLEVAMLVELNCULI
MATRIX                    MATRIX
  ROW001 4.777  -2.488  22.819  6.190  -11.885  3.944
  ROW002 4.777  -2.103  22.819  4.422  -10.046  3.595
  ROW003 4.777  -2.017  22.819  4.068   -9.635  3.332
  ROW004 4.973  -2.488  24.730  6.190  -12.372  3.211
  ROW005 4.973  -2.103  24.730  4.422  -10.458  3.016
  ROW006 4.973  -2.103  24.730  4.422  -10.458  2.939
  ROW007 4.973  -2.017  24.730  4.068  -10.030  2.833
  ROW008 5.205  -2.488  27.092  6.190  -12.950  2.434
  ROW009 5.205  -2.103  27.092  4.422  -10.946  2.298
  ROW010 5.205  -2.017  27.092  4.068  -10.498  2.208
  ROW011 5.205  -2.017  27.092  4.068  -10.498  2.104
END OF DATA
CROSS PRODUCT             MATRIX
COVARIANCE                MATRIX
CORRELATION               MATRIX
PRINT OBSERVATIONS        MATRIX  LP
```

CCF

NAME

DEPARTMENT

FORTRAN STATEMENT

```
C Statement
  Number
1 2   5 6 7  10   15   20   25   30   35   40   45   50   55   60   65   70
PRINT MEANS               MATRIX  LP
PRINT MEANS               MATRIX  LP    S
PRINT CØRRELATIØN         MATRIX  LP
REGRESSIØN ANALYSIS       MATRIX         CØVA
DEPENDENT VARIABLE        LNCULI
INDEPENDENT VARIABLES AT SIG LEVEL  99.00
  VARILVVARECTVASQLVVASQLEVAMLVE
PRINT REGRESSIØN LP
DEPENDENT VARIABLE        LNCULI
INDEPENDENT VARIABLES AT SIG LEVEL 99.00
  VARILVVARECT
PRINT REGRESSIØN LP
GETØFF
****
```

```
                    16/42/35    11/08/76     ICL  1900 STATISTICAL ANALYSIS    XDS3/25

 REGRESSION ANALYSIS     COVA   MATRIX    CUT OFF PARAMETER  .100000E- 5

 DEPENDENT VARIABLE    LNCULI      DEGREES OF FREEDOM               5

 INDEPENDENT VARIABLES AT SIGNIFICANT LEVEL      99,00 %

   VARILV  VARECT  VASQLV  VASQLE  VAMLVE

    VARIABLES     IN THE REGRESSION SET


  VAR      REGRESSION        STANDARD       CONFIDENCE   T STAT  PART    MULTIPLE         E S S
  NAME       COEFF            ERROR          INTERVAL            CORR  CORRELATION

 VARILV     62.4403845    .491271E  2                     1,27   0.49  0.907          .773437E  0

 VARECT     19.9328396    .361282E  2                     0,55   0.24  0.926          .620159E  0

 VASQLV -    6.3865373    .483833E  1                     1,32  -0.51  0.905          .788278E  0

 VASQLE      5.4365110    .693009E  1                     0,78   0.33  0.921          .656520E  0

 VAMLVE      0.8572893    .303654E  1                     0,28   0.13  0.929          .593889E  0

 E.S.S.            .584571E  0

 RESIDUAL ERROR  .341927E  0

 MULT CORR         0.930

 INTERCEPT TERM      -  122.5965160
```

APPENDIX V

```
DATA


     X[1]          Y

 ← 0.00          0.00
  0.000000     0.000000
 ← 36.82          2.83
  36.82000     2.830000
 ← 43.31          3.55
  43.31000     3.550000
 ← 50.10          4.80
  50.10000     4.800000
 ← 52.18          3.93
  52.18000     3.930000
 ← 58.18          4.07
  58.18000     4.070000
 ← 58.25          4.10
  58.25000     4.100000
 ← 63.40          4.70
  63.40000     4.700000
 ← 71.03          5.55
  71.03000     5.550000
 ← 80.07          6.33
  80.07000     6.330000
 ← 104.34         7.70
  104.3400     7.700000




INDEPENDENT VARIABLE X1


XBAR          56.15273

YBAR          4.323636

VARIANCE      0.151904


LINEAR REGRESSION OF Y ON X1

     Y =  0.177894  +    0.0738 X1

CORRELATION COEFFICIENT  R=  0.982


95% CONFIDENCE LIMITS:

  INTERCEPT  -0.473916      TO    0.829703

    SLOPE      0.0632       TO      0.0844

      R         0.931       TO      0.996

← -1
```

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Number of Tests	Cutting speed V_W (m/min)	Equivalent chip thickness h_W (mm)	Cutter Life T (mins)
1	63.19	0.075	143.2
2	75.96	0.116	120.8
3	95.75	0.116	61.8
4	95.75	0.143	41.8
5	120.65	0.043	72.4
6	120.65	0.116	39.0
7	120.65	0.116	38.2
8	120.65	0.143	16.6
9	146.82	0.116	20.4
10	146.82	0.143	8.7
11	185.12	0.116	10.6
12	185.12	0.143	7.2

Table 1.

Cutter life Test Results in Down-Cut Milling

Materials : Tool Steel
(B.H.N. 238)

Cutter: Walter Cutter

Number of Tests	Cutting speed V_s (m/min)	Equivalent Chip Thickness h_s (mm)	Cutter Life T (mins)
1	118.75	0.083	51.6
2	118.75	0.122	36.4
3	118.75	0.133	28.4
4	144.51	0.083	24.8
5	144.51	0.122	20.8
6	144.51	0.122	18.9
7	144.51	0.133	17.0
8	182.21	0.083	11.4
9	182.21	0.122	9.95
10	182.21	0.133	9.1
11	182.21	0.133	8.2

Table 2.

Cutter Life Test Results in Down-cut Milling.

Material : Tool Steel (B.H.N.238)

Cutter : the Sandvik Cutter

Number of Tests	Cutting speed V_s (m/min)	Equivalent Chip Thickness h_s (mm)	Cutter Life T (mins)
1	118.75	0.083	Two edges were chipped at the first pass
2	118.75	0.122	Three edges were chipped at the first pass
3	118.75	0.133	Three edges were chipped after 0.328 mm flank wear.
4	144.51	0.083	Two edges were chipped at the first pass
5	144.51	0.122	Two edges were chipped after 0.320 mm flank wear.
6	144.51	0.133	20.1
7	182.21	0.083	12.6
8	182.21	0.122	10.9
9	182.21	0.133	11.49
10	182.21	0.133	11.17
11	213.62	0.083	8.1
12	213.62	0.122	7.91
13	213.62	0.133	5.74

Table 3.

Cutter Life Tests Results in Up-Cut Milling

Material : Tool Steel
(B.H.N. 197)
Cutter : the Sandvik Cutter

Number of Tests	Cutting speed V_w (m/min)	Equivalent Chip Thickness h_w (nm)	Cutter Life T (mins)
1	120.65	0.091	Four edges were chipped at the first pass
2	120.65	0.127	Two edges were chipped after the 5 mins cutting
3	120.65	0.143	Two edges were chipped at the second pass.
4	146.82	0.091	Three edges were chipped at the first pass.
5	146.82	0.127	Two edges were chipped at the first pass.
6	146.12	0.143	Five edges were chipped at the first pass.
7	185.12	0.091	Two edges were chipped at the second pass.
8	185.12	0.127	9.48
9	185.12	0.143	Three edges were chipped at the second pass.

Table 4.

Cutter Life Test Results in Up-Cut Milling

Material : Tool Steel
(B.H.N.197)
Cutter : the Walter Cutter

Test No.	Metal Removal Rate (in cm^3/min)	Power required at the cutter in H.P.
5	17.25	1.73
1	22.90	1.83
2	29.03	2.20
7	30.38	2.30
3	32.14	2.40
8	50.10	3.50
4	52.84	3.60
9	56.05	4.37
10	61.18	4.60
6	72.81	5.50
12	77.10	5.80
11	87.49	6.70

Table 5

Power Required at the Walter Cutter in Down-cut Milling

Material : Tool Steel
(B.H.N. 238)

Test No.	Metal Removal Rate in cm^3/min	Power Required at the cutter in H.P.
1	36.83	2.83
4	43.31	3.55
8	50.10	4.80
3	52.18	3.93
2	58.18	4.07
5	58.25	4.10
7	63.40	4.70
6	71.03	5.55
10 and 11	80.07	6.33
9	104.34	7.70

Table 6

Power Required at the Sandvik Cutter in Down-Cut Milling

Material : Tool Steel
(B.H.N. 238)

Test No.	Metal Removal Rate in cm^3/min	Power Required at the cutter in H.P.
7	52.54	3.5
6	66.95	4.0
11	73.40	5.97
9 and 10	85.88	6.30
13	95.67	6.50
12	97.51	6.57
8	104.26	7.37

Table 7

Power required at the Sandvik Cutter in Up-cut Milling

Material : Tool Steel
(B.H.N. 197)

Test No.	Cutting speed V_w (in m/min)	Feed per tooth f (in mm/tooth)	Surface Finish (C.L.A.) (in μm)
1	63.19	0.224	2.5
2	75.96	0.235	0.64
3	95.75	0.233	0.44
4	95.75	0.286	0.58
5	120.75	0.148	0.44
6	120.75	0.227	0.49
7	120.75	0.285	0.44
8	120.75	0.286	0.36
9	146.82	0.235	0.51
10	146.82	0.297	0.54
11	185.82	0.235	0.44
12	185.82	0.292	0.48

Table 8

Surface Finish (C.L.A. index) in Down-cut Milling

Material : Tool Steel
(B.H.N. 238)
Cutter : the Walter
Cutter

Test No.	Cutting speed V_s (in m/min)	Feed per tooth (in mm/tooth)	Surface Finish (C.L.A.) (in μm)
1	118.75	0.185	0.46
2	118.75	0.226	0.33
3	118.75	0.286	0.27
4	144.75	0.185	0.31
5	144.75	0.297	0.27
6	144.75	0.235	0.30
7	144.75	0.297	0.35
8	182.21	0.186	0.46
9	182.21	0.235	0.20
10	182.21	0.292	0.20
11	182.21	0.292	0.18

Table9

Surface Finish (C.L.A. index) in Down-cut Milling.

Material : Tool Steel (B.H.N. 238)
Cutter : the Sandvik Cutter

Test No.	Cutting speed V_s (in m/min)	Feed per tooth (in mm/tooth)	Surface Finish (C.L.A.) (in μm)
6	144.51	0.286	0.88
7	182.21	0.186	0.18
8	182.21	0.235	0.85
9	182.21	0.292	0.23
10	182.21	0.292	0.25
11	213.62	0.159	0.47
12	213.62	0.249	0.28
13	213.62	0.306	0.45

Table 10

Surface Finish (C.L.A.index) in Up-cut Milling

Material : Tool Steel (B.H.N.197)
Cutter : The Sandvik Cutter

Test No.	Cutting speed V_w (in m/min)	Maximum Area = d.f s_{max} (in mm^2)	P.T.P.VIB. AMP. in Axial direction (in μ m)	P.T.P.VIB.AMP in Feed direction (in μ m)
1	63.19	0.569	9	30
2	75.96	0.357	7	27
3	95.75	0.294	7	24
4	95.75	0.543	9	31
5	120.65	0.225	8	25
6	120.65	0.633	14	42
7	120.65	0.219	5	19
8	120.65	0.363	8	24
9	146.82	0.357	7	25
10	146.82	0.377	8	23
11	185.82	0.477	14	30
12	185.82	0.371	10	22

Table 11

Amplitudes of Vibrations in Axial and Feed directions in Down-Cut Milling

Material: Tool Steel
(B.H.N. 238)
Cutter : the Walter
Cutter

Test No.	Cutting speed V_s (in m/min)	Maximum Area = d.f s_{max} (in mm^2)	P.T.P.VlB.AMP in Axial direction (in μm)	P.T.P.VlB.AMP in Feed direction (in μm)
1	118.75	0.305	9	27
2	118.75	0.431	11	34
3	118.75	0.363	10	25
4	144.51	0.281	7	17
5	144.51	0.377	6	21
6	144.51	0.448	6	23
7	144.51	0.377	6	20
8	182.21	0.236	7	14
9	182.21	0.597	10	35
10	182.21	0.371	8	20
11	182.21	0.371	8	20

Table 12

Amplitudes of Vibrations in Axial and Feed directions in Down-cut Milling

Material : Tool Steel
(B.H.N. 238)
Cutter : the Sandvik
Cutter.

Test No.	Cutting speed V_s (in m/min)	Maximum Area = d.f. s_{max} (in mm^2)	P.T.P.VIB.AMP in Axial Direction (in μm)	P.T.P.VIB.AMP. in Feed Direction (in μm)
6	144.51	0.406	9	30
7	182.21	0.262	4	14
8	182.21	0.597	7	22
9	182.21	0.429	7	20
10	182.21	0.429	7	20
11	213.62	0.323	5	18
12	213.62	0.411	6	16
13	213.62	0.407	5	20

Table 13

Amplitudes of Vibrations in Axial and Feed directions in Up-cut Milling

Material : Tool Steel
(B.H.N. 197)
Cutter : the Sandvik
cutter.

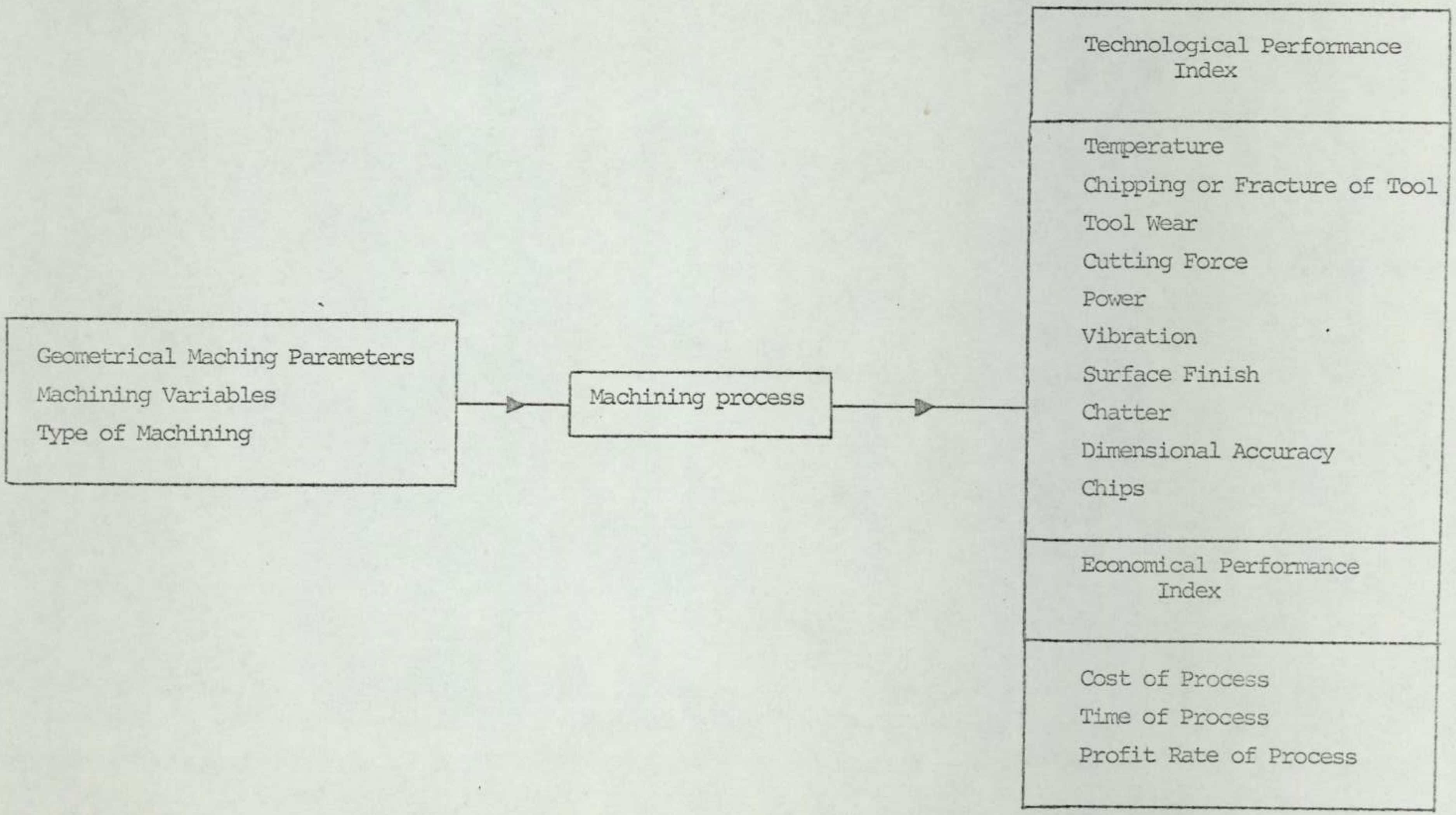


Fig. 1. Responses of Machining Process

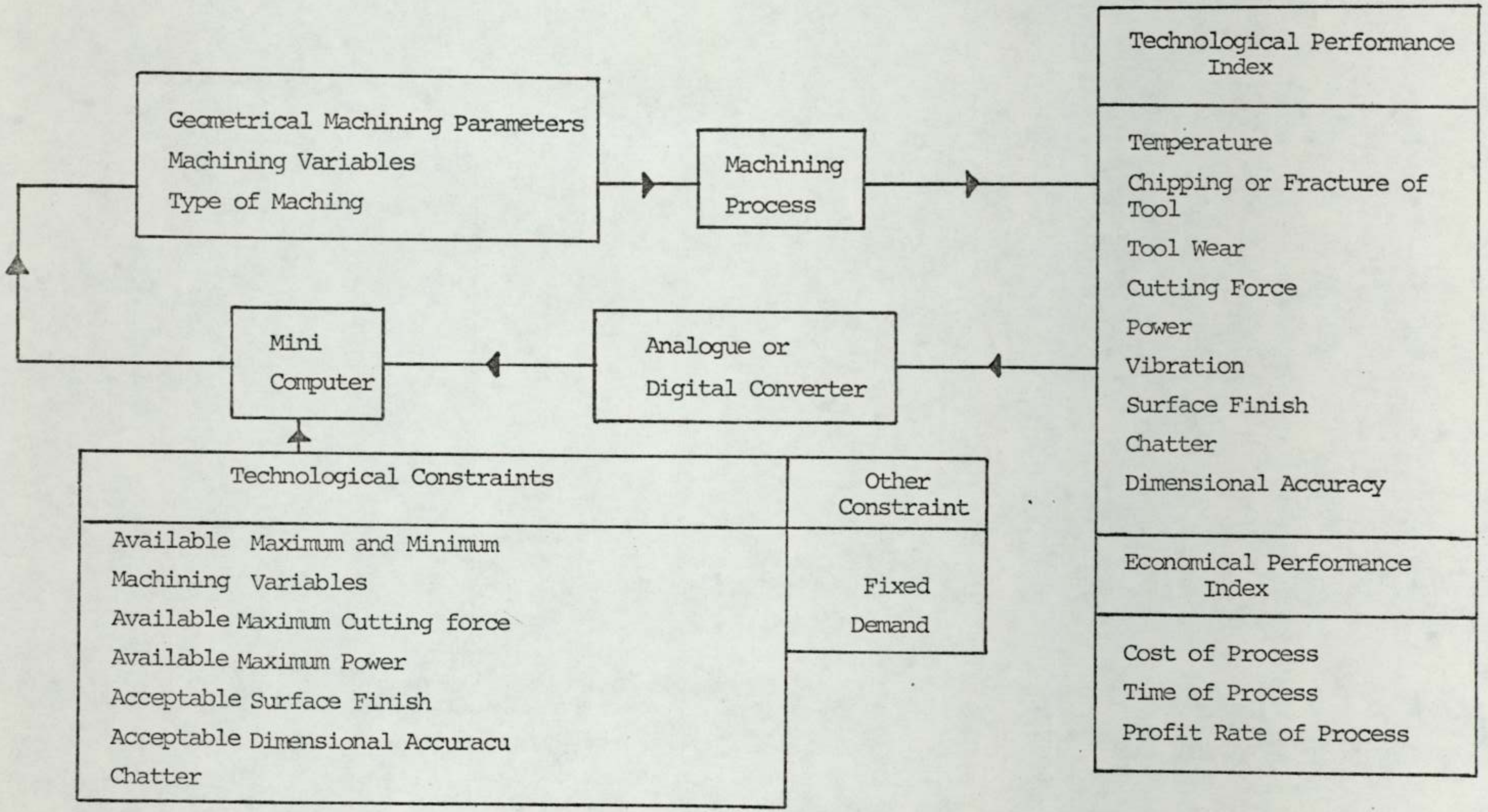


Figure 2. Controlled Machining Process

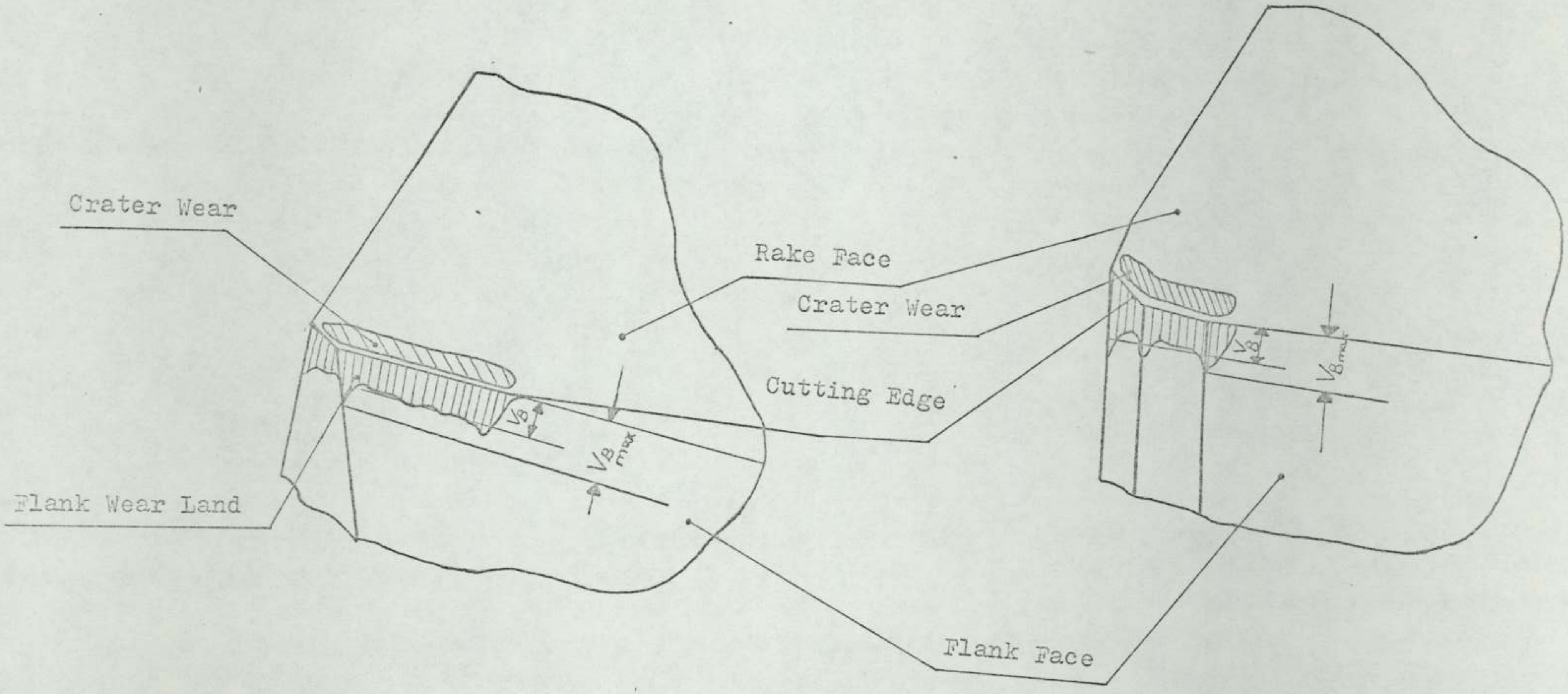


Fig.3 General Configuation of Wear of Cutting Edge

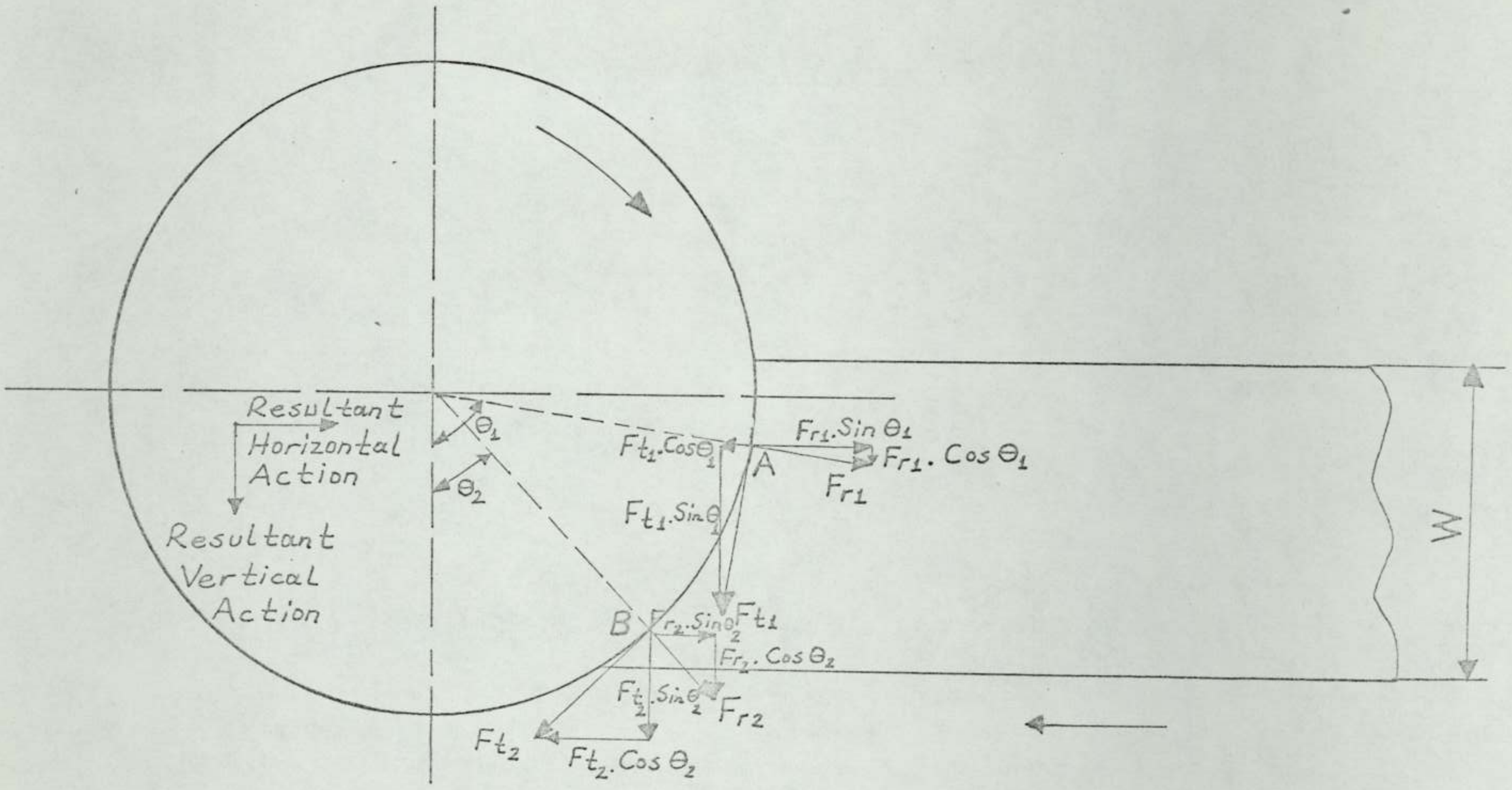


Fig.4 Resolution Diagram of Forces in Down-Cut Face Milling

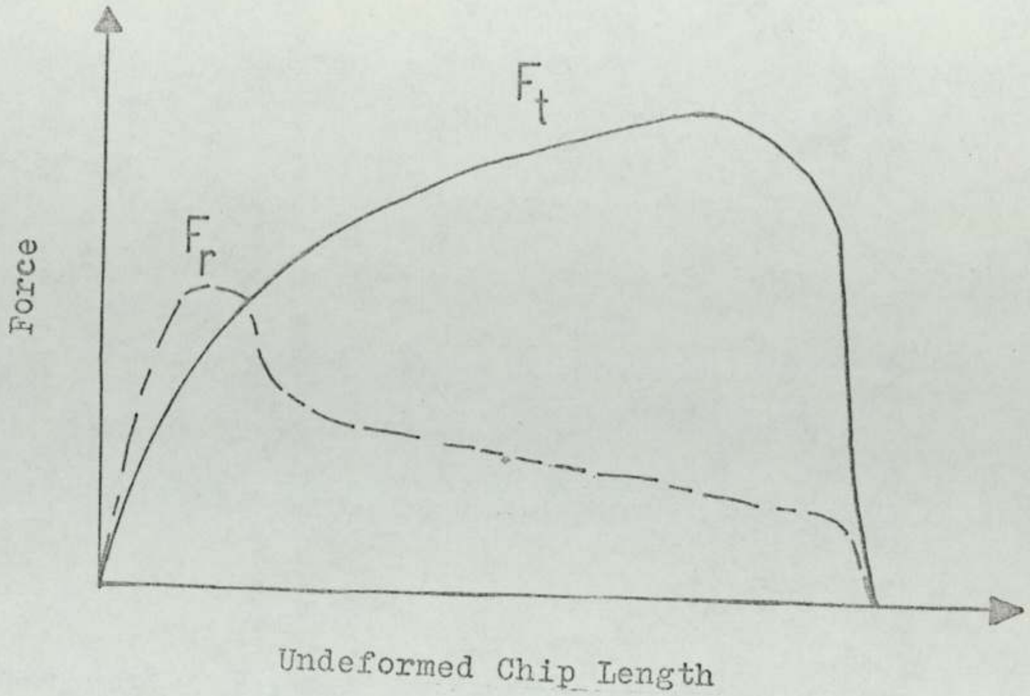


Fig.5 Relationship between Forces Acting on Cutter Tooth and Undeformed Chip Thickness in Up-Cut Peripheral Milling

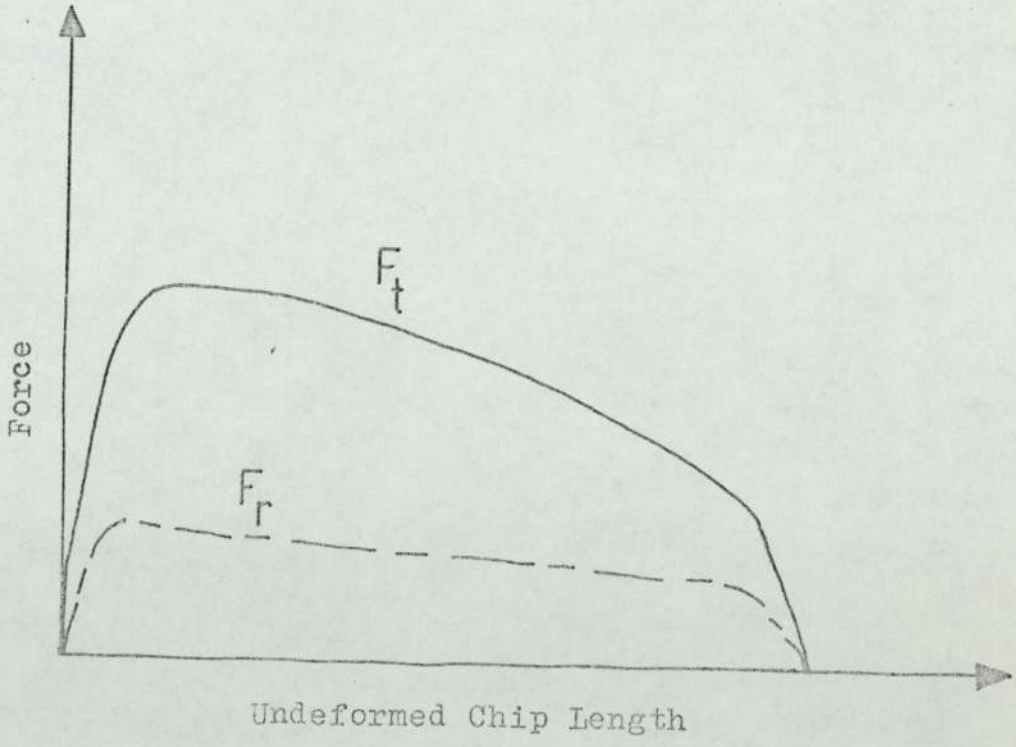
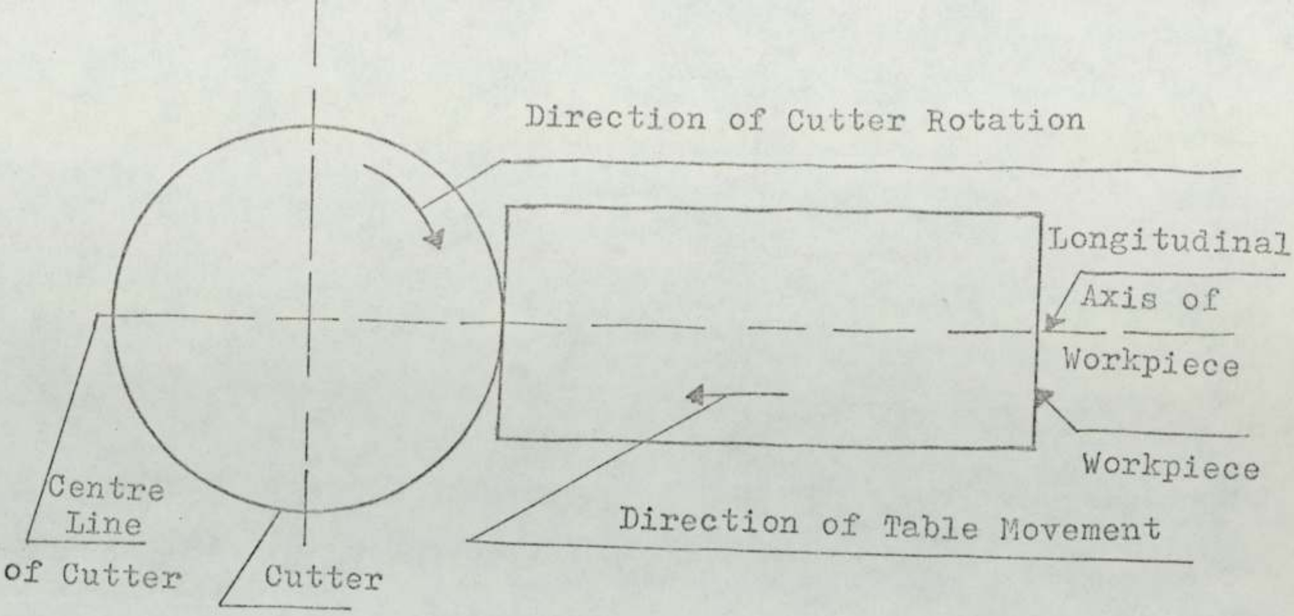
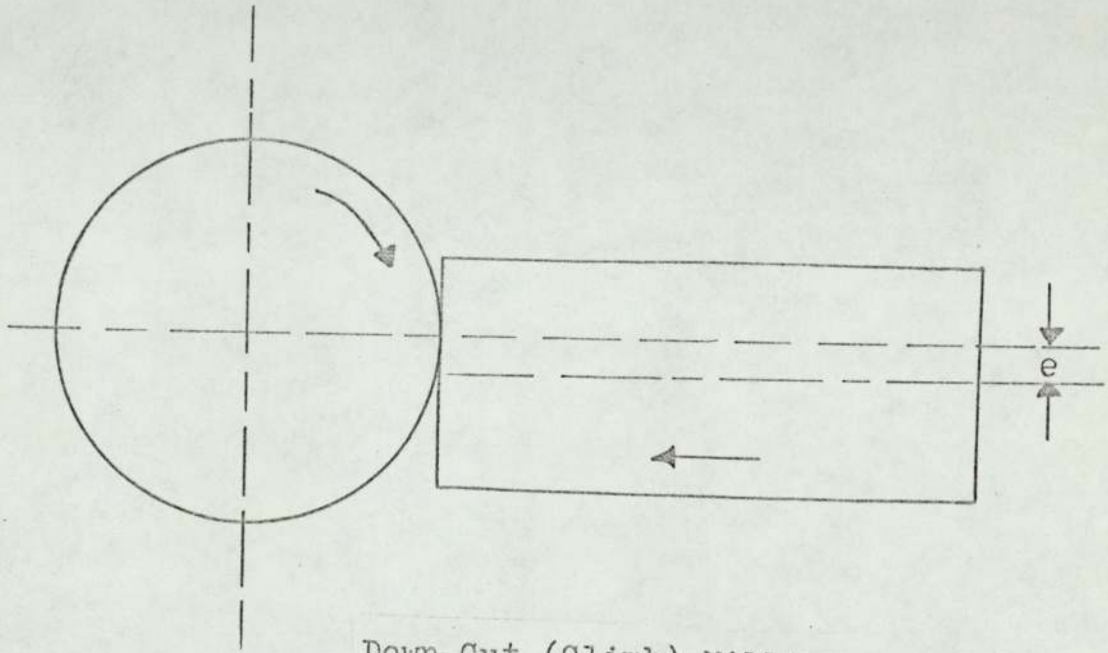


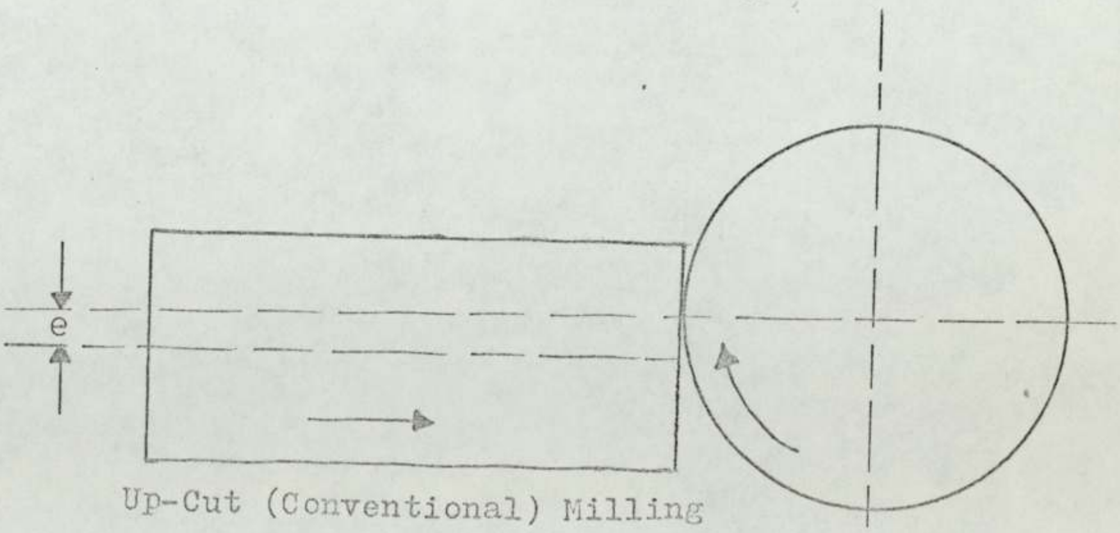
Fig.6 Relationship between Forces Acting on Cutter Tooth and Undeformed Chip Thickness in Down-Cut Peripheral Milling



Central Milling

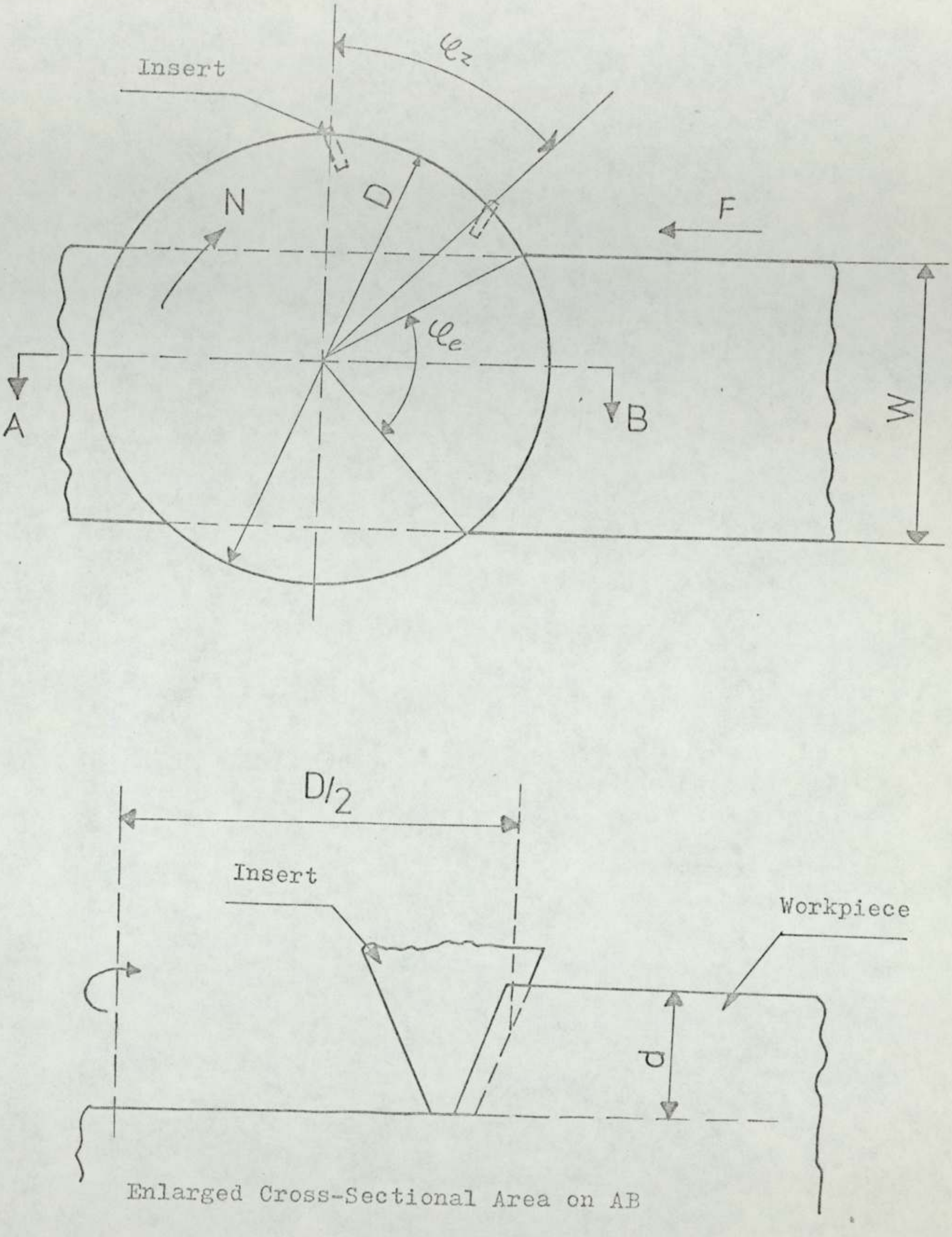


Down-Cut (Climb) Milling



Up-Cut (Conventional) Milling

Fig.7 Three Types of Face Milling



Enlarged Cross-Sectional Area on AB

Fig.8 One Typical Down-Cut Face Milling

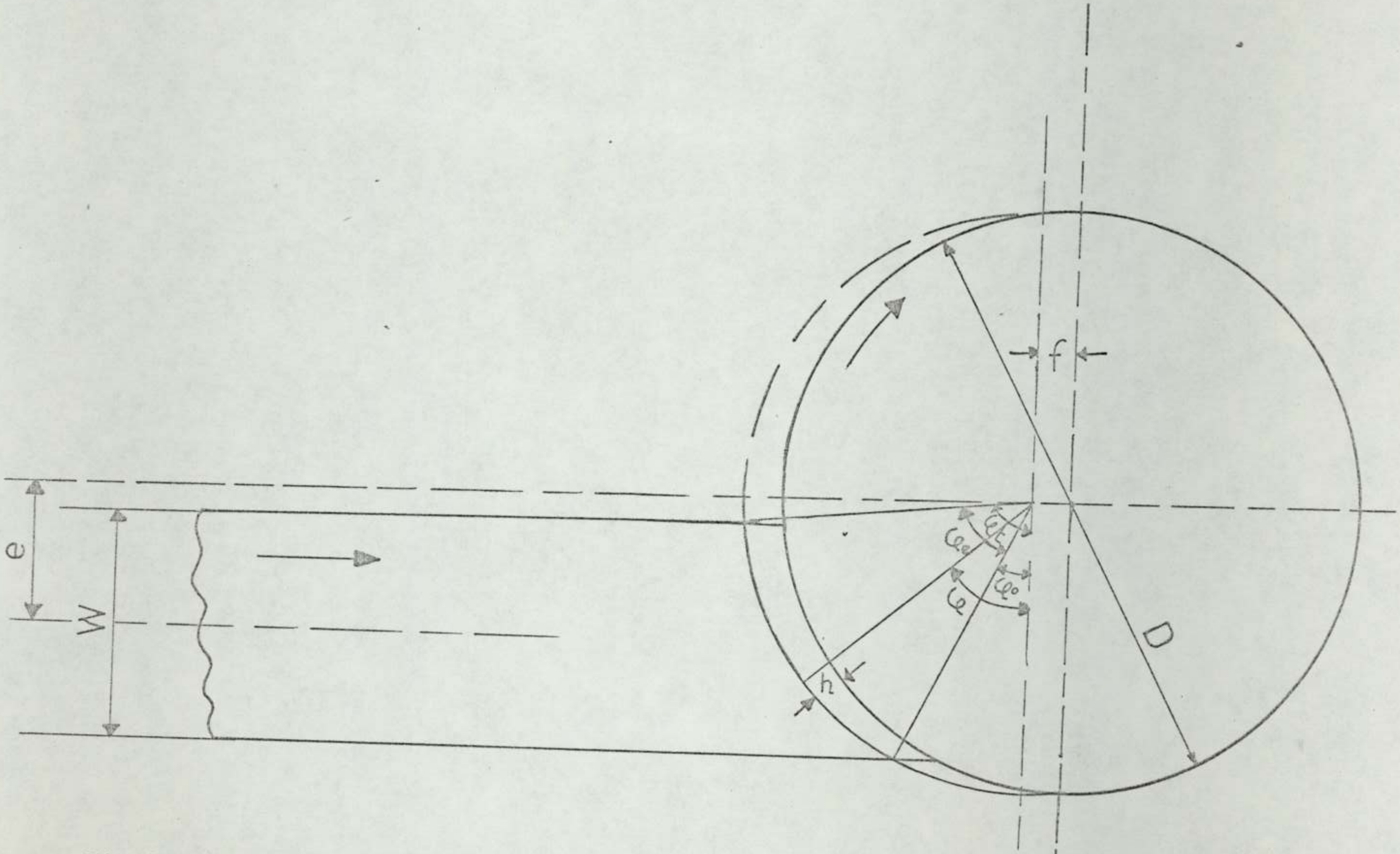


Fig.9 The Variation of Chip Thickness in Up-Cut Face Milling

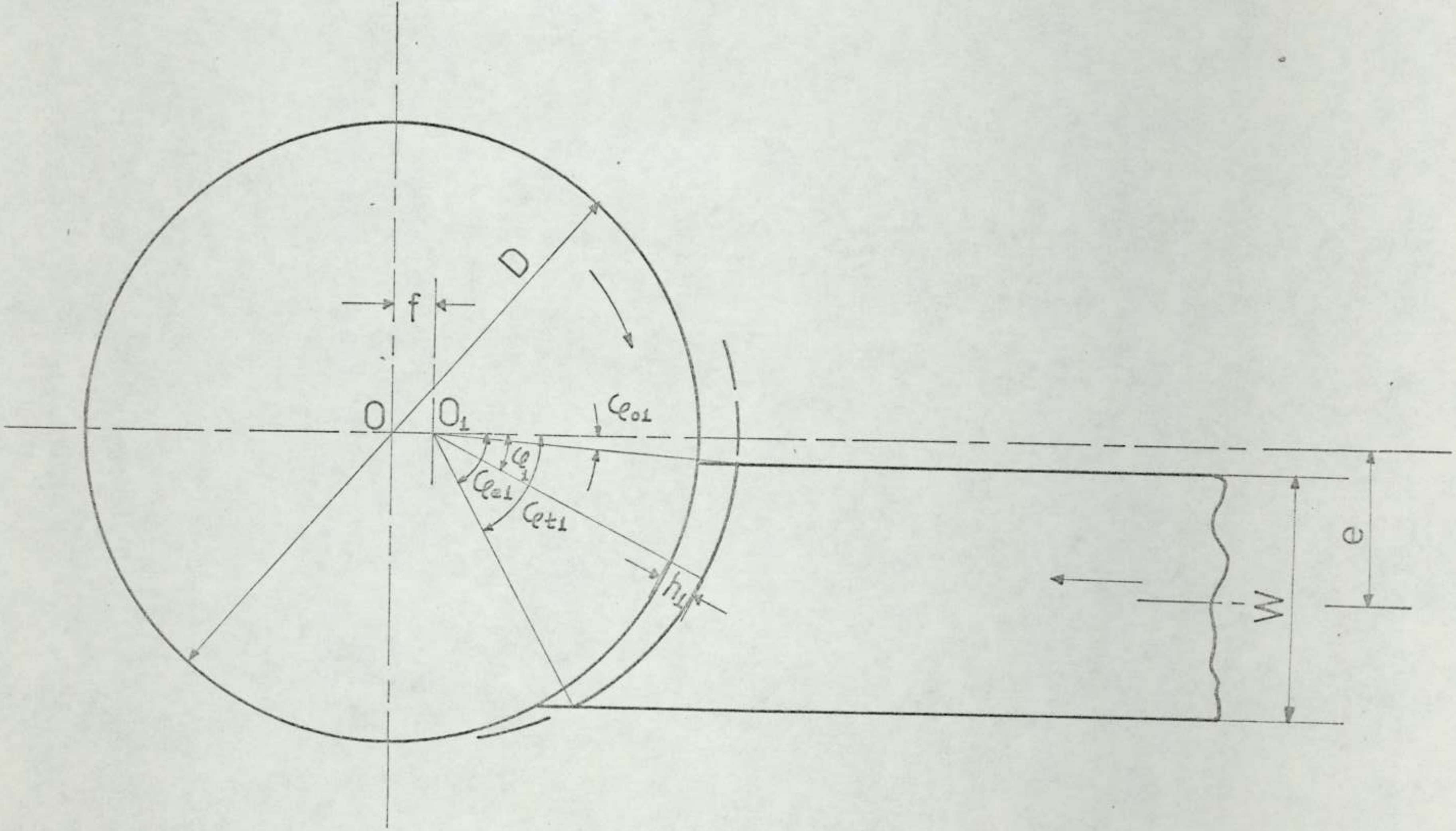


Fig. 10 The Variation of Chip Thickness in Down-Cut Milling

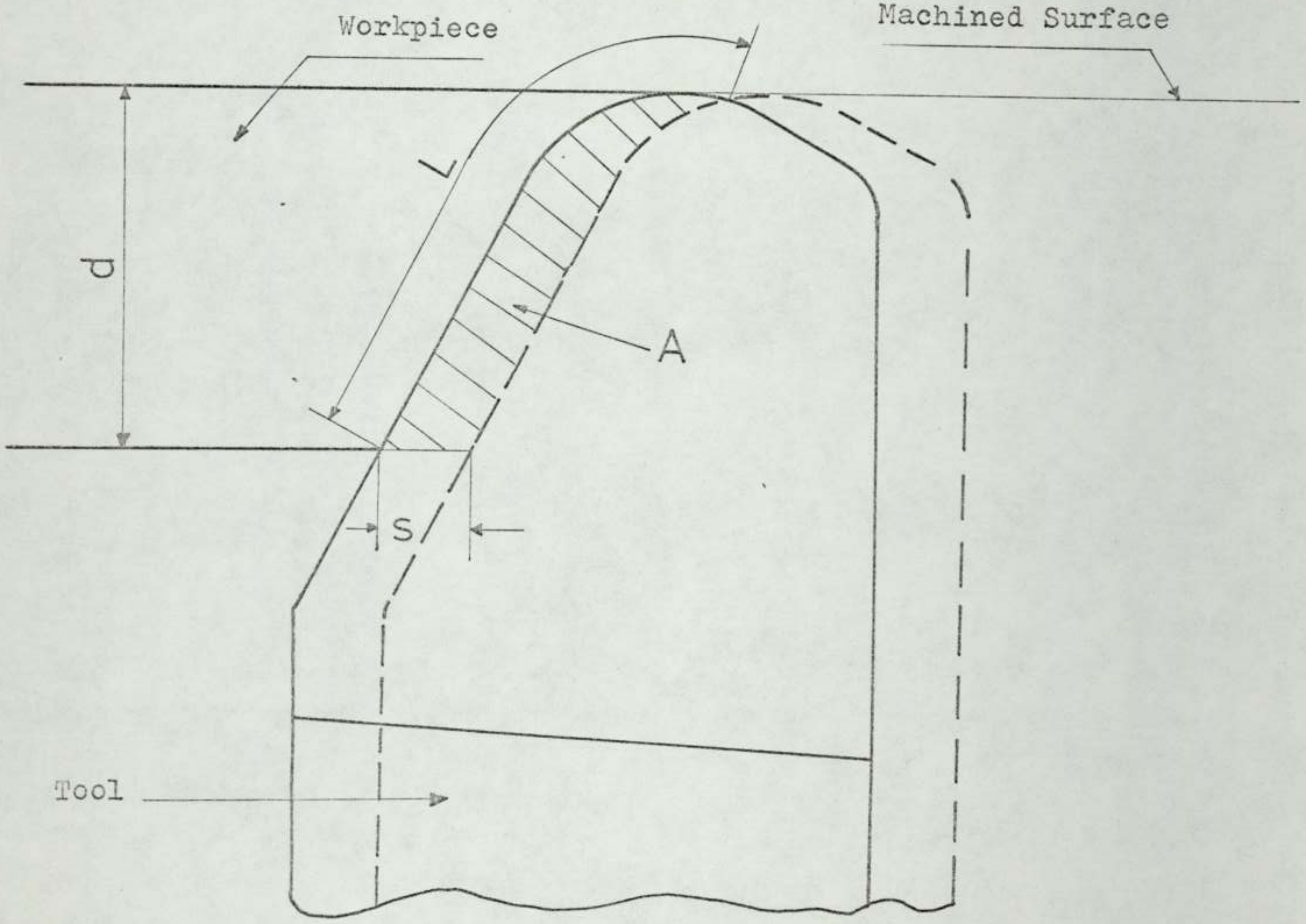


Fig. 11 General Configuration of Area Cut A and length engaged with workpiece L

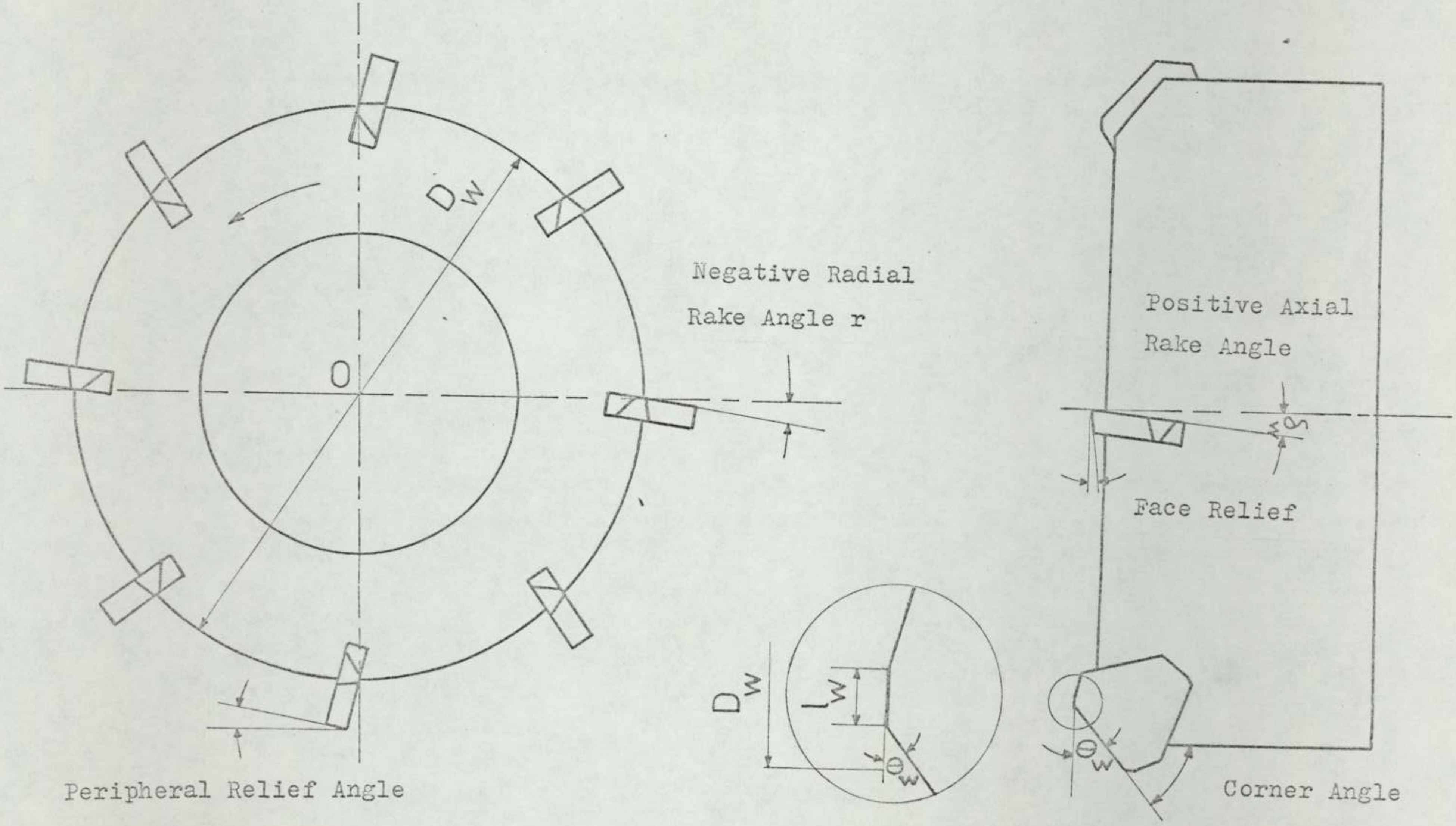


Fig. 12 Wendelnovex F244 Walter Milling Cutter with Indexable Rigth Hand P25 inserts

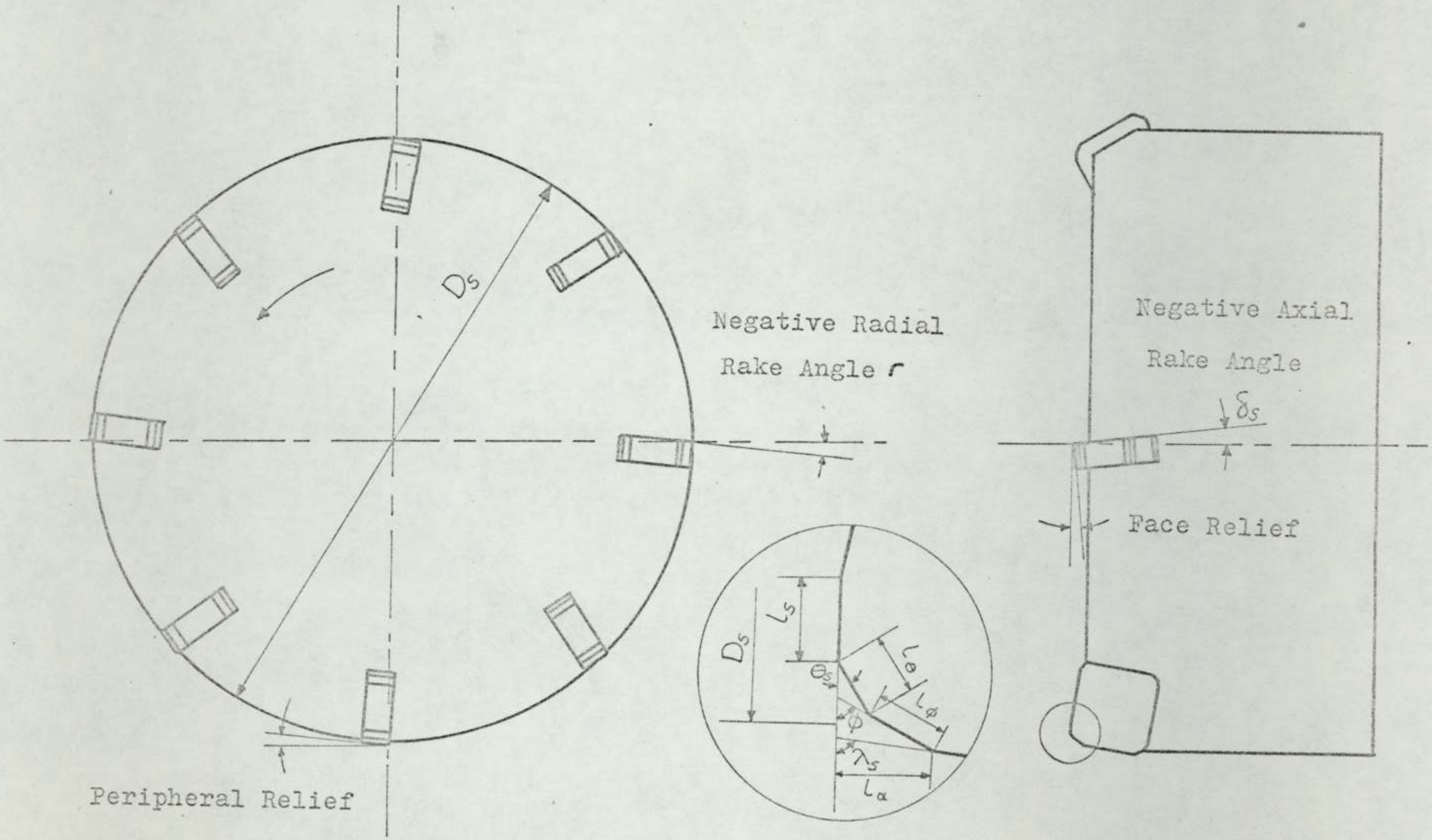


Fig.13 T-Max 265.1 Sandvik Milling Cutter with Indexable Right Hand P25 Inserts

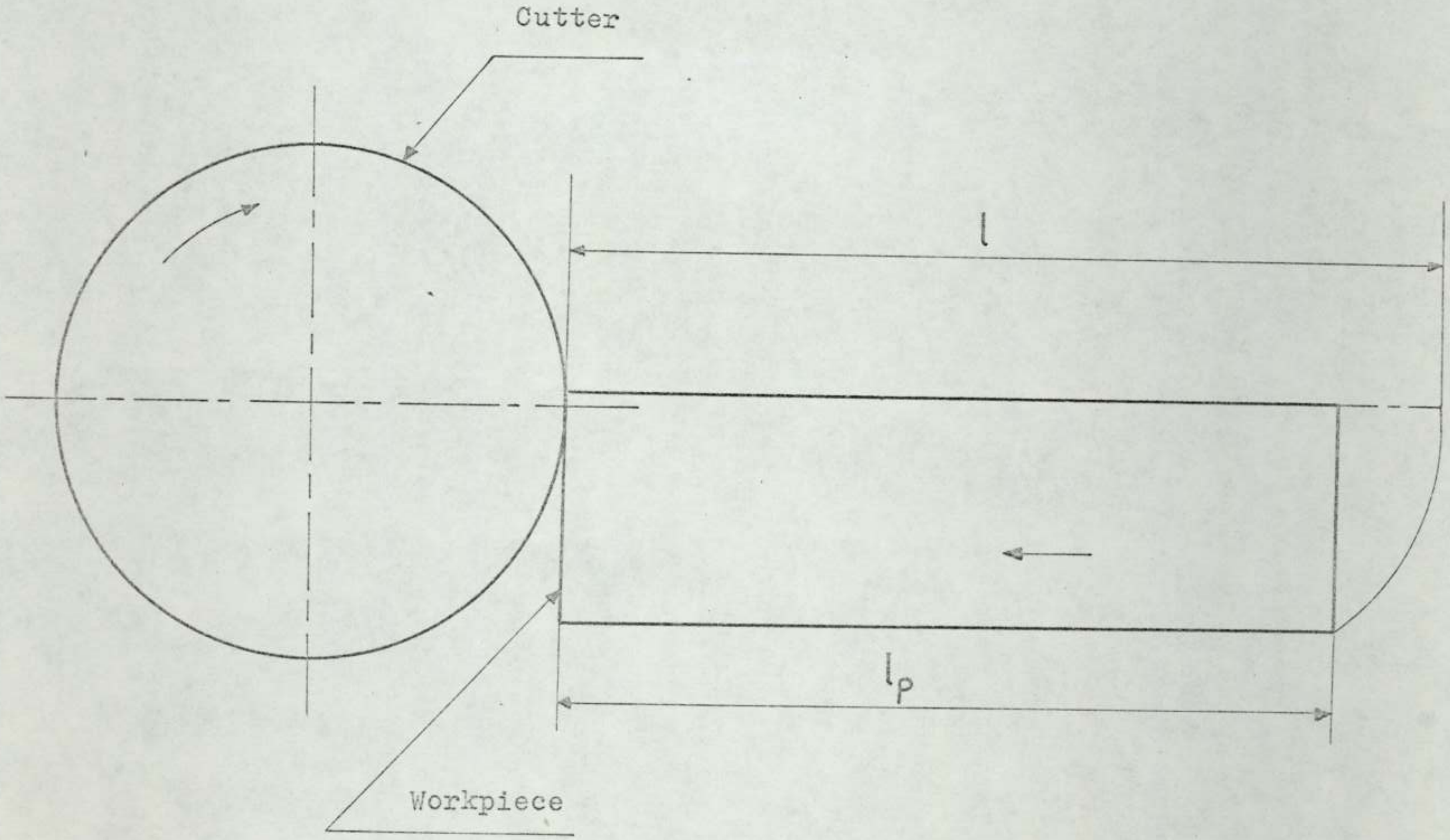


Fig.14 The Length l to Cut the Given Material

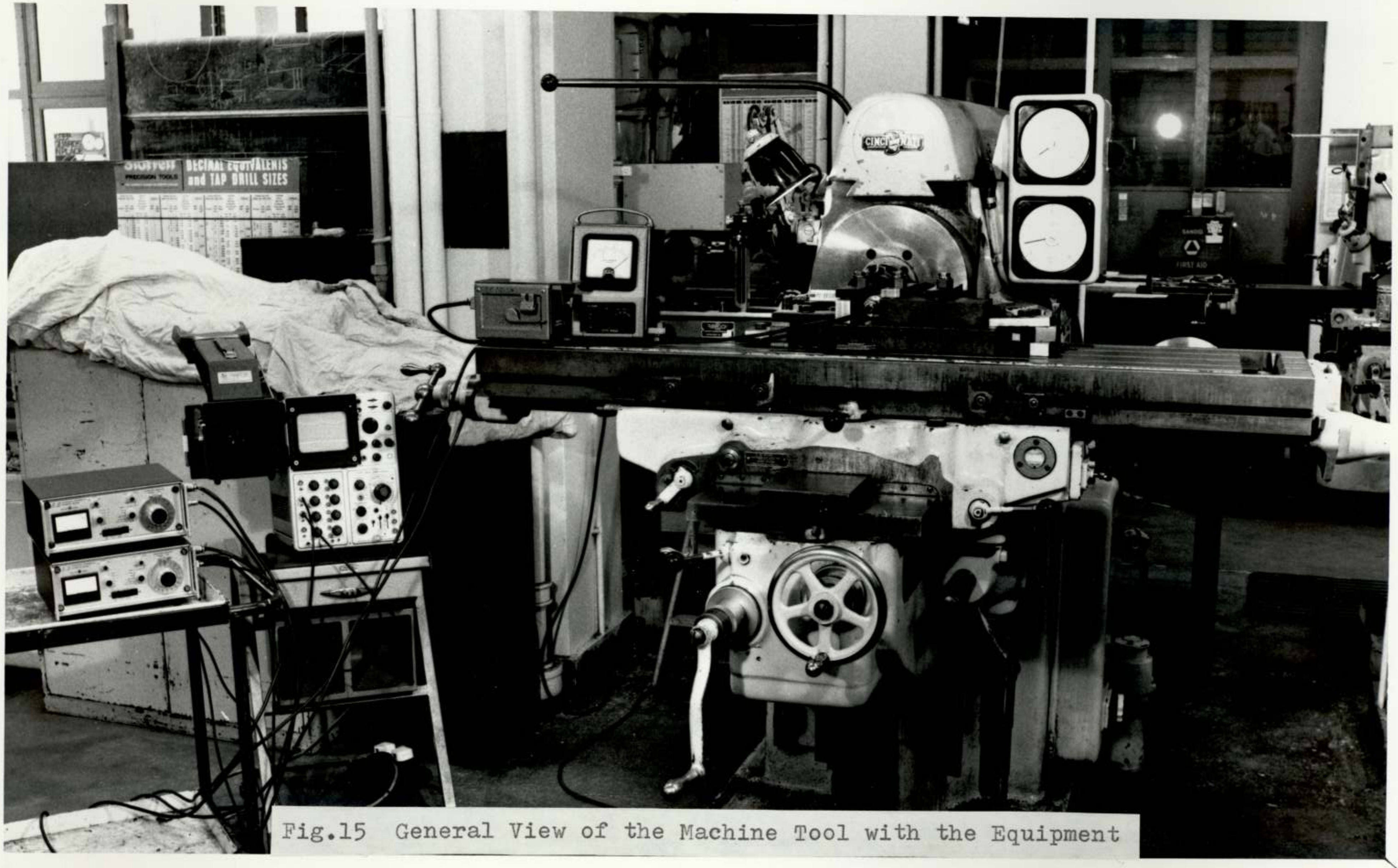


Fig.15 General View of the Machine Tool with the Equipment

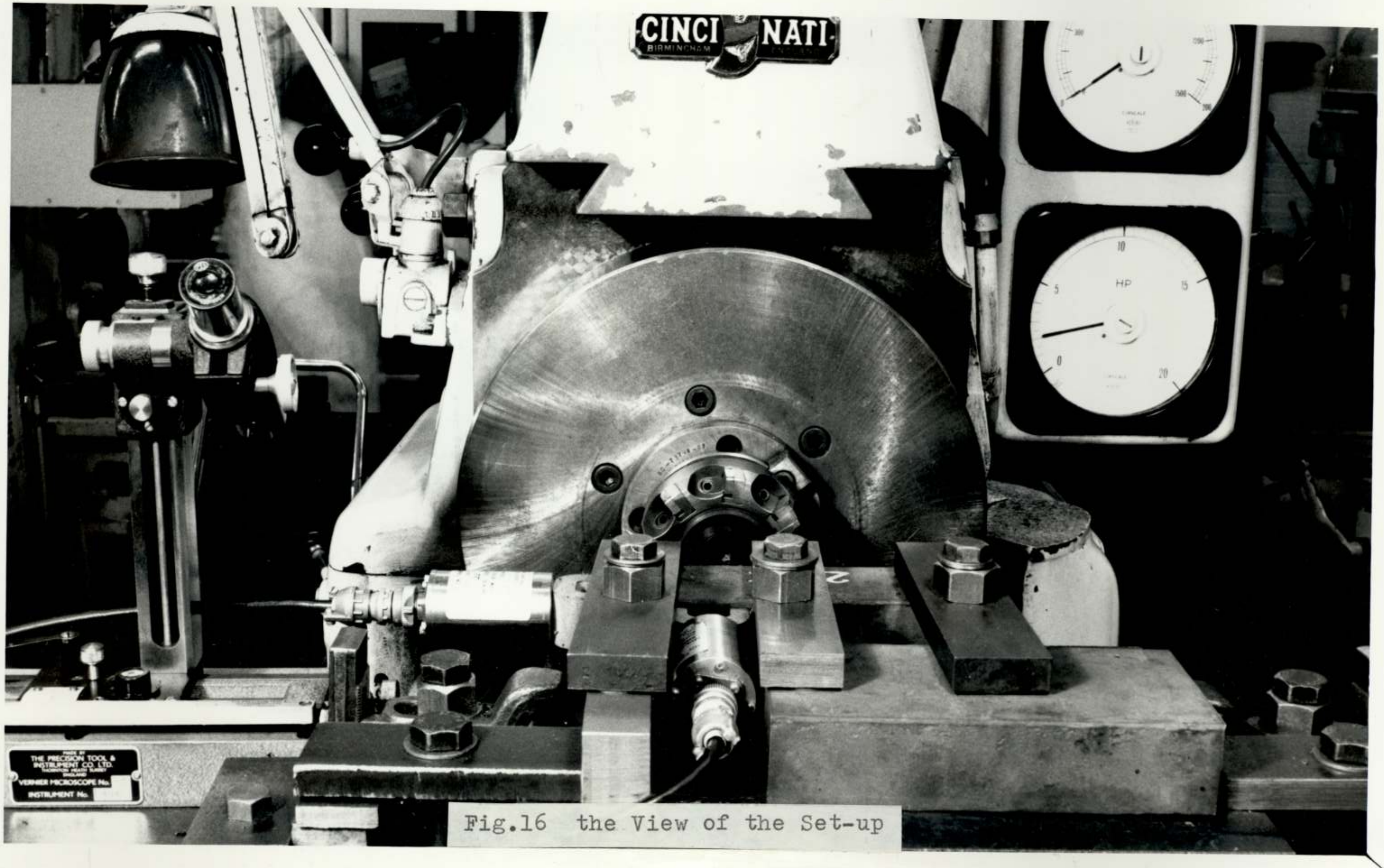


Fig.16 the View of the Set-up

Fig.17 General View of the Walter Cutter with one Workpiece

Fig.18 the Top View of One of the Inserts using with the Walter Cutter

Fig.19 General View of the Sandvik Cutter with One Workpiece

Fig.20 the Top View of One of the Inserts using with the Sandvik Cutter

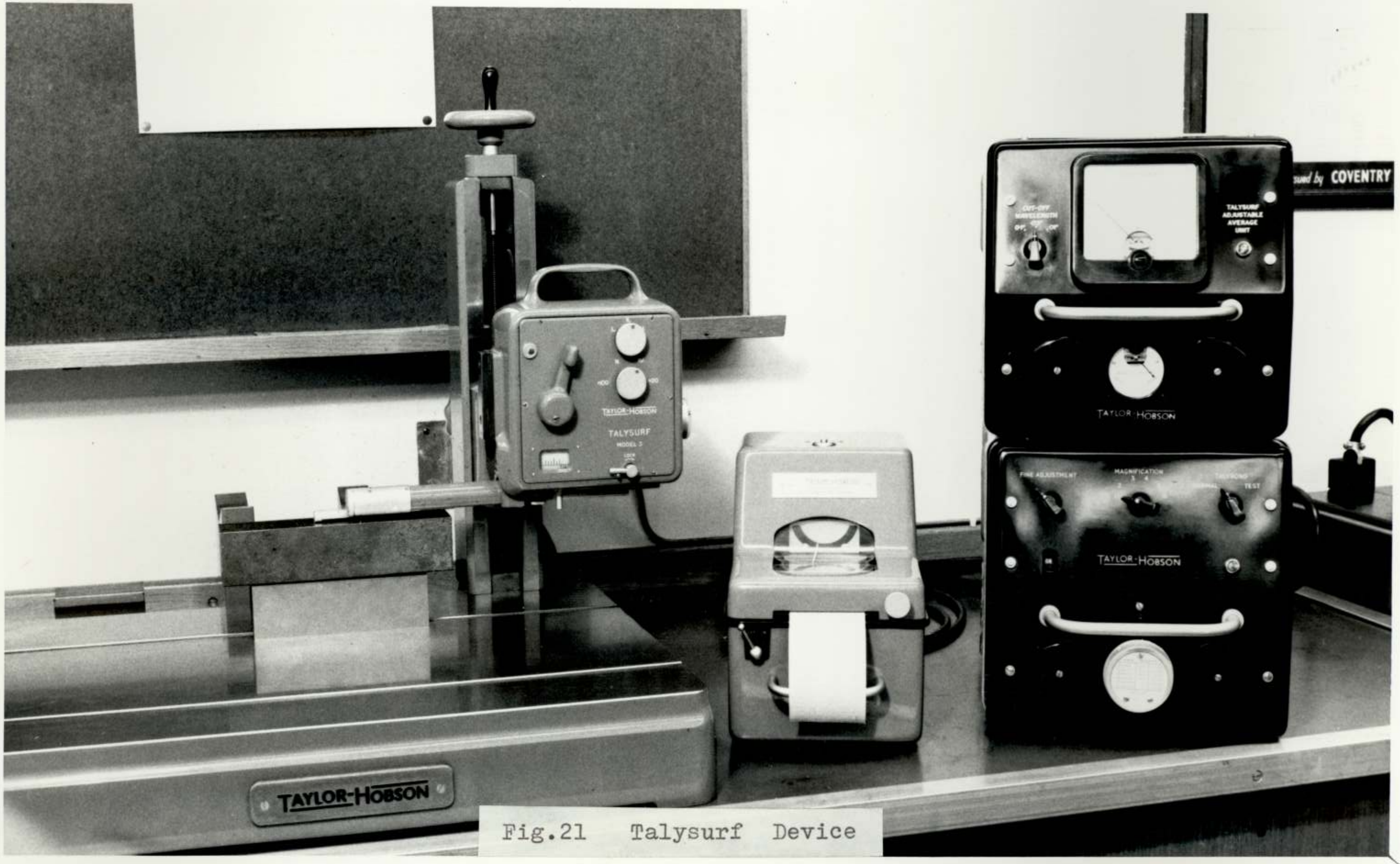


Fig.21 Talysurf Device

Fig.22 Chips Obtained under the Conditions of Cutting Speed of 182.21 m/min,F 1.666 m/min,d 2.03 mm,W 57 mm

Fig.23 Crater Wear on One Insert using with the Sandvik Cutter

Fig.24 Crater Wear on One Insert using with the Walter Cutter

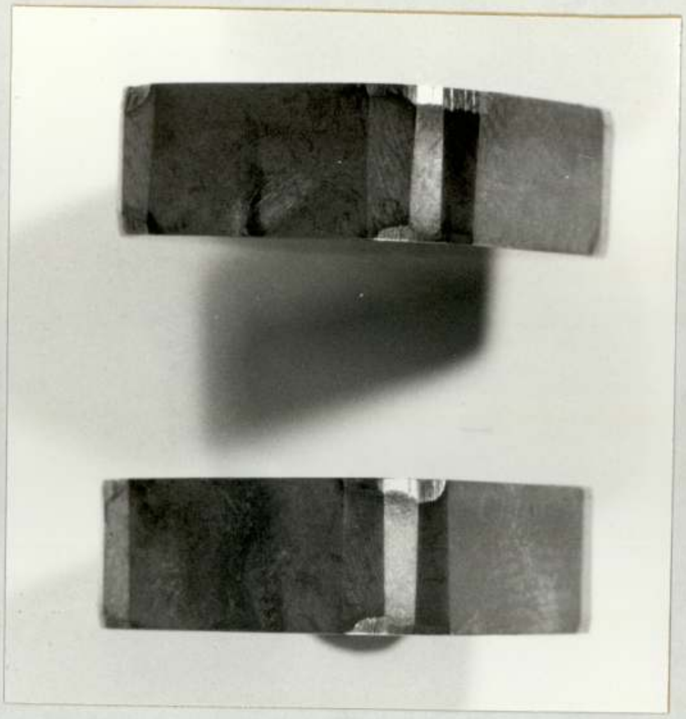


Fig.25 Flank Wear on One Insert using with the Sandvik Cutter

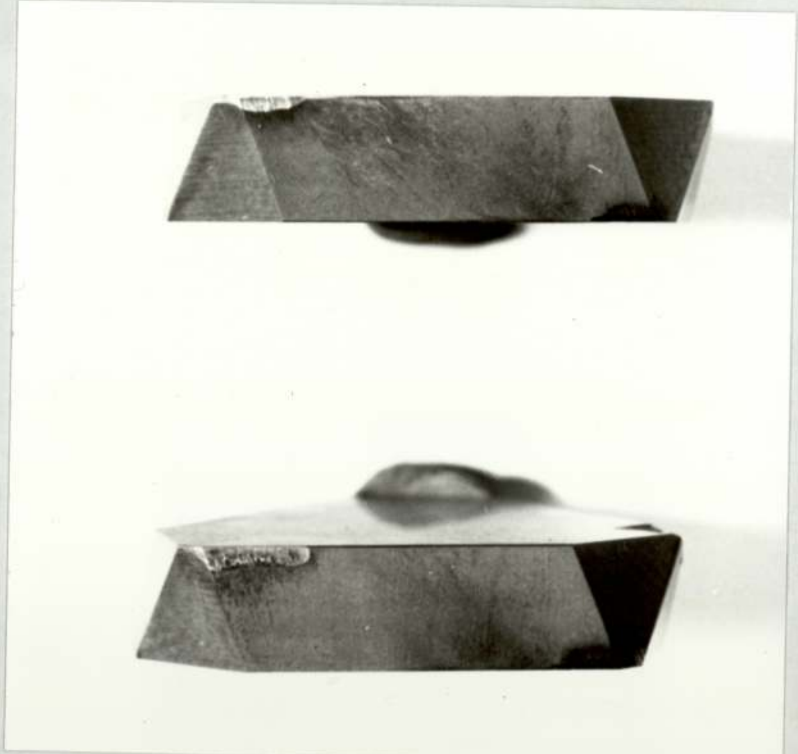
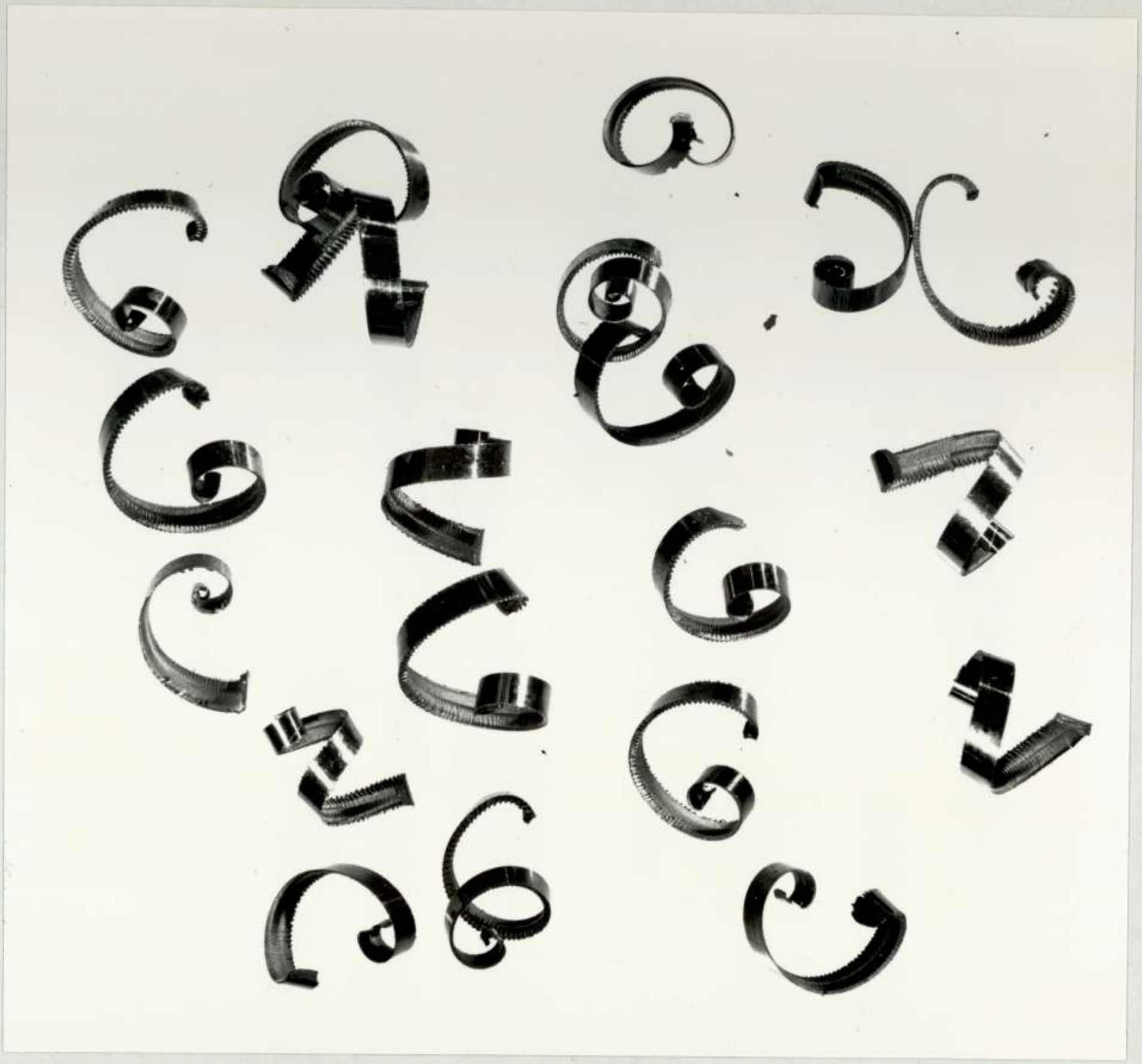


Fig.26 Flank Wear on One Insert using with the Walter Cutter



Material: Tool Steel(B.H.N.238)

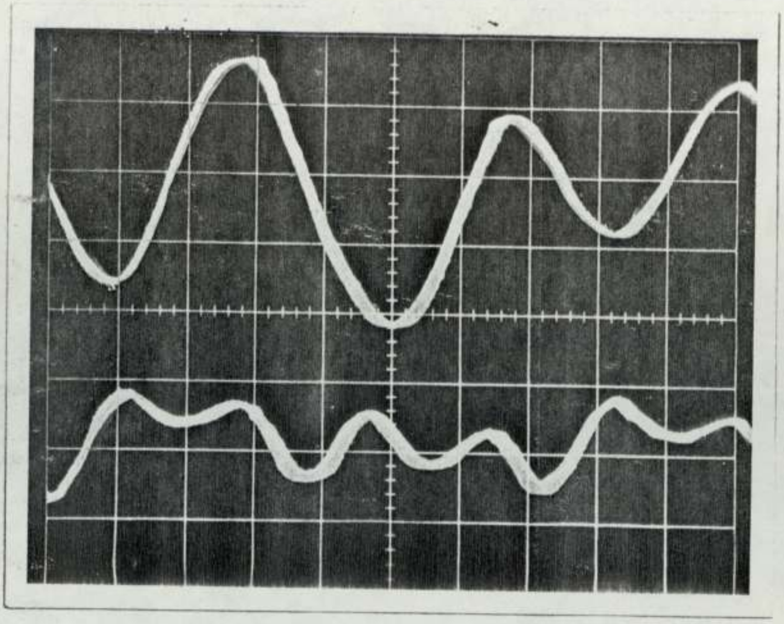
Cutter: the Sandvik Cutter

Fig.27 Chips Obtained During Cutter Life Tests in Down-Cut Milling

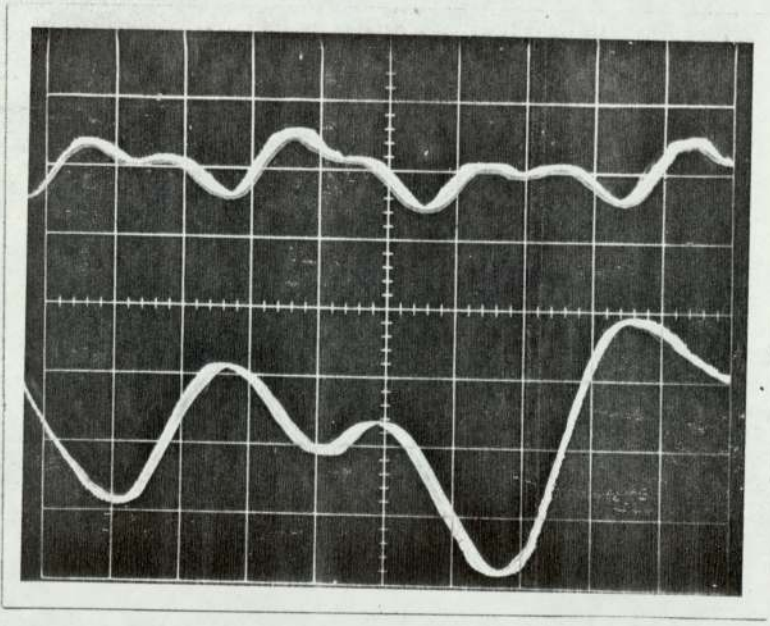
Material: Tool Steel(B.H.N.238)

Cutter: the Walter Cutter

Fig.28 Chips Obtained During Cutter Life Tests in Down-Cut Milling



Test No.1 V_s=118.75 m/min , S_{max}=0.305 mm^2

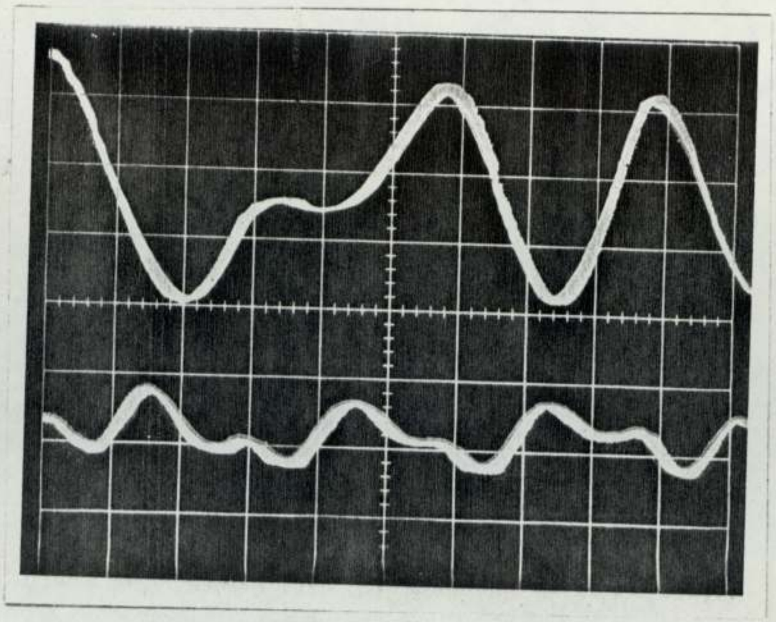


Test No.5 V_s=144.51 m/min , S_{max}=0.377 mm^2

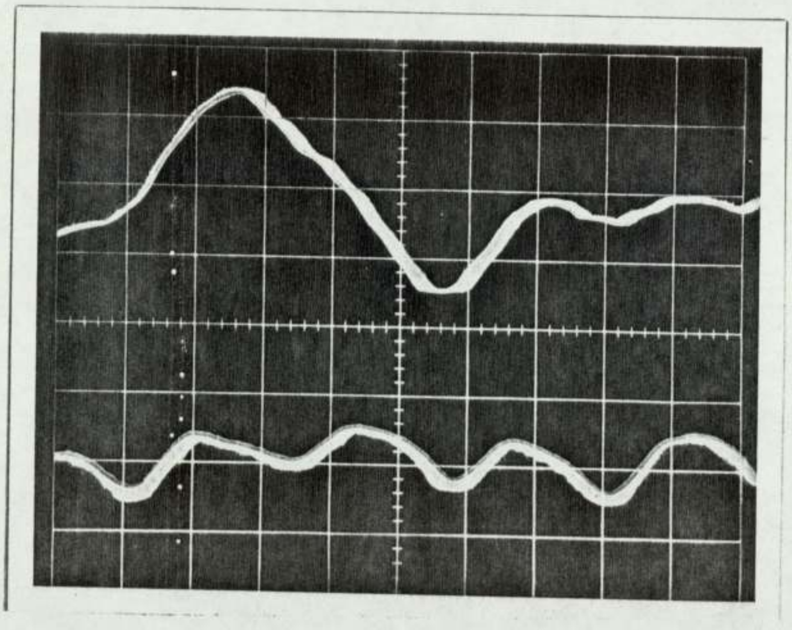
in Vertical line 0.1 volts/div 1 m/div

in Horizantal line 5 msec/div

Fig.29 Vibrations of Workpiece in Feed and Axial Directions During Down-Cut Milling



Test No.6 V_s=144.51 m/min , S_{max}=0.448 mm^2

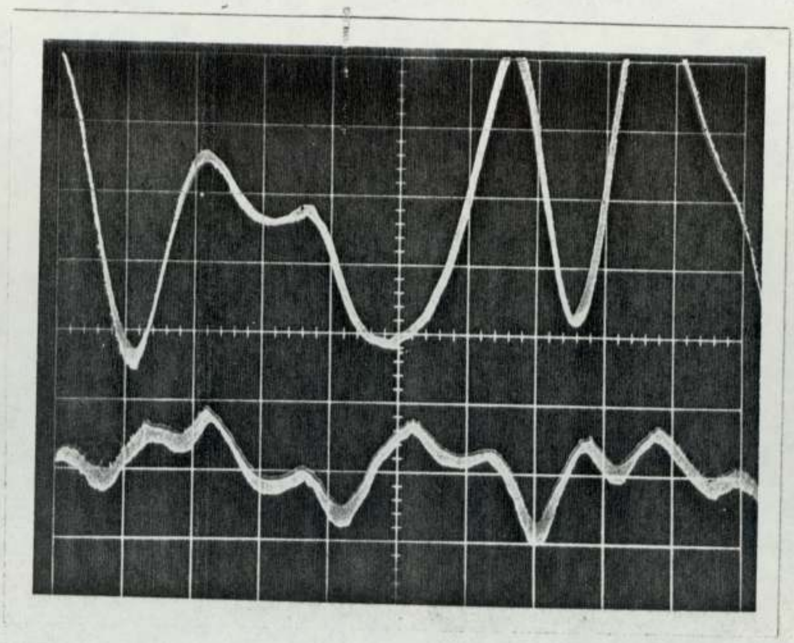


Test No.10 V_s=182.21 m/min , S_{max}=0.371 mm^2

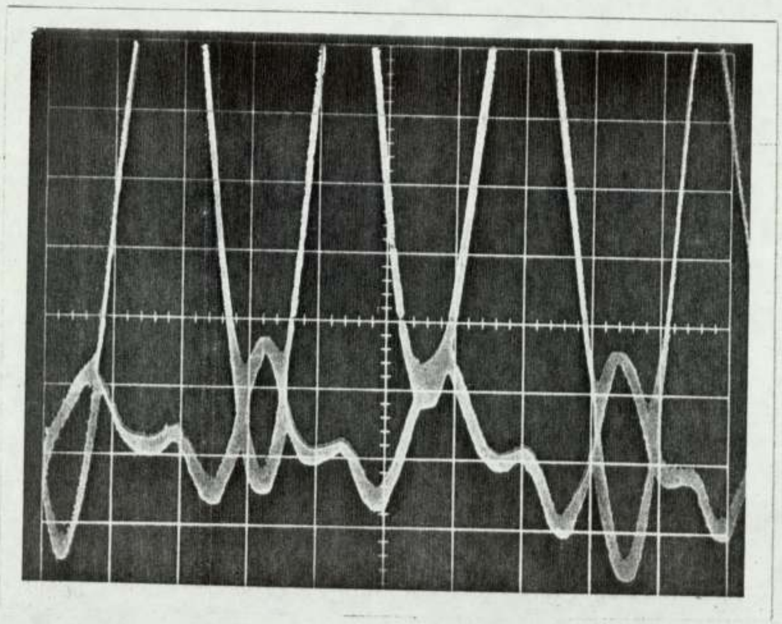
in Vertical line 0.1 volts/div=1μm/div

in Horizantal line 5 msec/div

Fig.29 Vibrations of Workpiece in Feed and Axial Directions During Down-Cut Milling



Test No.3 V_w=95.75 m/min , S_{max}=0.294 mm^2

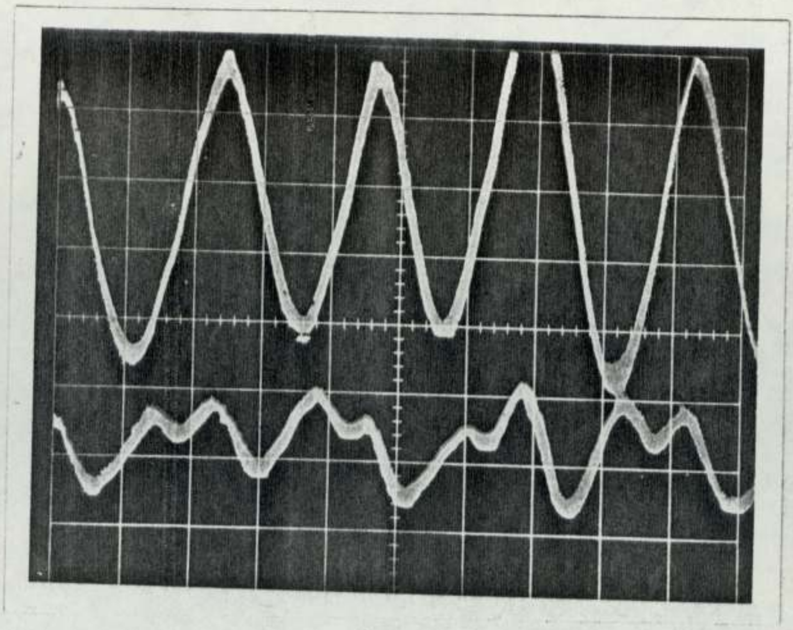


Test No.6 V_w=120.65 m/min , S_{max}= 0.633 mm^2

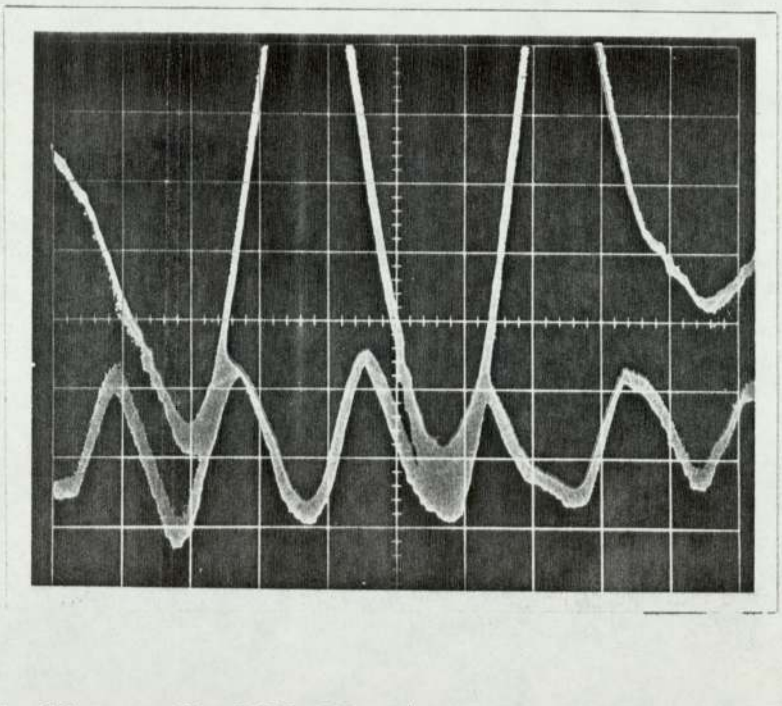
in Vertical line 0.1 volts/div.= 1μm/div.

in Horizantal line 5 msec/div.

Fig.30 Vibrations of Workpiece in Feed and Axial Directions During Down-Cut Milling



Test No.9 V_w=146.82 m/min , S_{max}= 0.357 mm^2

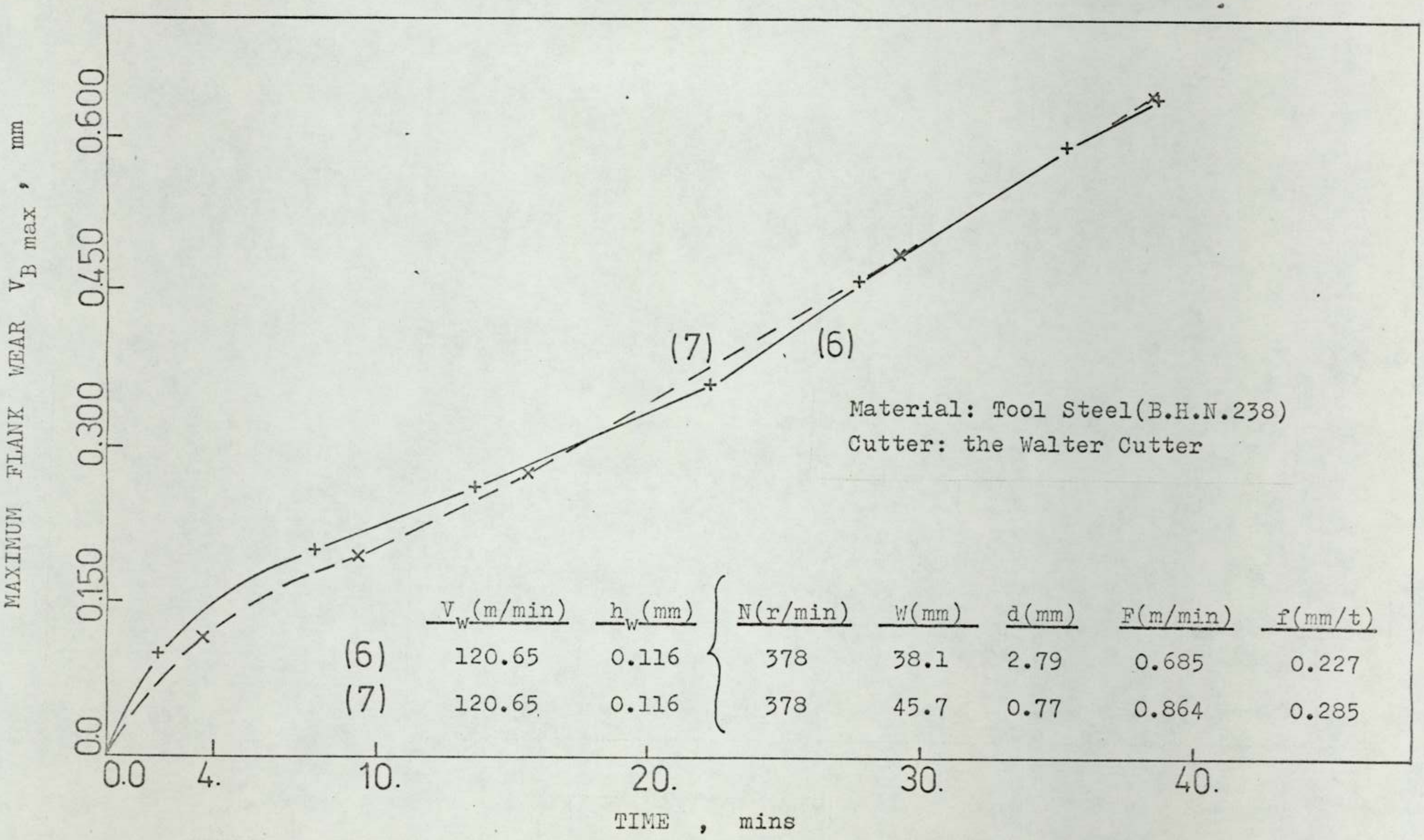


Test No.11 V_w=185.82 m/min , S_{max}=0.477 mm^2

in Vertical line 0.1 volts/div=1μm/div

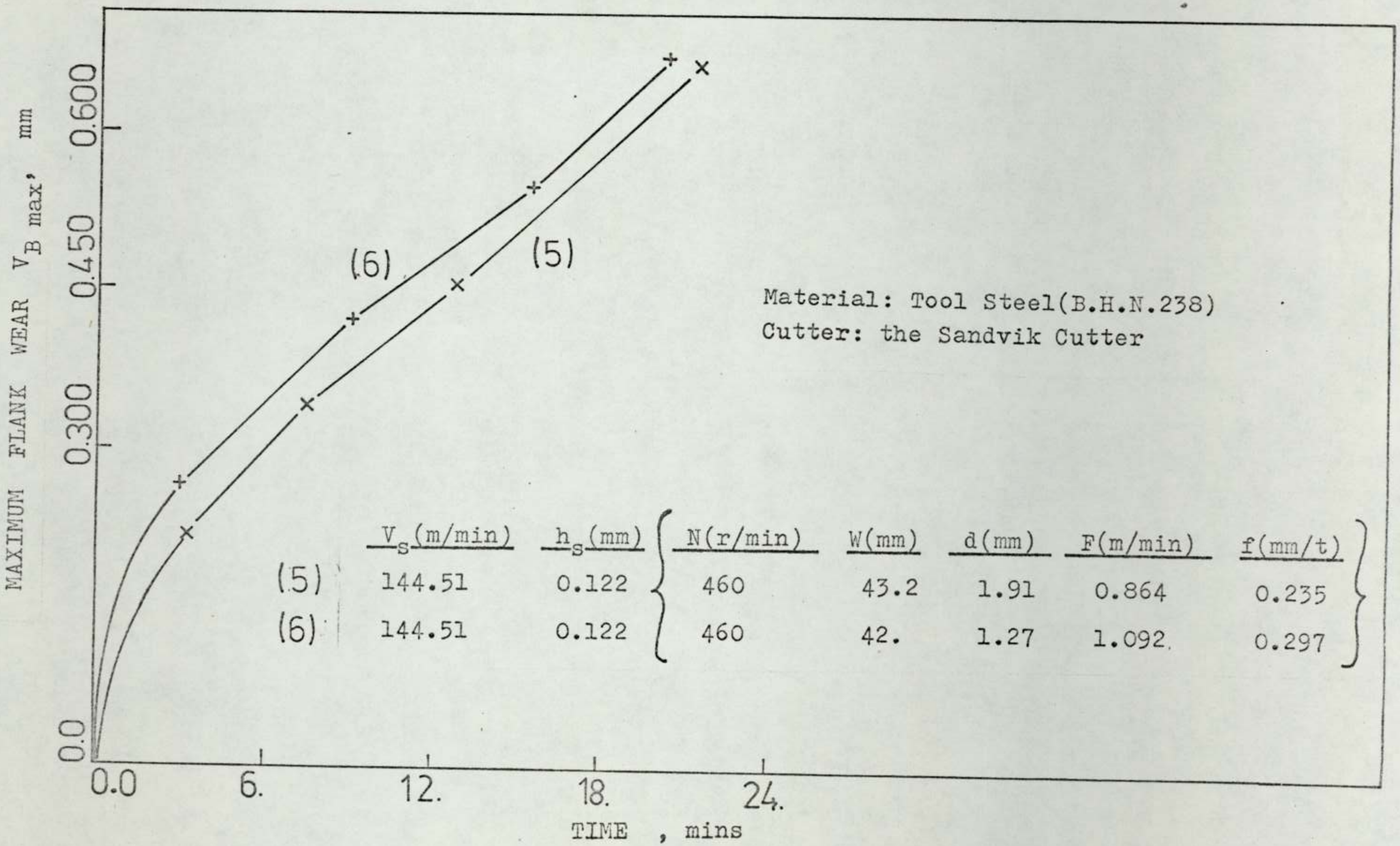
in Horizantal line 5 msec/div

Fig.30 Vibrations of Workpiece in Feed and Axial Directions During Down-Cut Milling



	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(6)	120.65	0.116	378	38.1	2.79	0.685	0.227
(7)	120.65	0.116	378	45.7	0.77	0.864	0.285

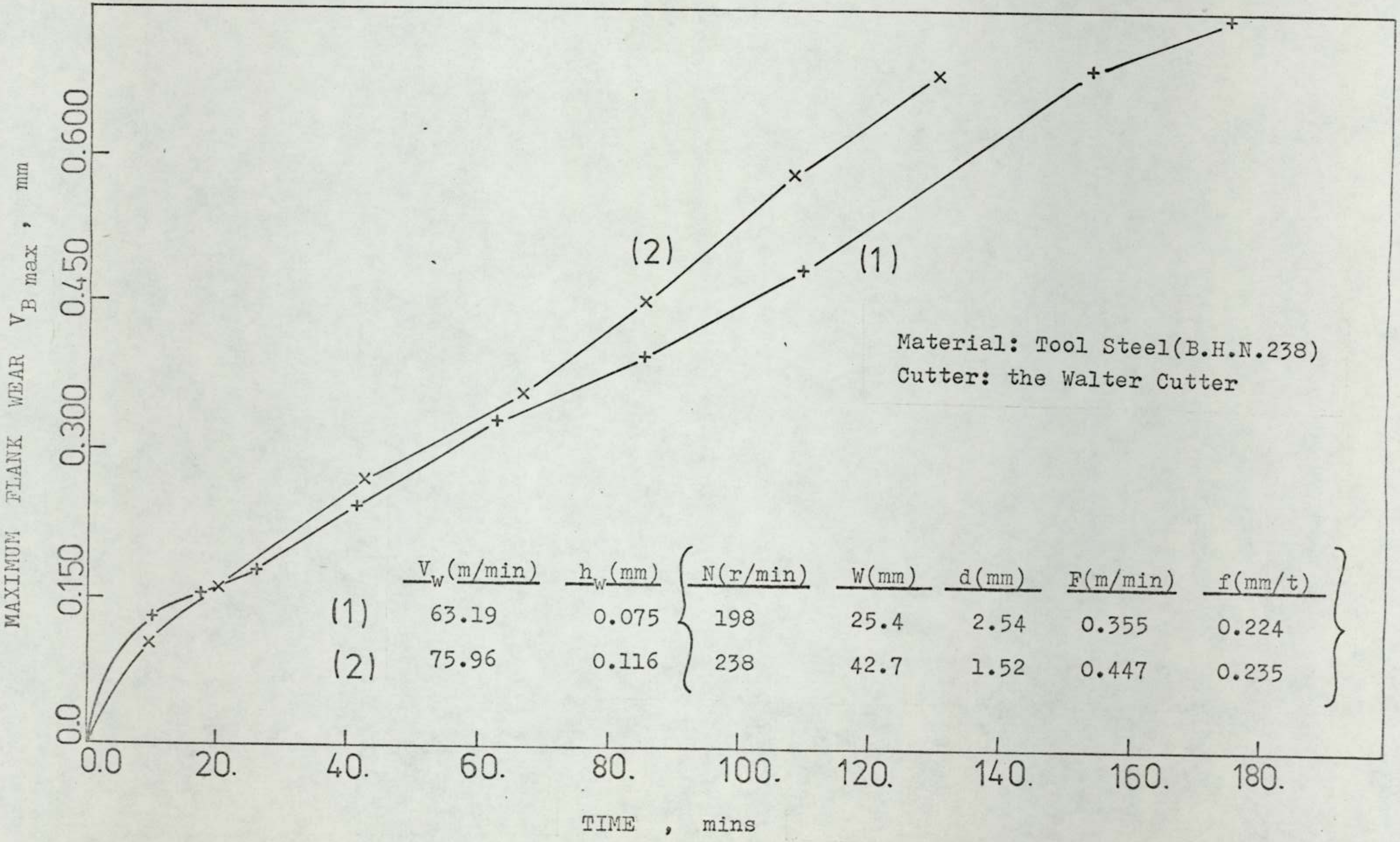
Fig. 31 the Validity of Equivalent Chip Thickness in Down-Cut Milling



Material: Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(5)	144.51	0.122	460	43.2	1.91	0.864	0.235
(6)	144.51	0.122	460	42.	1.27	1.092	0.297

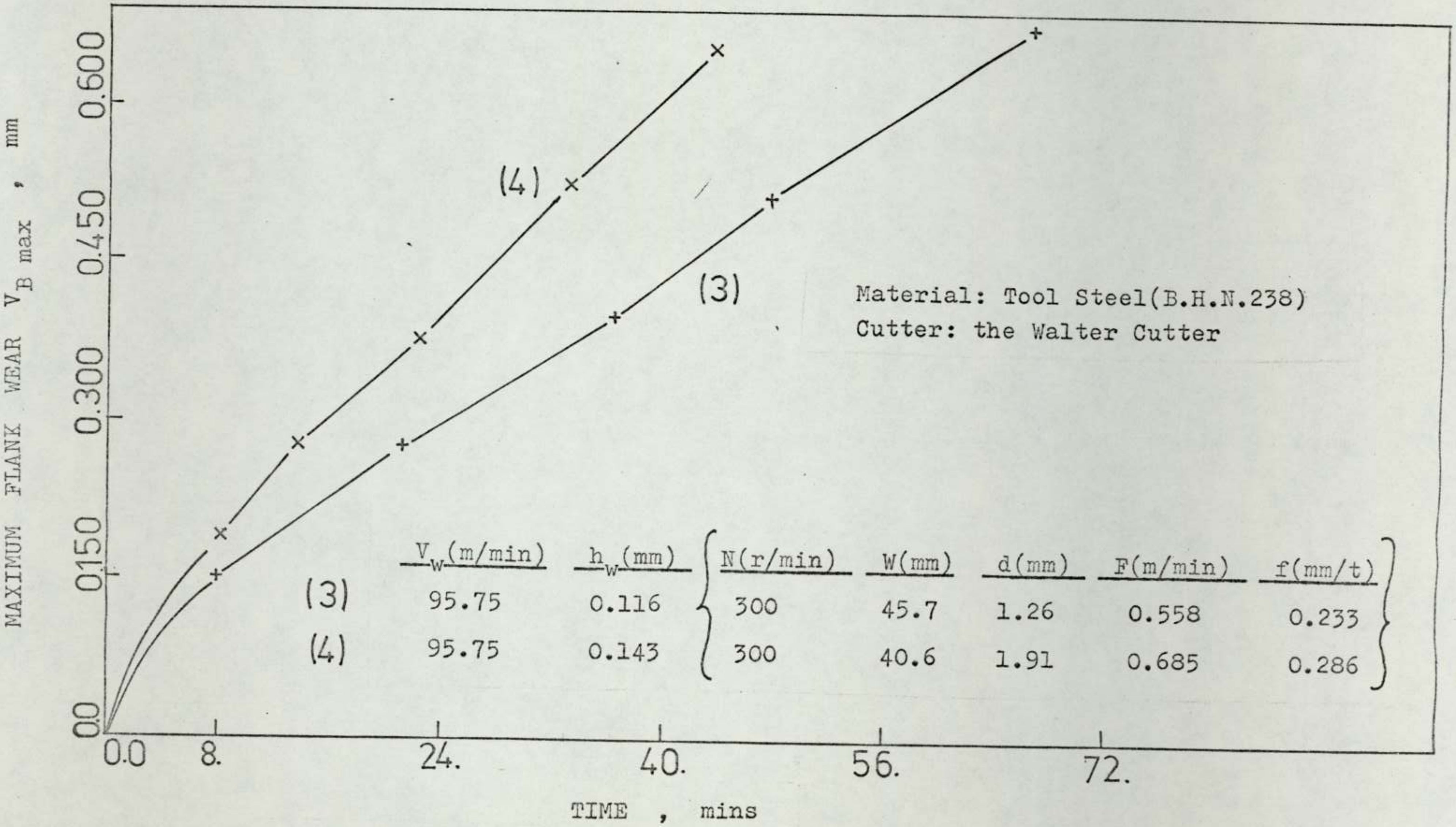
Fig.32 the Validity of Equivalent Chip Thickness in Down-Cut Milling



Material: Tool Steel(B.H.N.238)
Cutter: the Walter Cutter

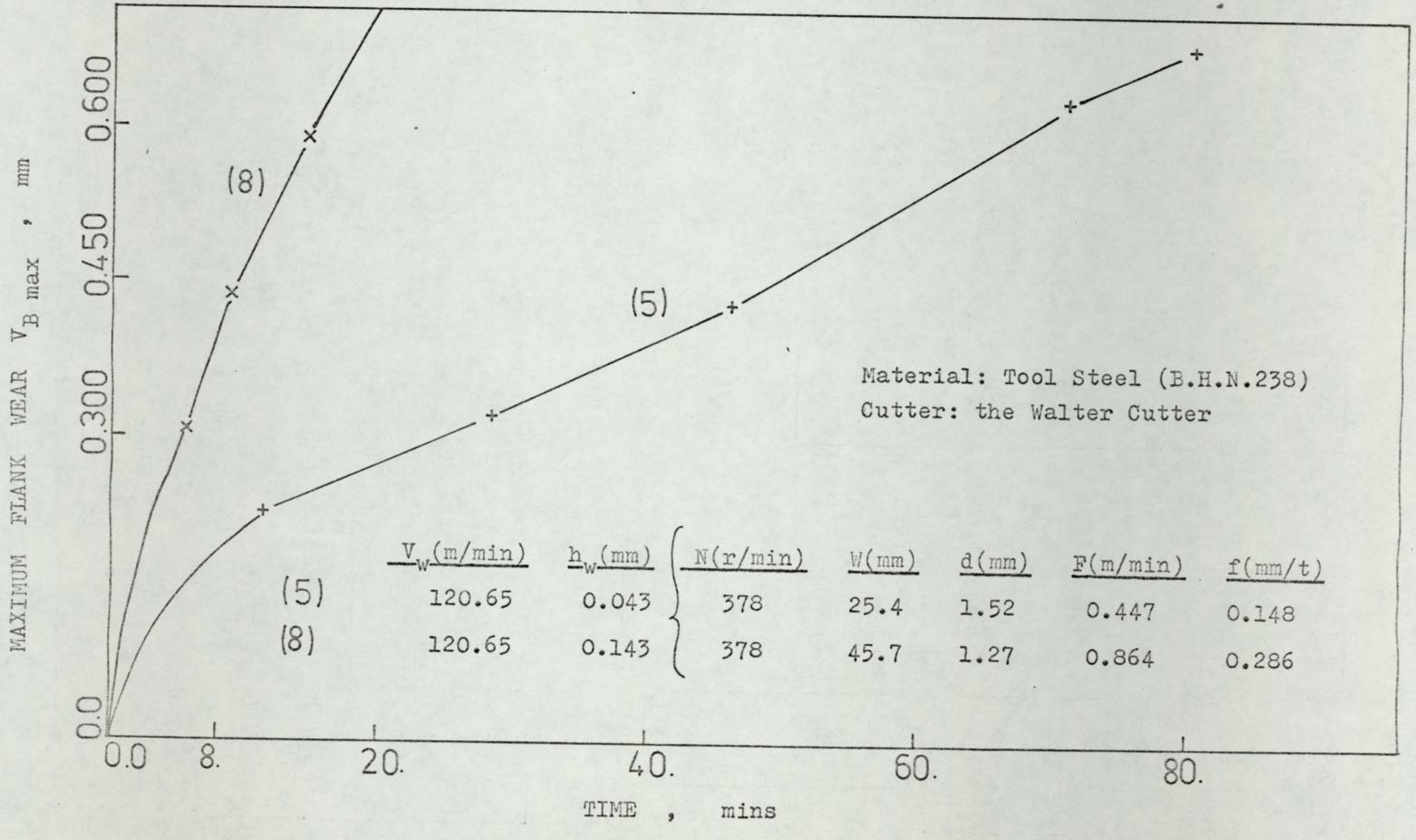
	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(1)	63.19	0.075	198	25.4	2.54	0.355	0.224
(2)	75.96	0.116	238	42.7	1.52	0.447	0.235

Fig.33 Wear-Time Progresses in Down-Cut Milling



	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(3)	95.75	0.116	300	45.7	1.26	0.558	0.233
(4)	95.75	0.143	300	40.6	1.91	0.685	0.286

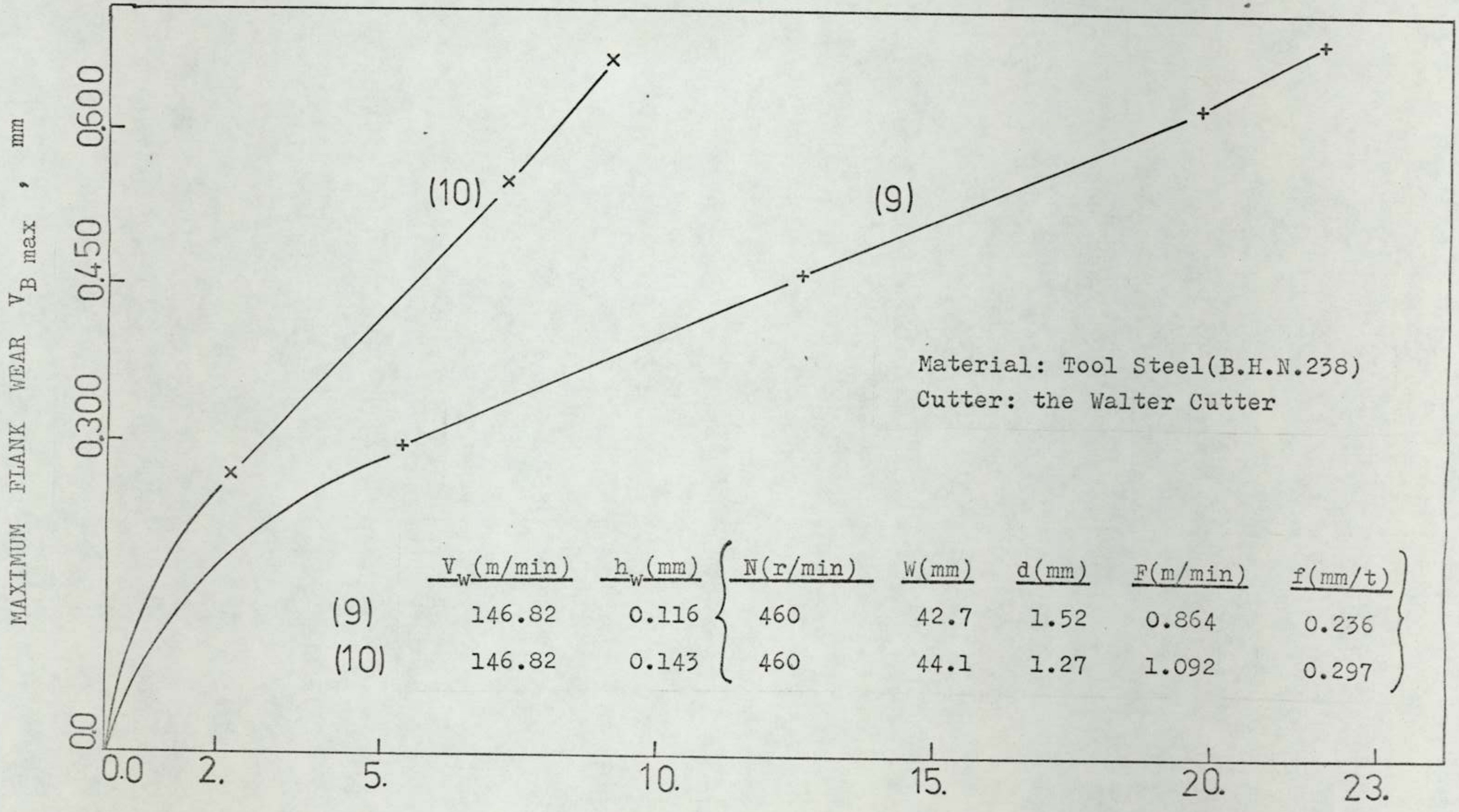
Fig. 34 Wear-Time Progresses in Down-Cut Milling



Material: Tool Steel (B.H.N.238)
Cutter: the Walter Cutter

	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(5)	120.65	0.043	378	25.4	1.52	0.447	0.148
(8)	120.65	0.143	378	45.7	1.27	0.864	0.286

Fig. 35 Wear-Time Progresses in Down-Cut Milling



	V_w(m/min)	h_w(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(9)	146.82	0.116	460	42.7	1.52	0.864	0.236
(10)	146.82	0.143	460	44.1	1.27	1.092	0.297

Fig.36 Wear-Time Progresses in Down-Cut Milling

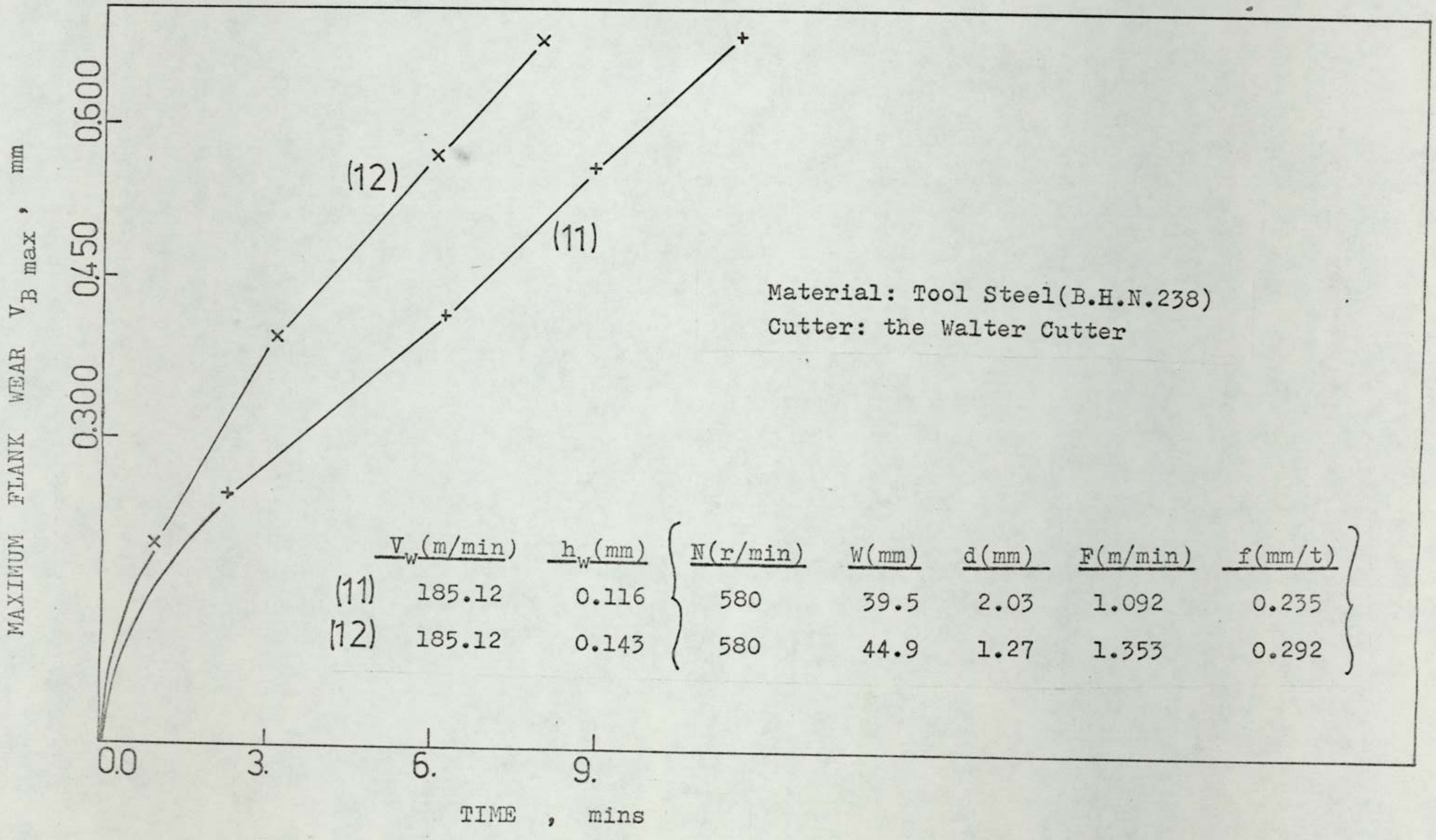
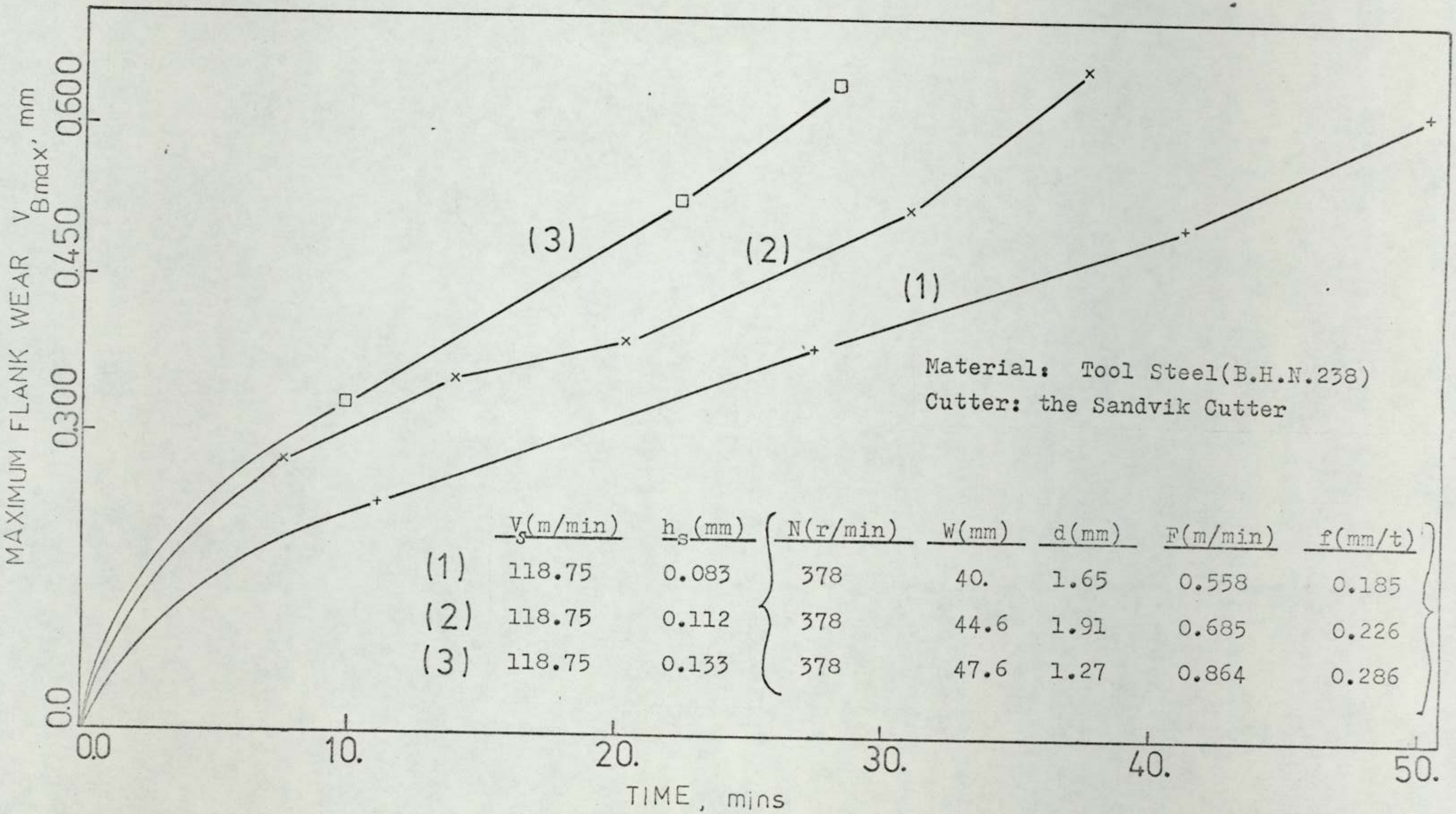


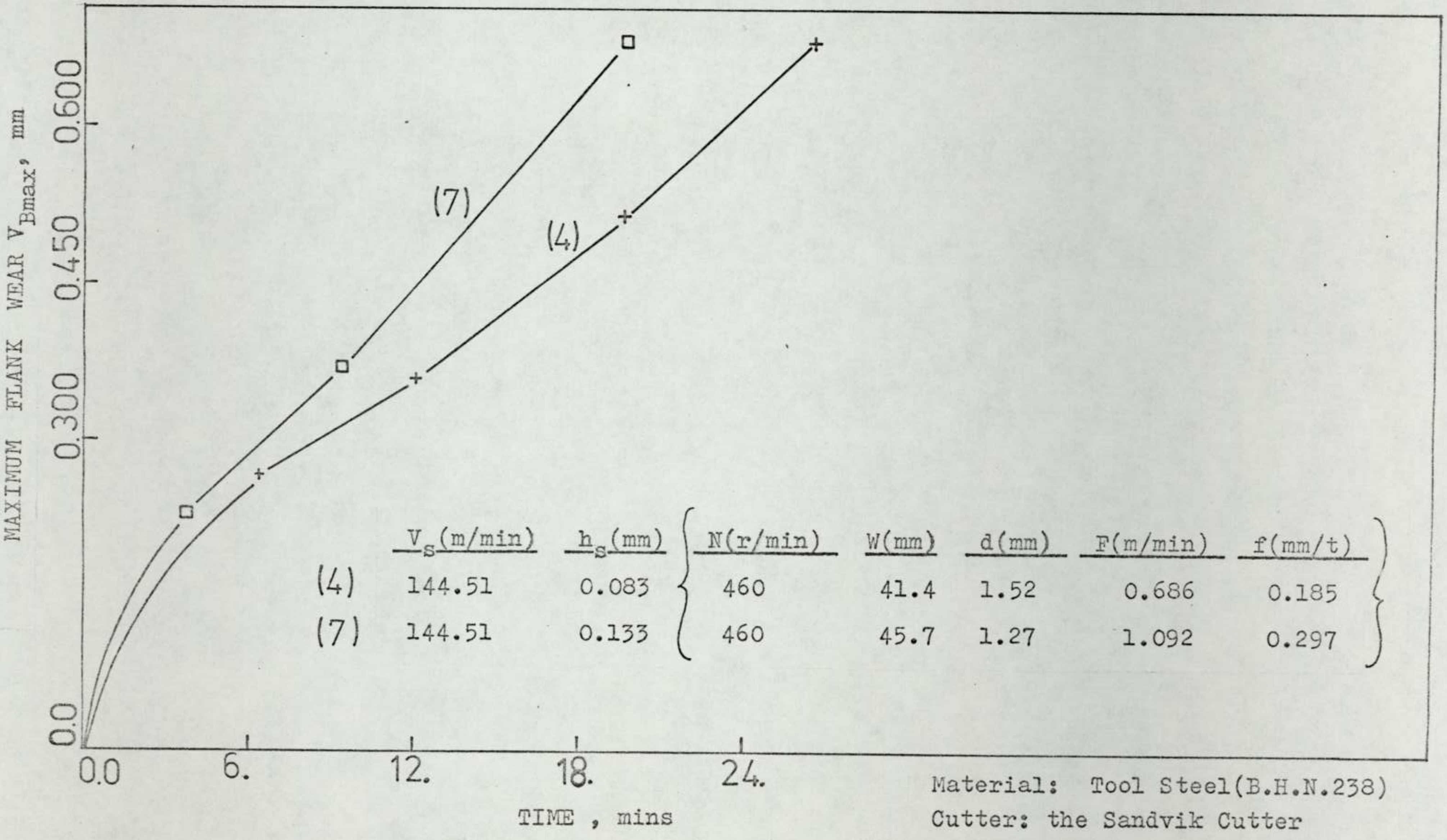
Fig.37 Wear-Time Progresses in Down-Cut Milling



Material: Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(1)	118.75	0.083	378	40.	1.65	0.558	0.185
(2)	118.75	0.112	378	44.6	1.91	0.685	0.226
(3)	118.75	0.133	378	47.6	1.27	0.864	0.286

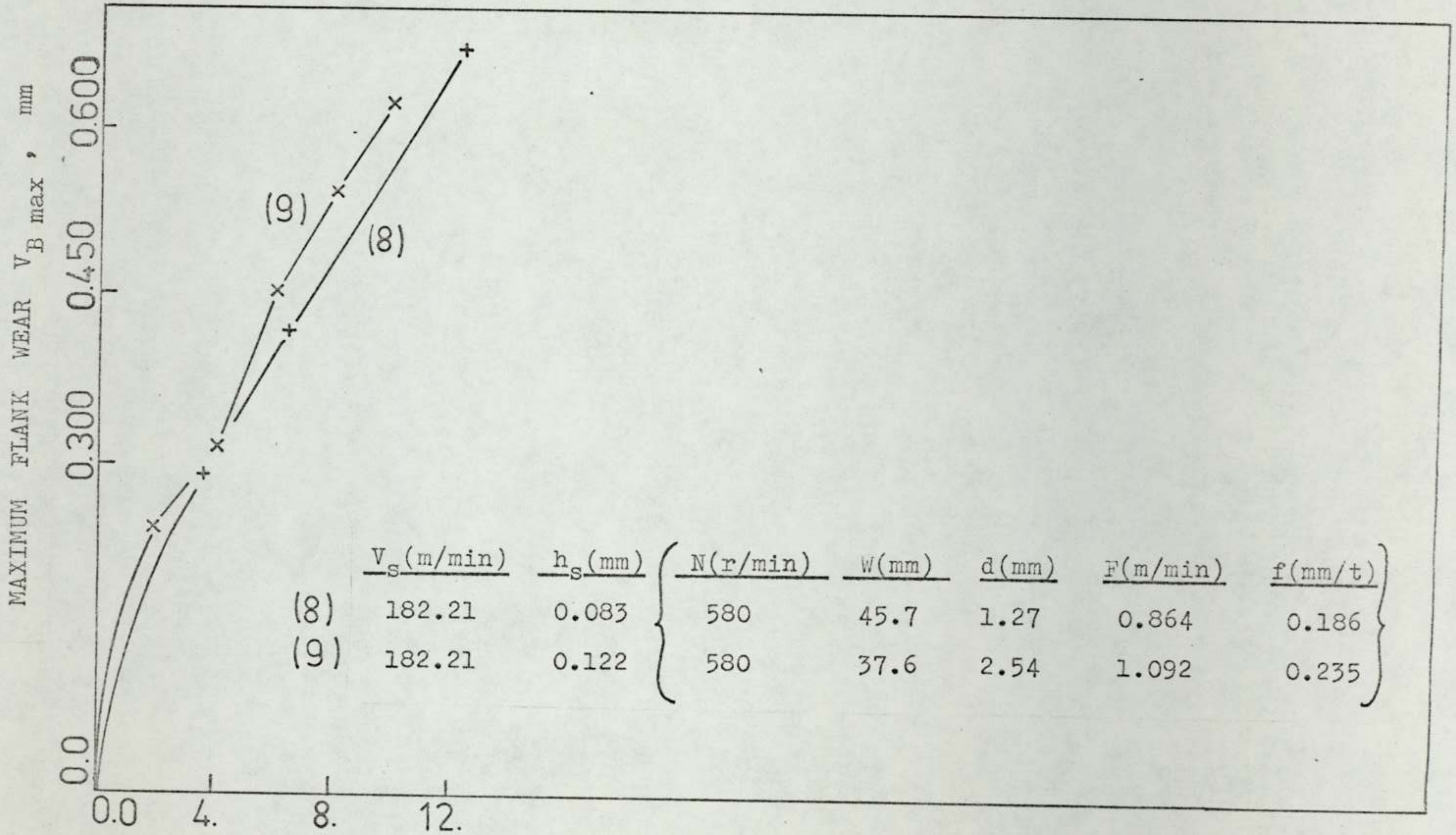
Fig.38 Wear-Time Progresses in Down-Cut Milling



	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(4)	144.51	0.083	460	41.4	1.52	0.686	0.185
(7)	144.51	0.133	460	45.7	1.27	1.092	0.297

Material: Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

Fig.39 Wear-Time Progresses in Down-Cut Milling



	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(8)	182.21	0.083	580	45.7	1.27	0.864	0.186
(9)	182.21	0.122	580	37.6	2.54	1.092	0.235

Material: Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

Fig.40 Wear-Time Progresses in Down-Cut Milling

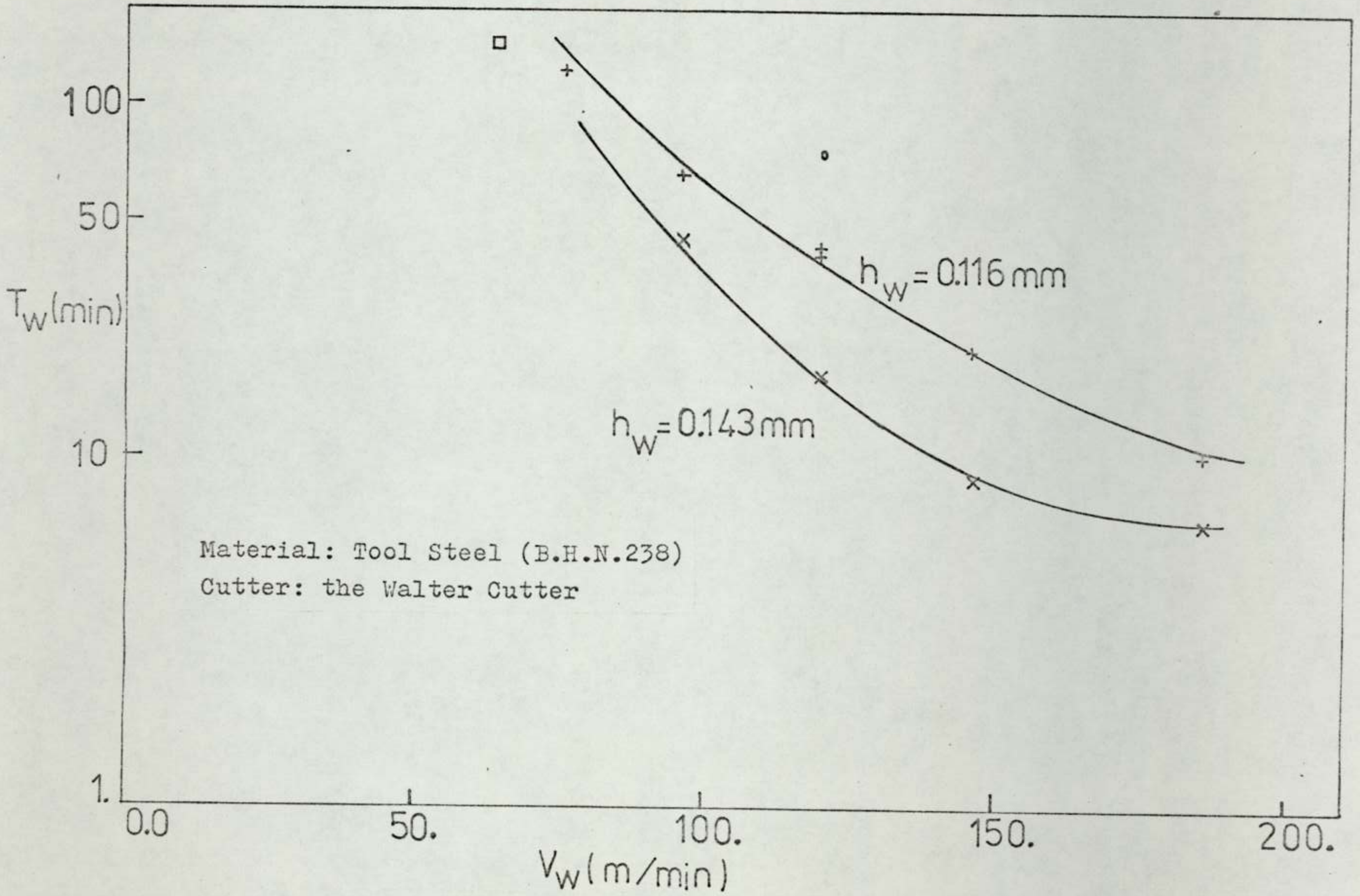


Fig. 41 Cutter Life Results in Down-Cut Milling

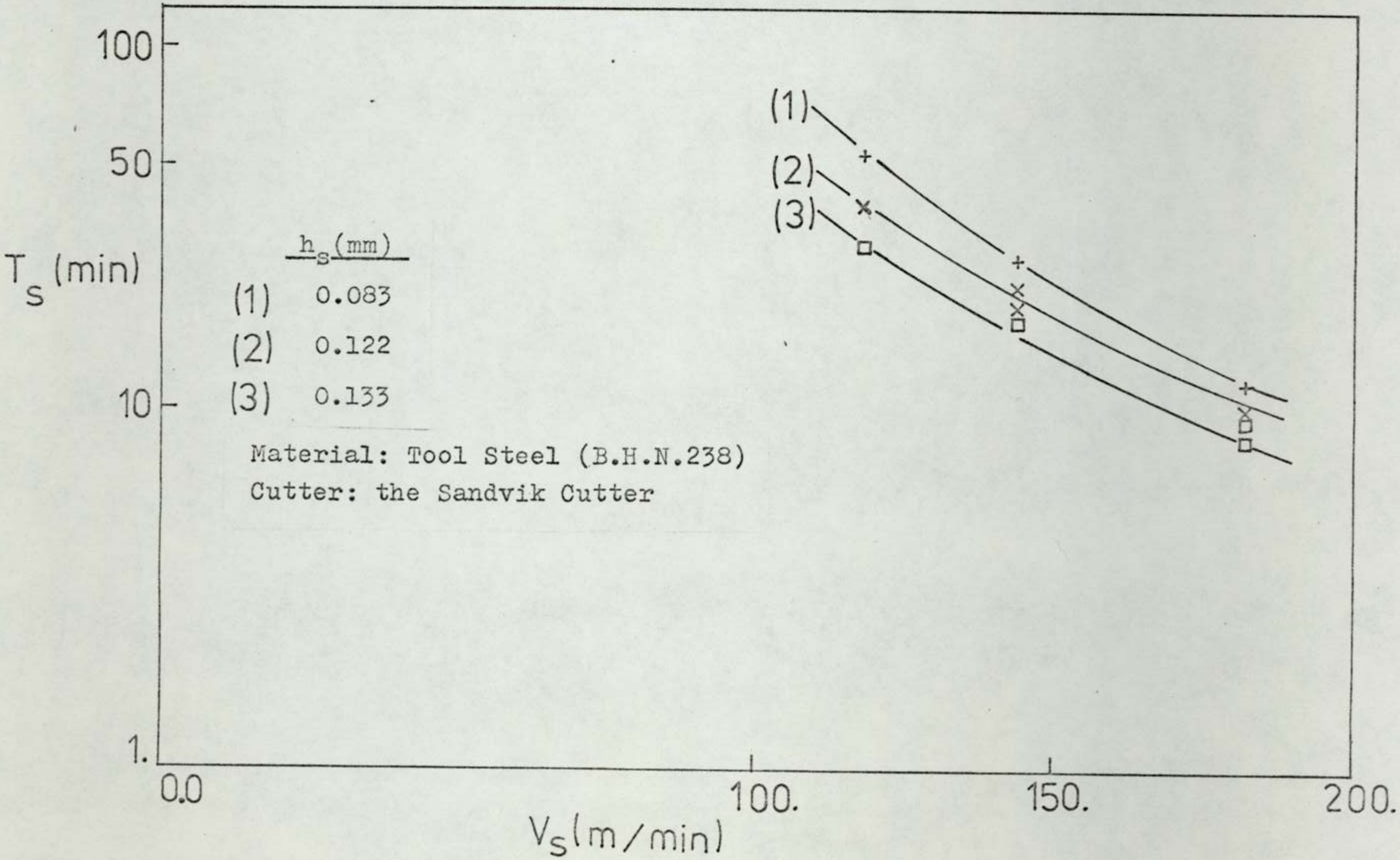
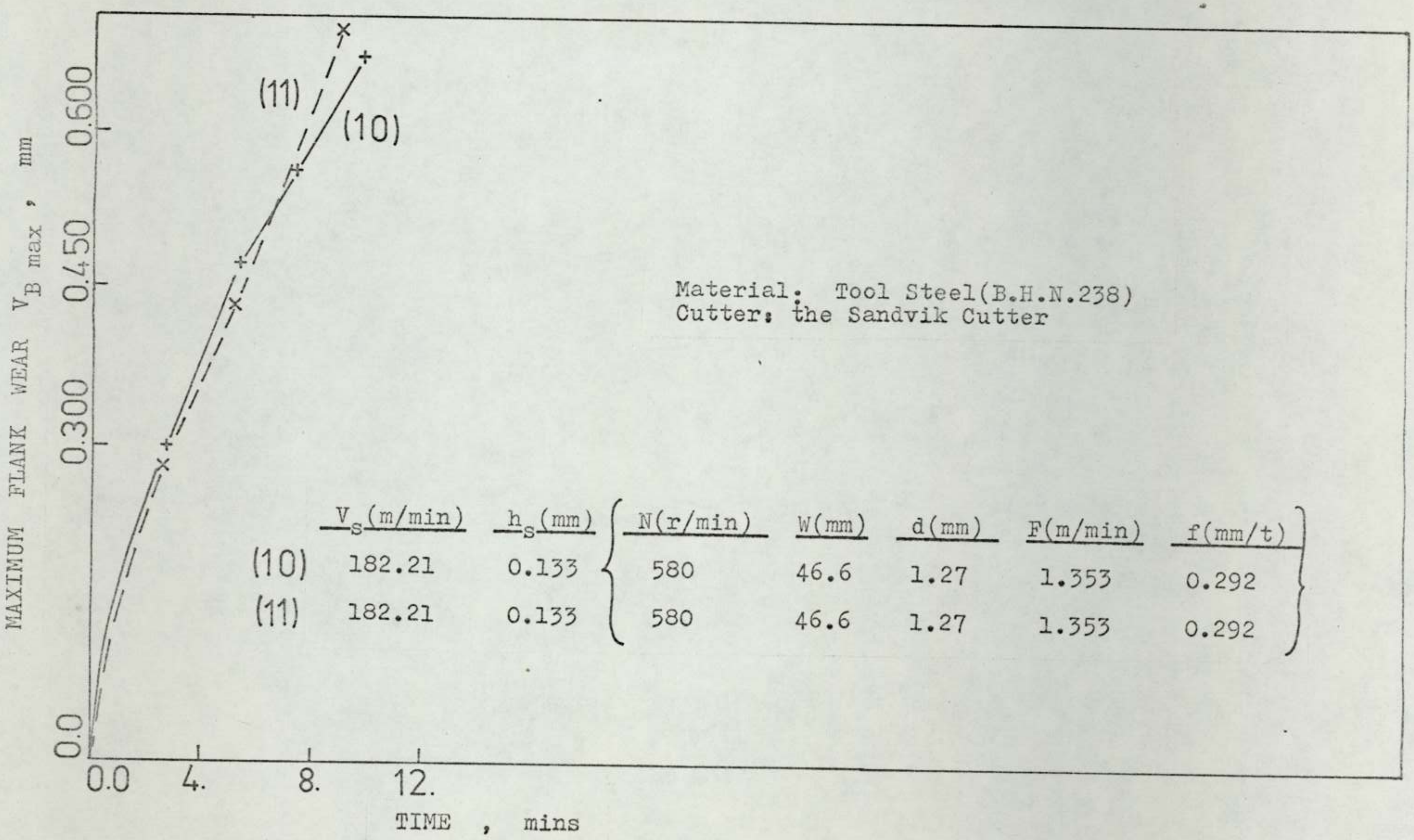


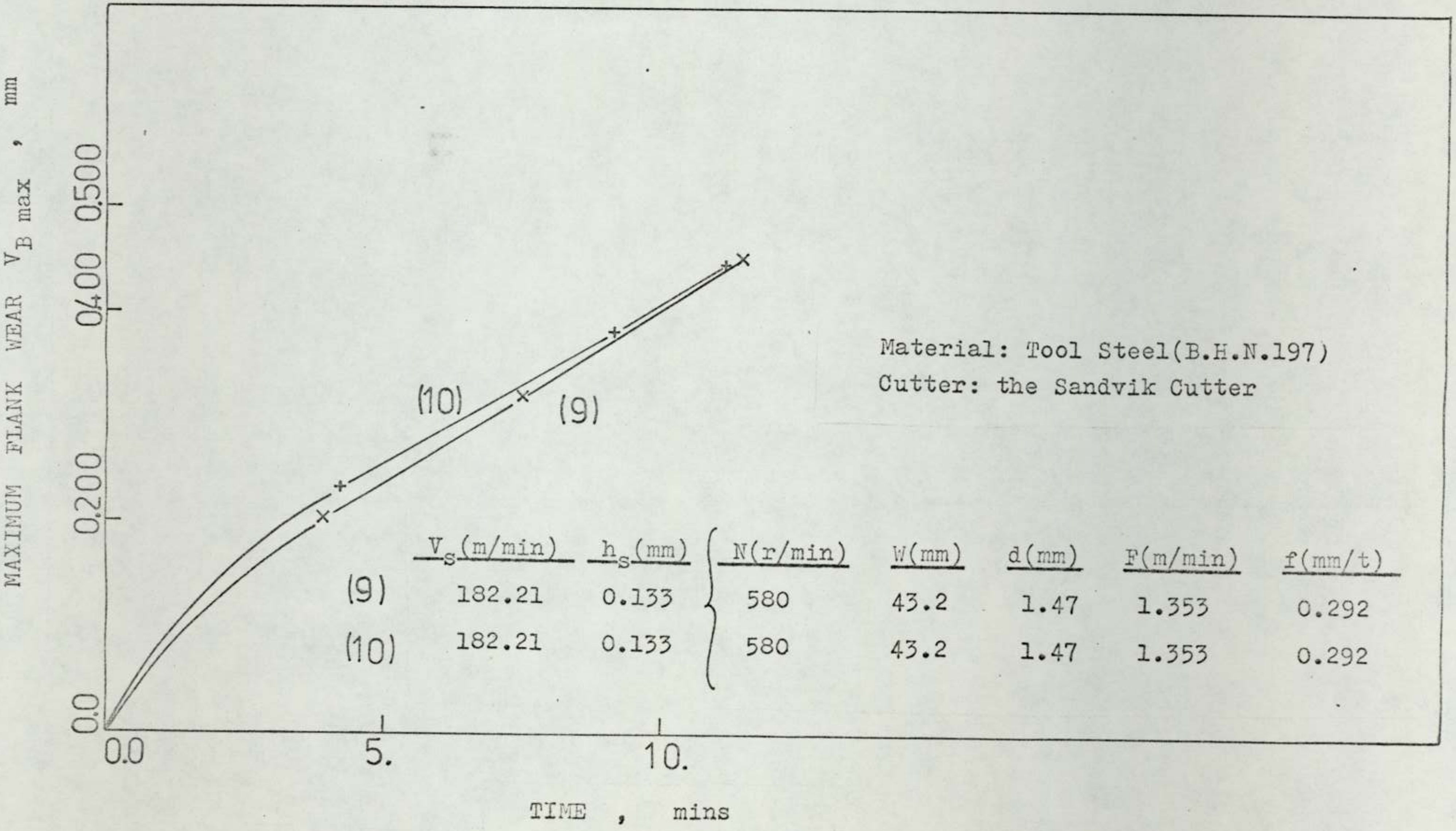
Fig.42 Cutter Life Results in Down-Cut Milling



Material. Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(10)	182.21	0.133	580	46.6	1.27	1.353	0.292
(11)	182.21	0.133	580	46.6	1.27	1.353	0.292

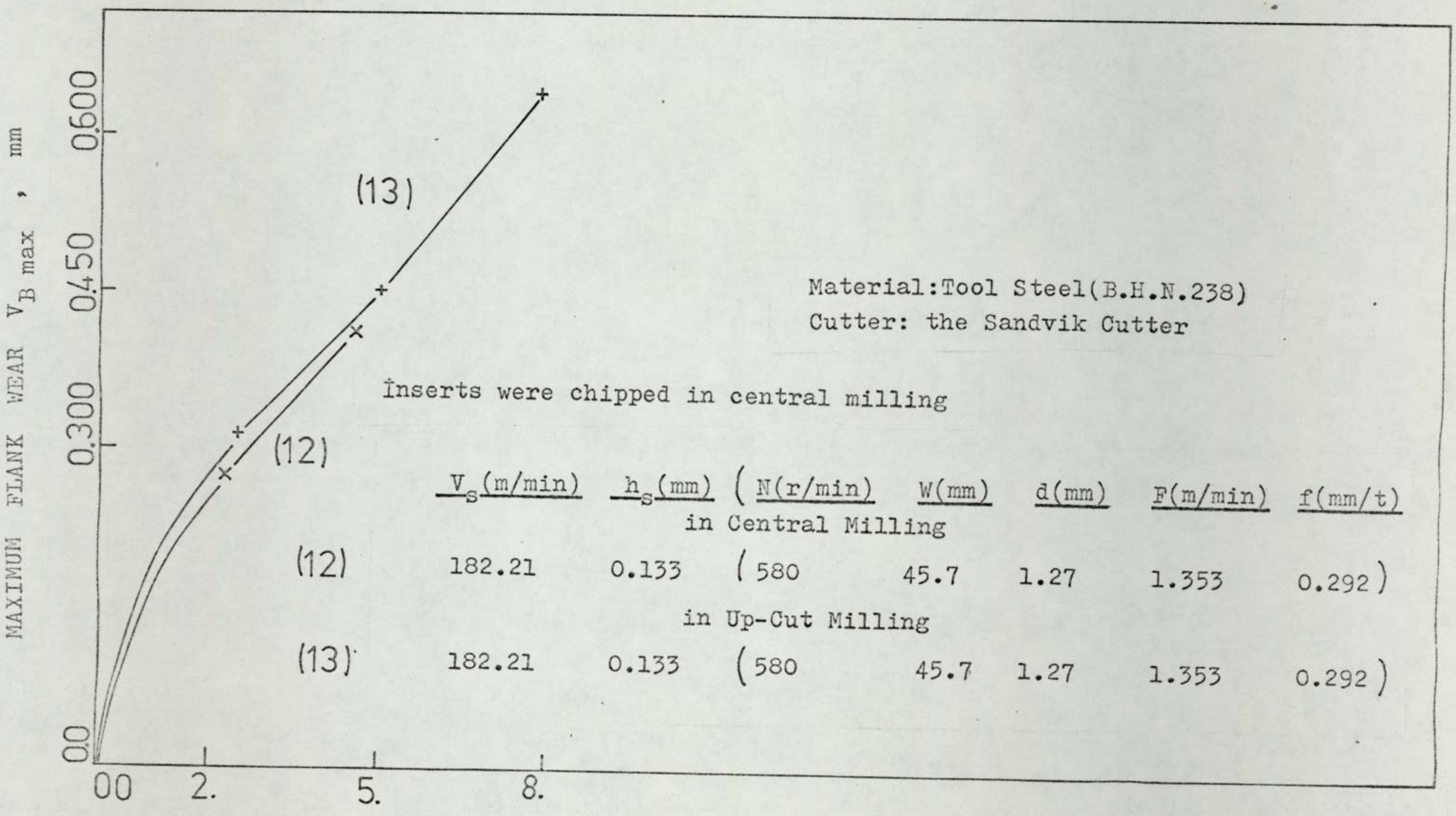
Fig.43 Wear-Time Progresses in Down-Cut Milling



Material: Tool Steel(B.H.N.197)
Cutter: the Sandvik Cutter

	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(9)	182.21	0.133	580	43.2	1.47	1.353	0.292
(10)	182.21	0.133	580	43.2	1.47	1.353	0.292

Fig.44 Wear-Time Progresses in Up-Cut Milling

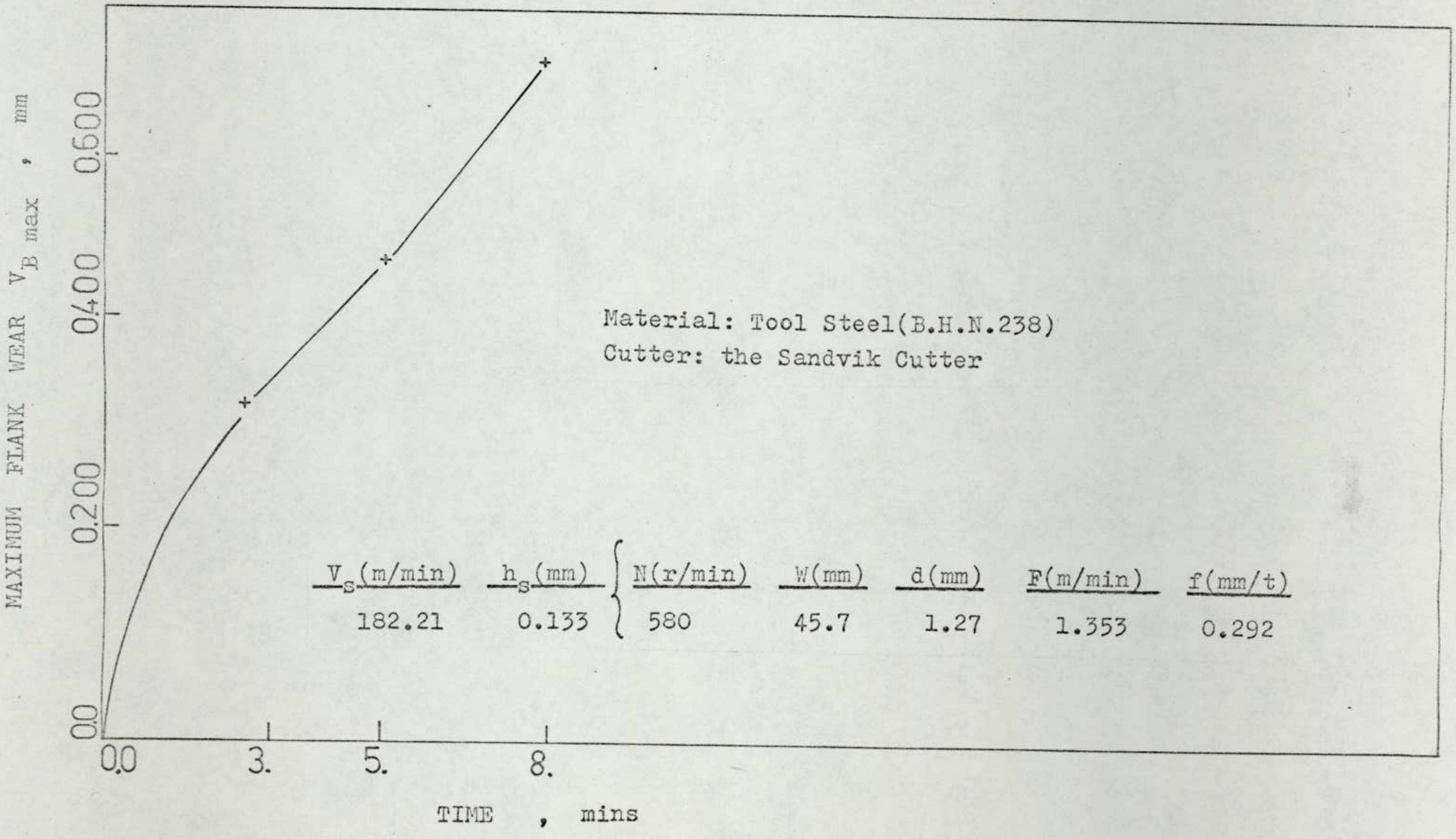


Material:Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

Inserts were chipped in central milling

	V_s(m/min)	h_s(mm)	(N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
	in Central Milling						
(12)	182.21	0.133	(580	45.7	1.27	1.353	0.292)
	in Up-Cut Milling						
(13)	182.21	0.133	(580	45.7	1.27	1.353	0.292)

Fig.45 Wear-Time Progresses



Material: Tool Steel(B.H.N.238)
Cutter: the Sandvik Cutter

V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
182.21	0.133	580	45.7	1.27	1.353	0.292

Fig.45 Wear-Time Progress in Up-Cut Milling

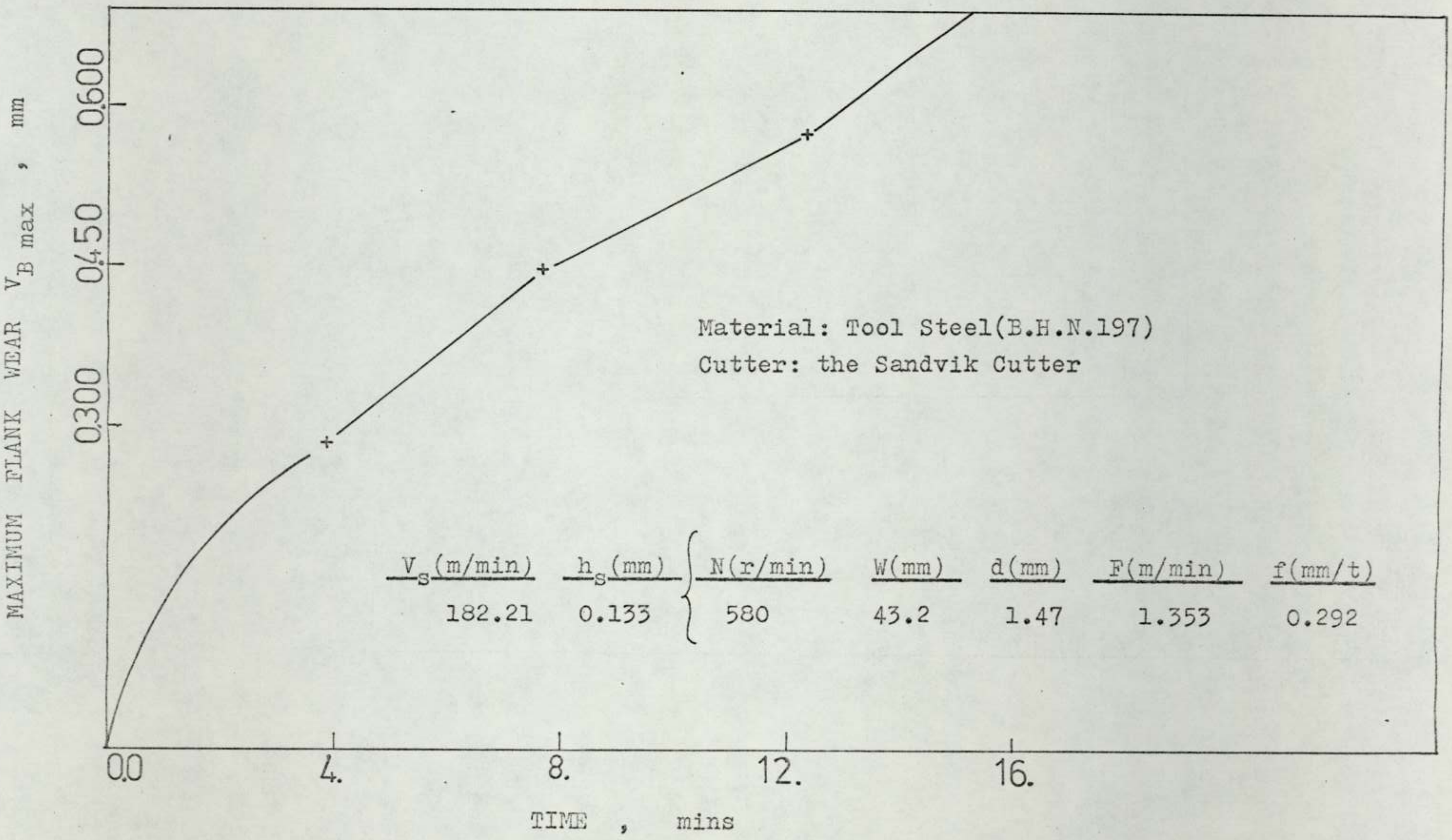


Fig.46 Wear-Time Progresses in Down-Cut Milling

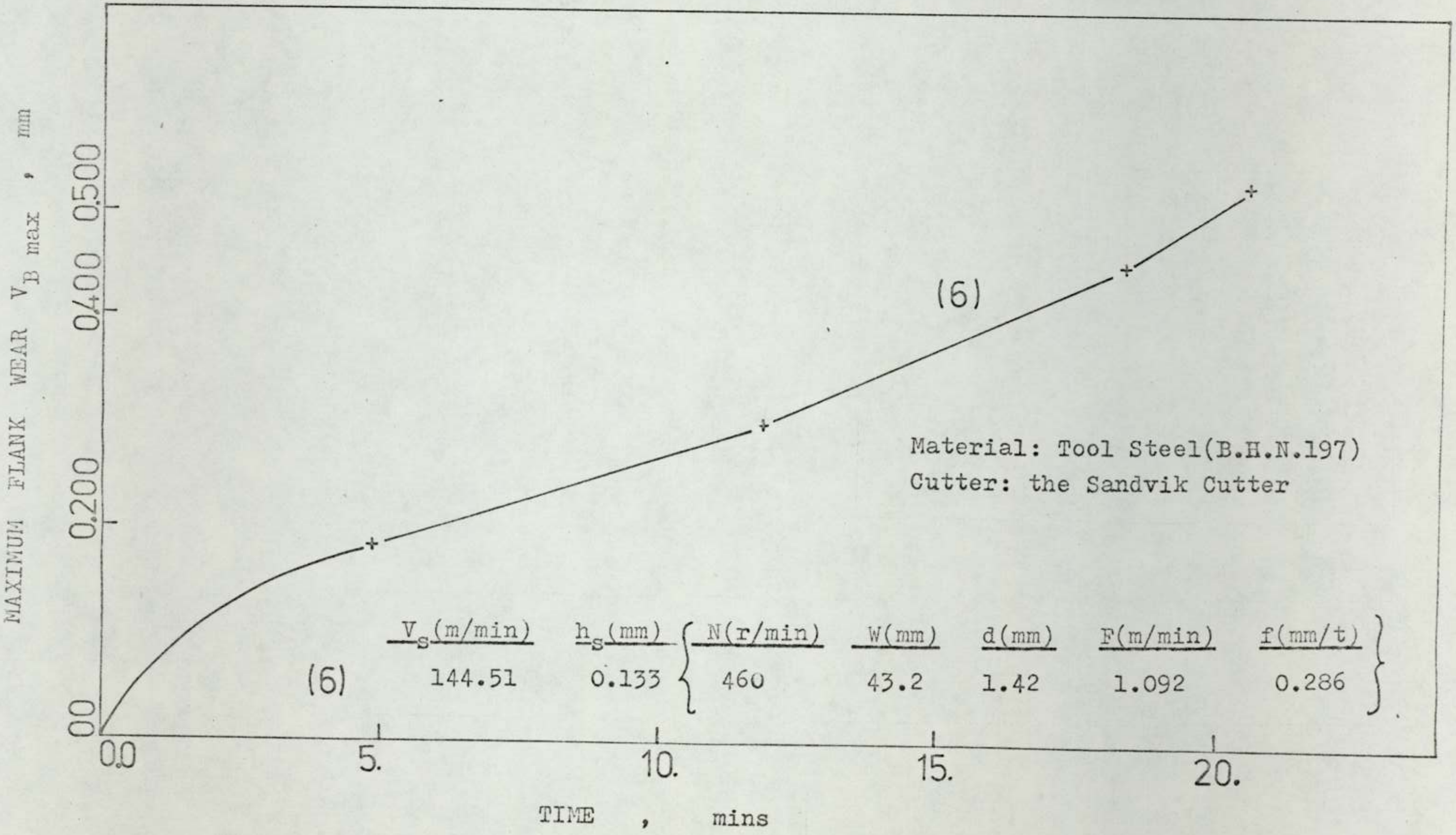
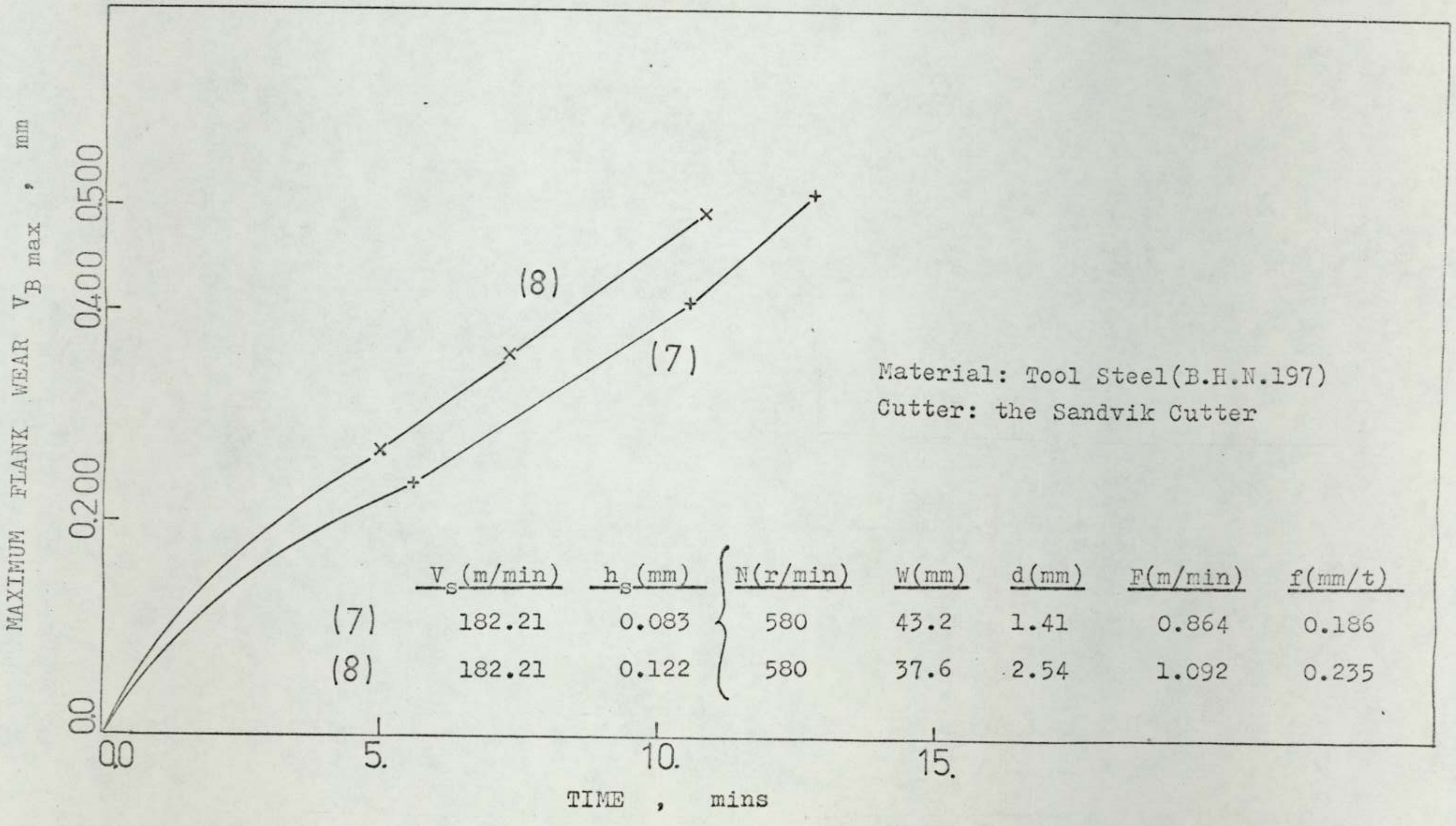
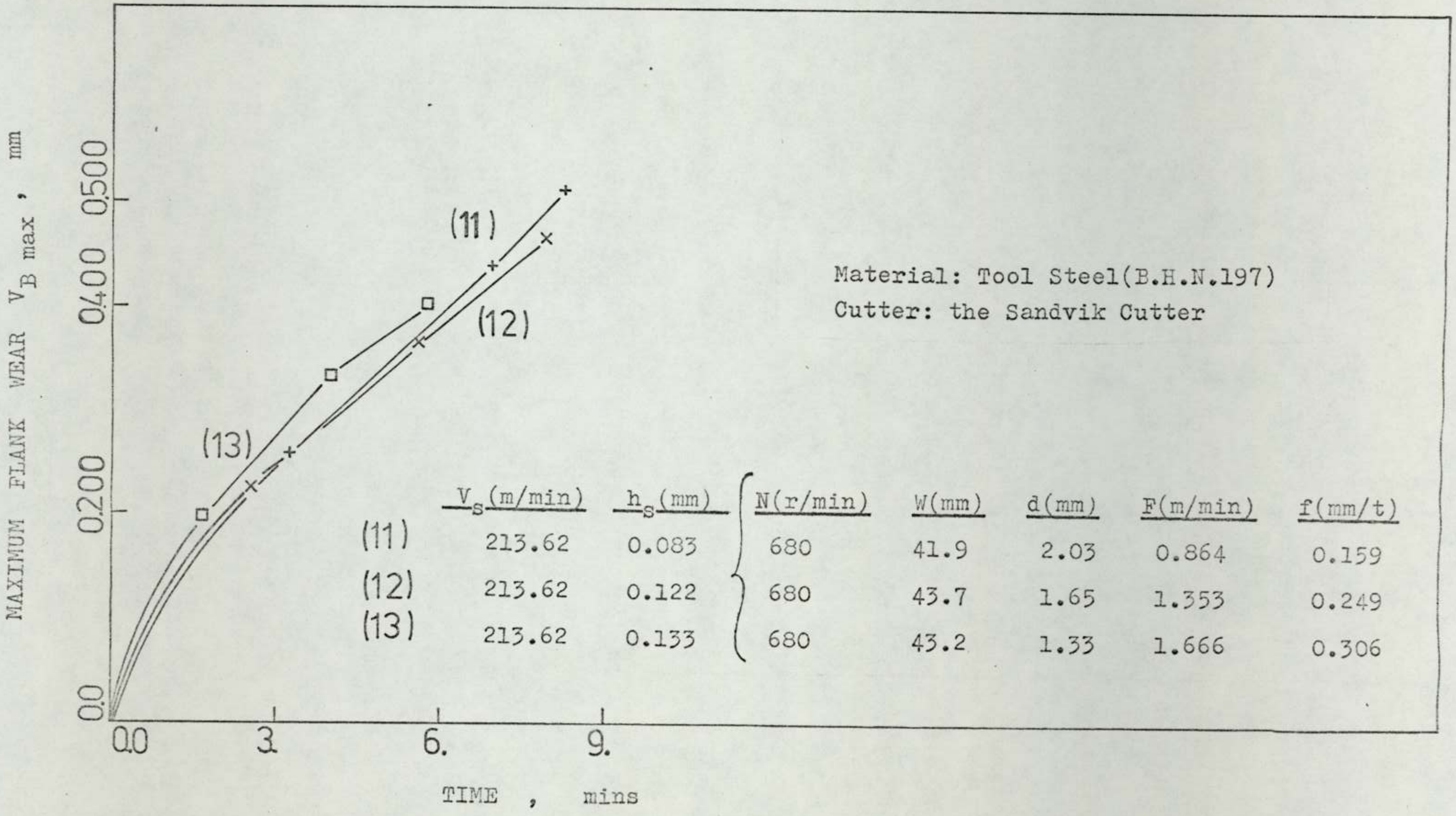


Fig. 47 Wear-Time Progress in Up-Cut Milling



	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(7)	182.21	0.083	580	43.2	1.41	0.864	0.186
(8)	182.21	0.122	580	37.6	2.54	1.092	0.235

Fig.48 Wear-Time Progresses in Up-Cut Milling



Material: Tool Steel(B.H.N.197)
Cutter: the Sandvik Cutter

	V_s(m/min)	h_s(mm)	N(r/min)	W(mm)	d(mm)	F(m/min)	f(mm/t)
(11)	213.62	0.083	680	41.9	2.03	0.864	0.159
(12)	213.62	0.122	680	43.7	1.65	1.353	0.249
(13)	213.62	0.133	680	43.2	1.33	1.666	0.306

Fig.49 Wear-Time Progresses in Up-Cut Milling

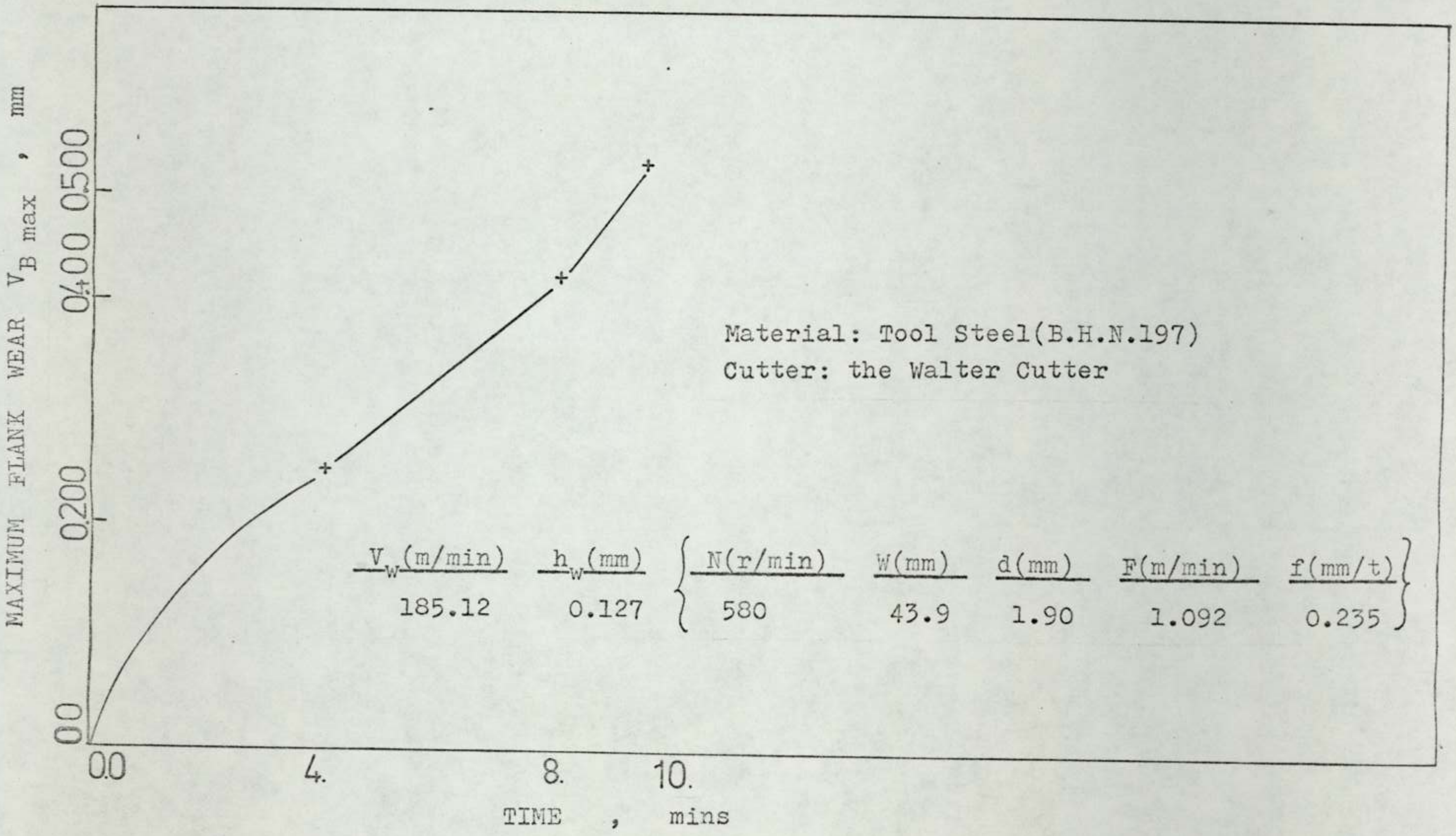


Fig.50 Wear-Time Progress in Up-Cut Milling

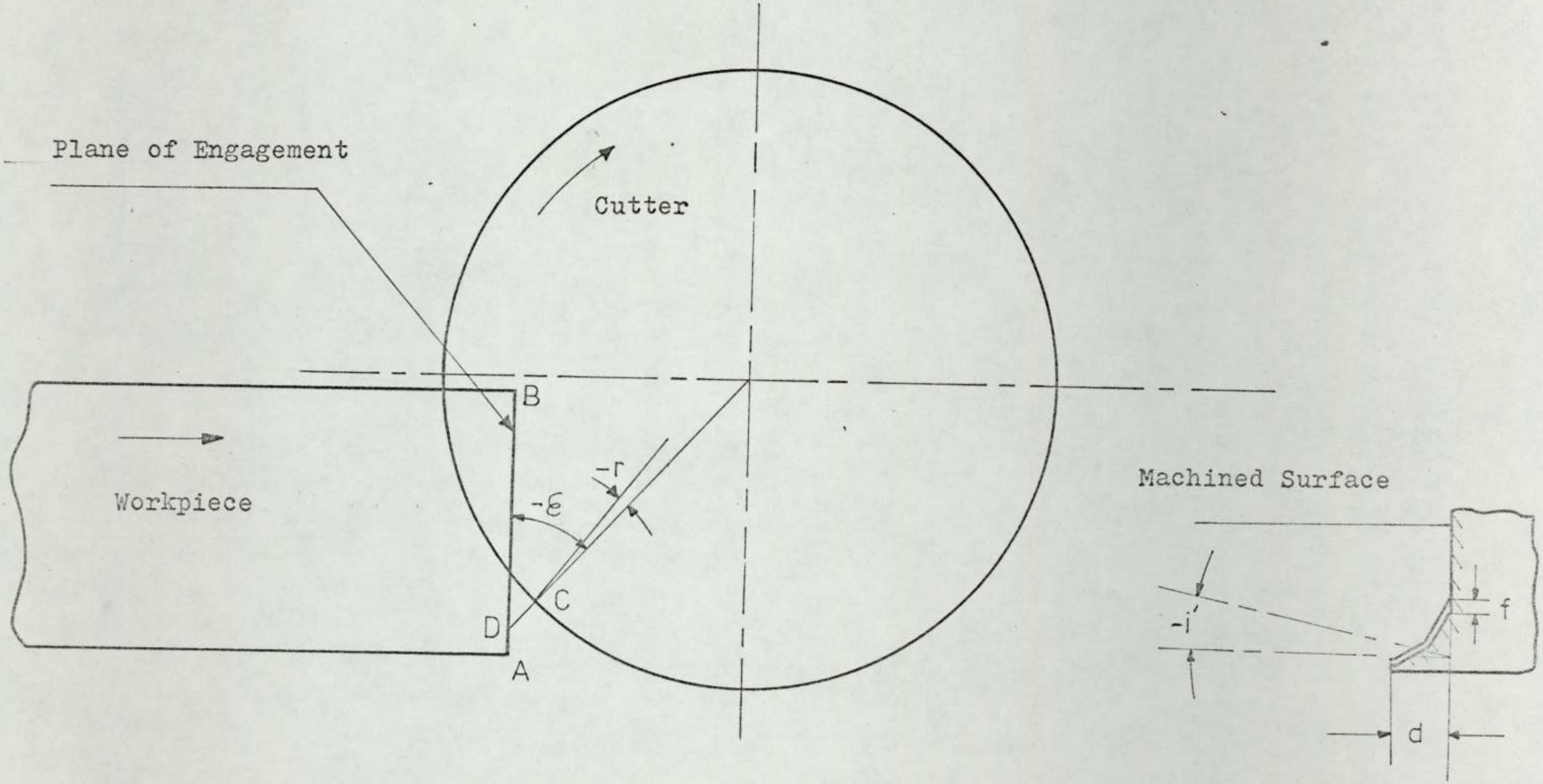


Fig.51 The Intersection Angle i′ in Up-Cut Milling using the Sandvik Cutter

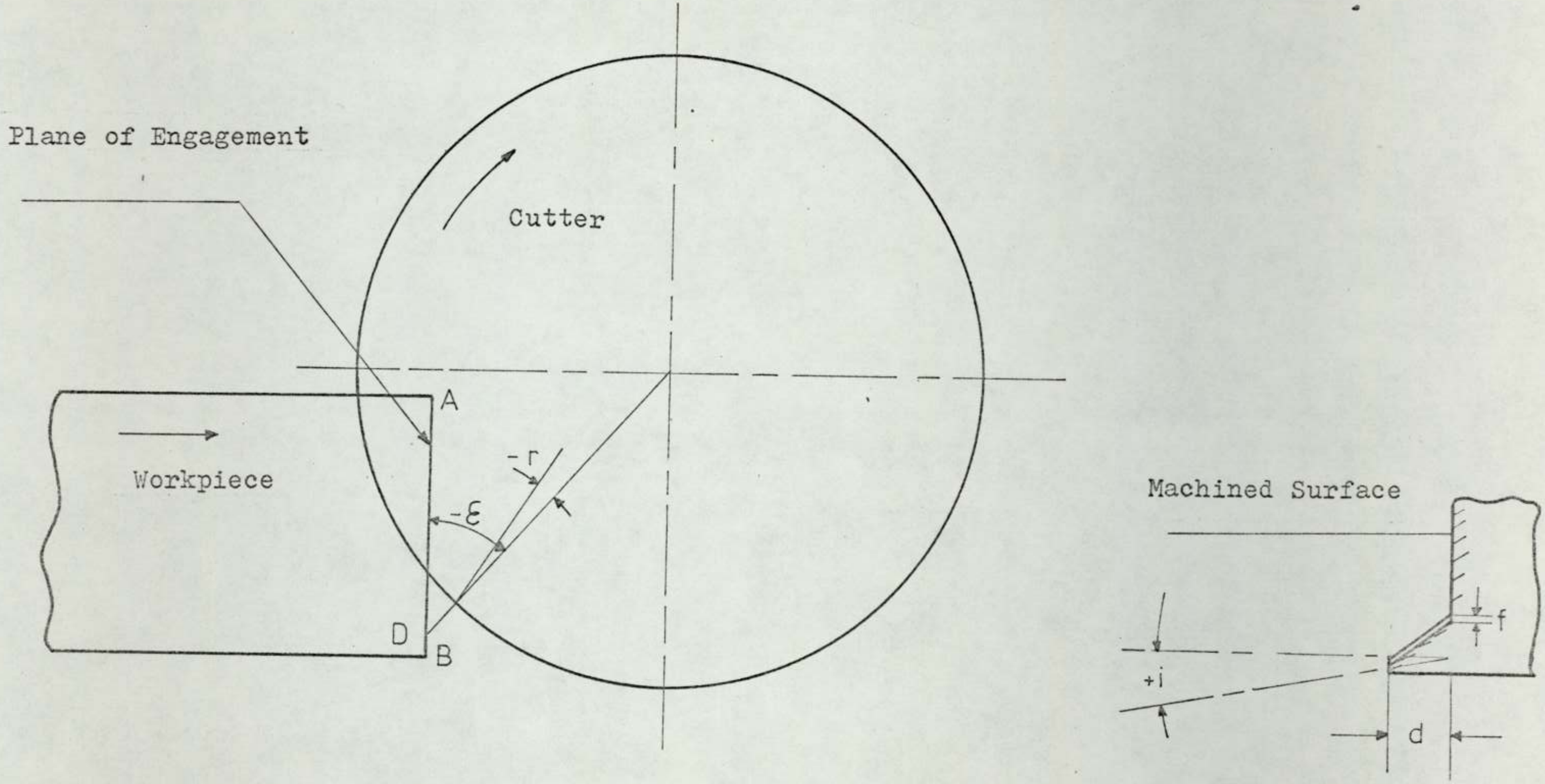


Fig.52 The Intersection Angle i′ in Up-Cut Milling using the Walter Cutter

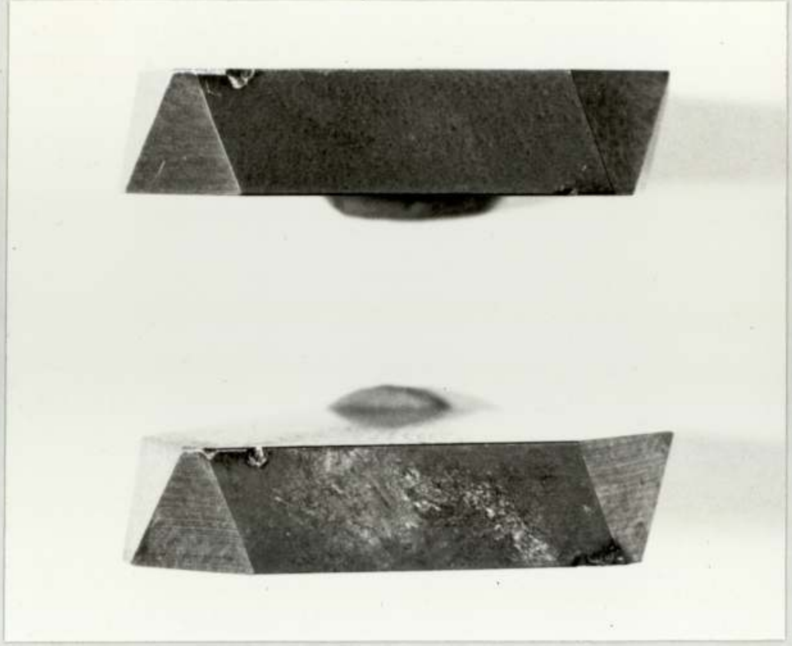


Fig.53 Chipping of Cutting Edges in Up-Cut Milling

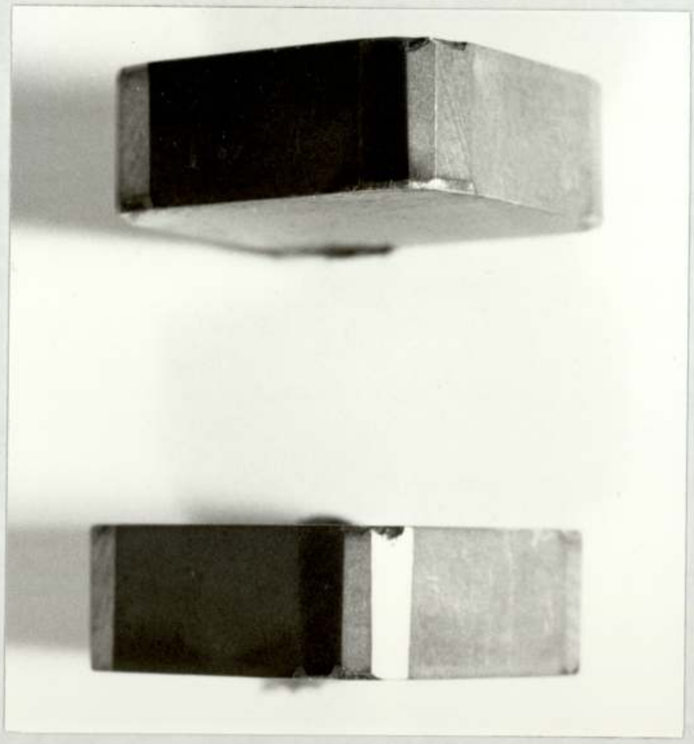


Fig.54 Chipping of Cutting Edges in Up-Cut Milling

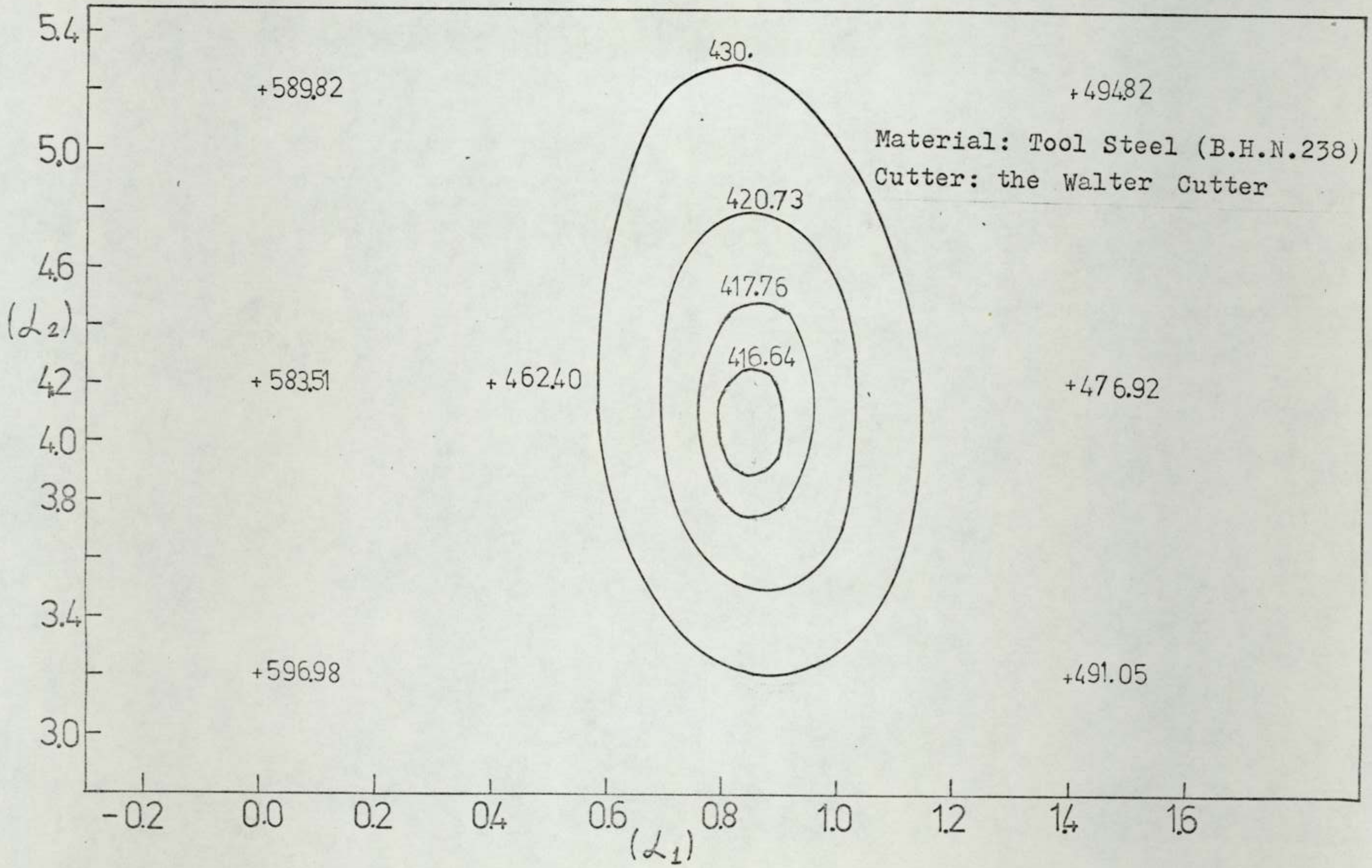


Fig.55 R.S.S. Contour Diagram in α_1-α_2 Plane

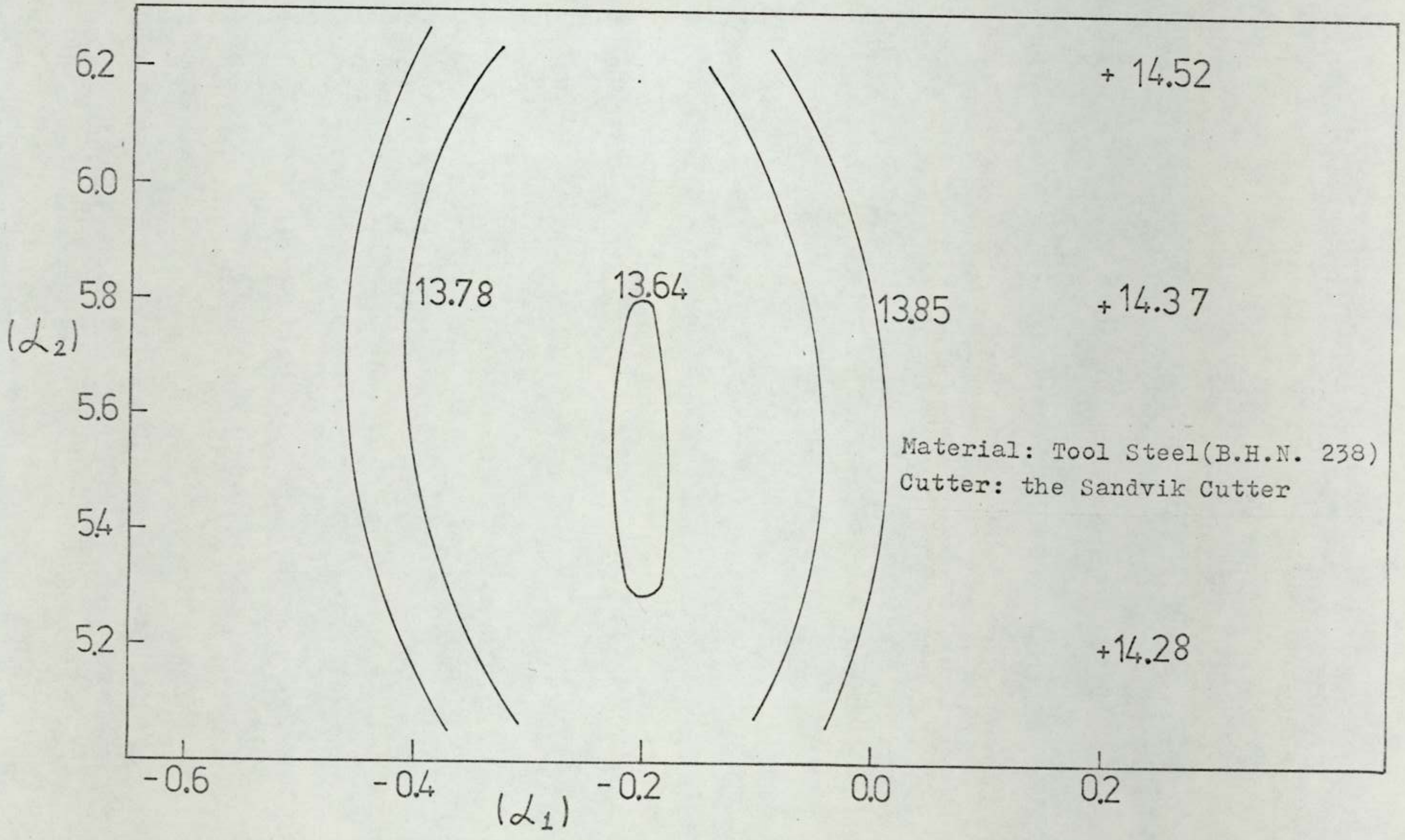


Fig.56 R.S.S. Contour Diagram in $\alpha_1-\alpha_2$ Plane

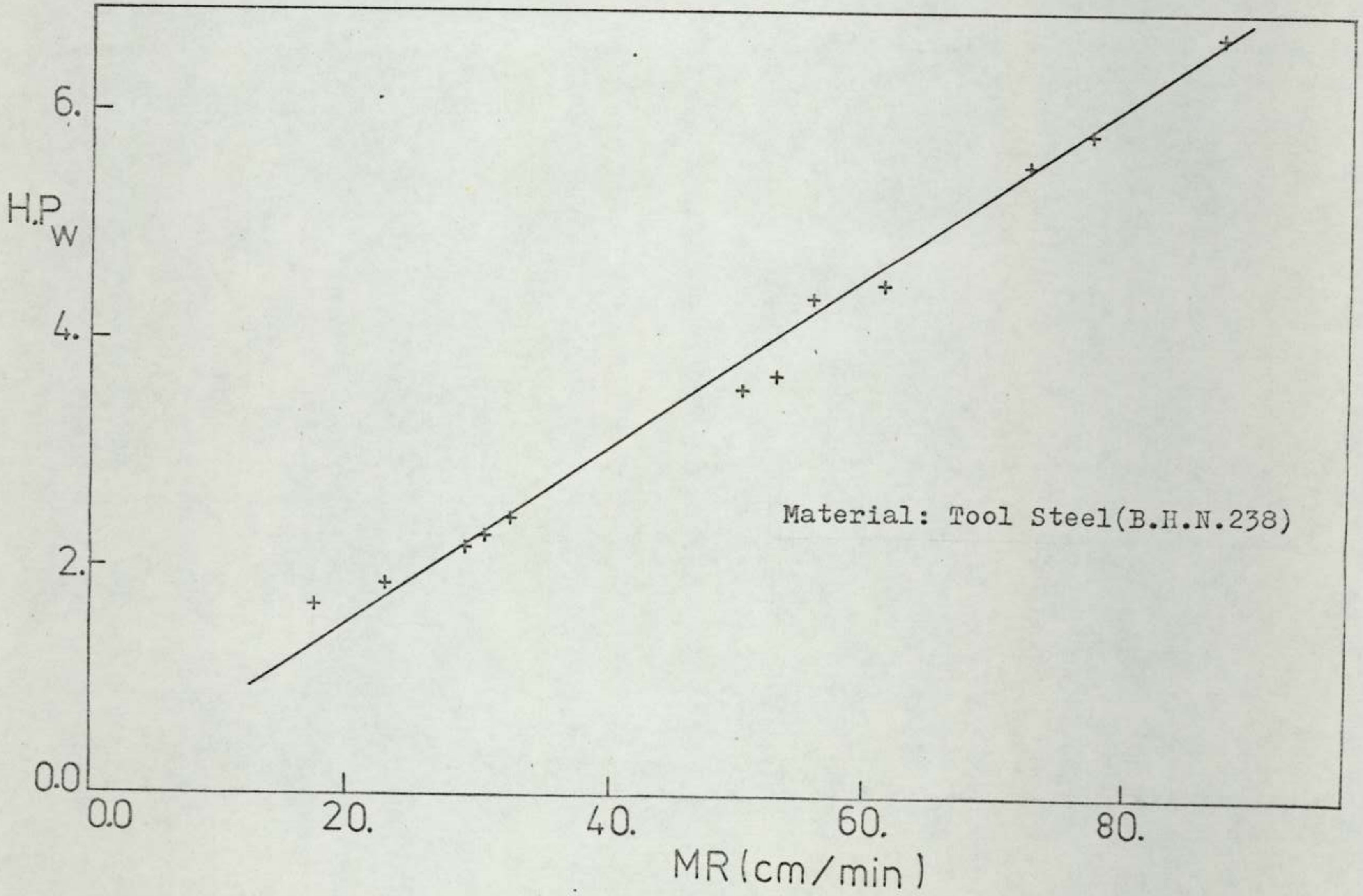


Fig.57 Power Required at the Walter Cutter in Down-Cut Milling

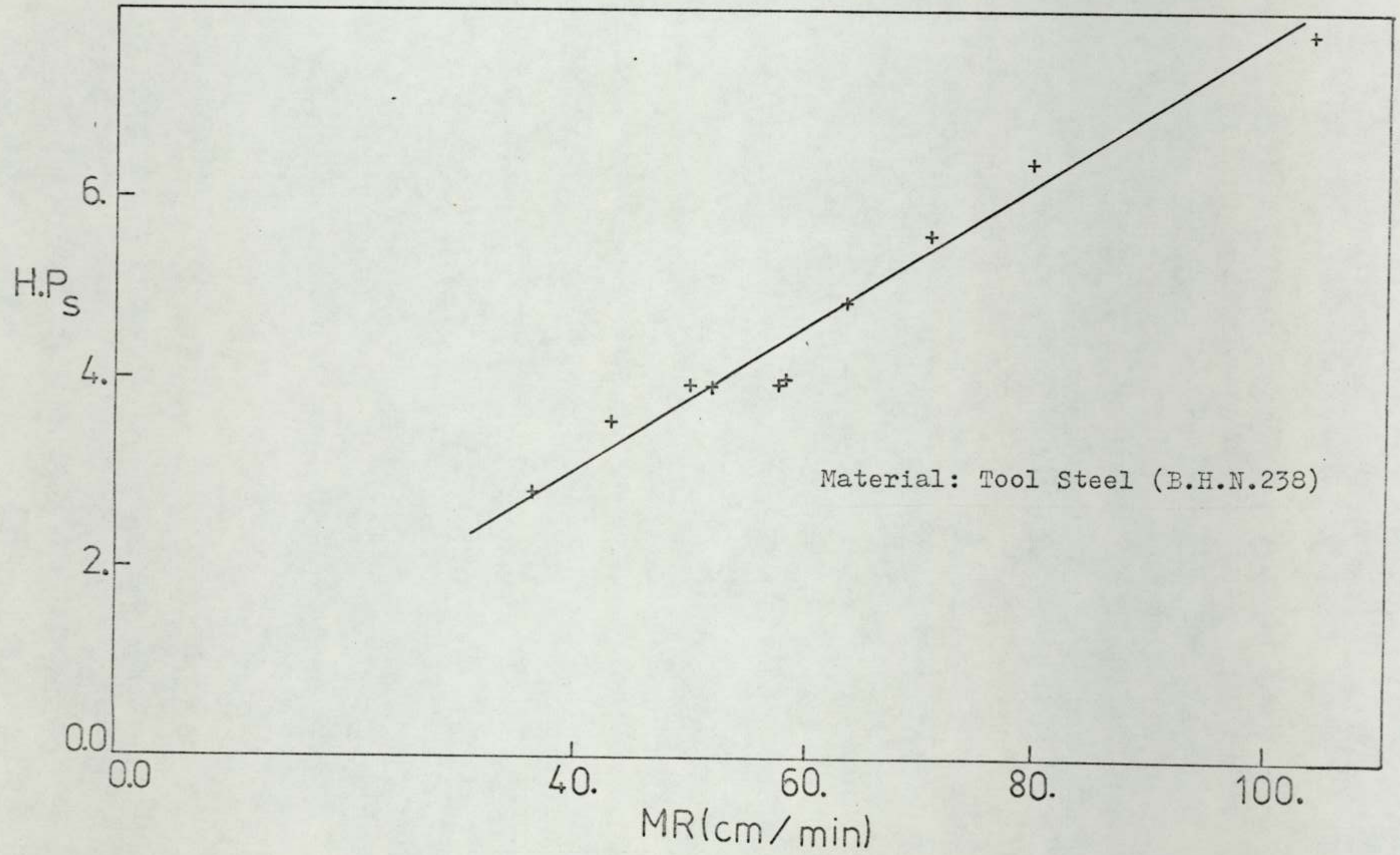


Fig.58 Power Required at the Sandvik Cutter in Down-Cut Milling

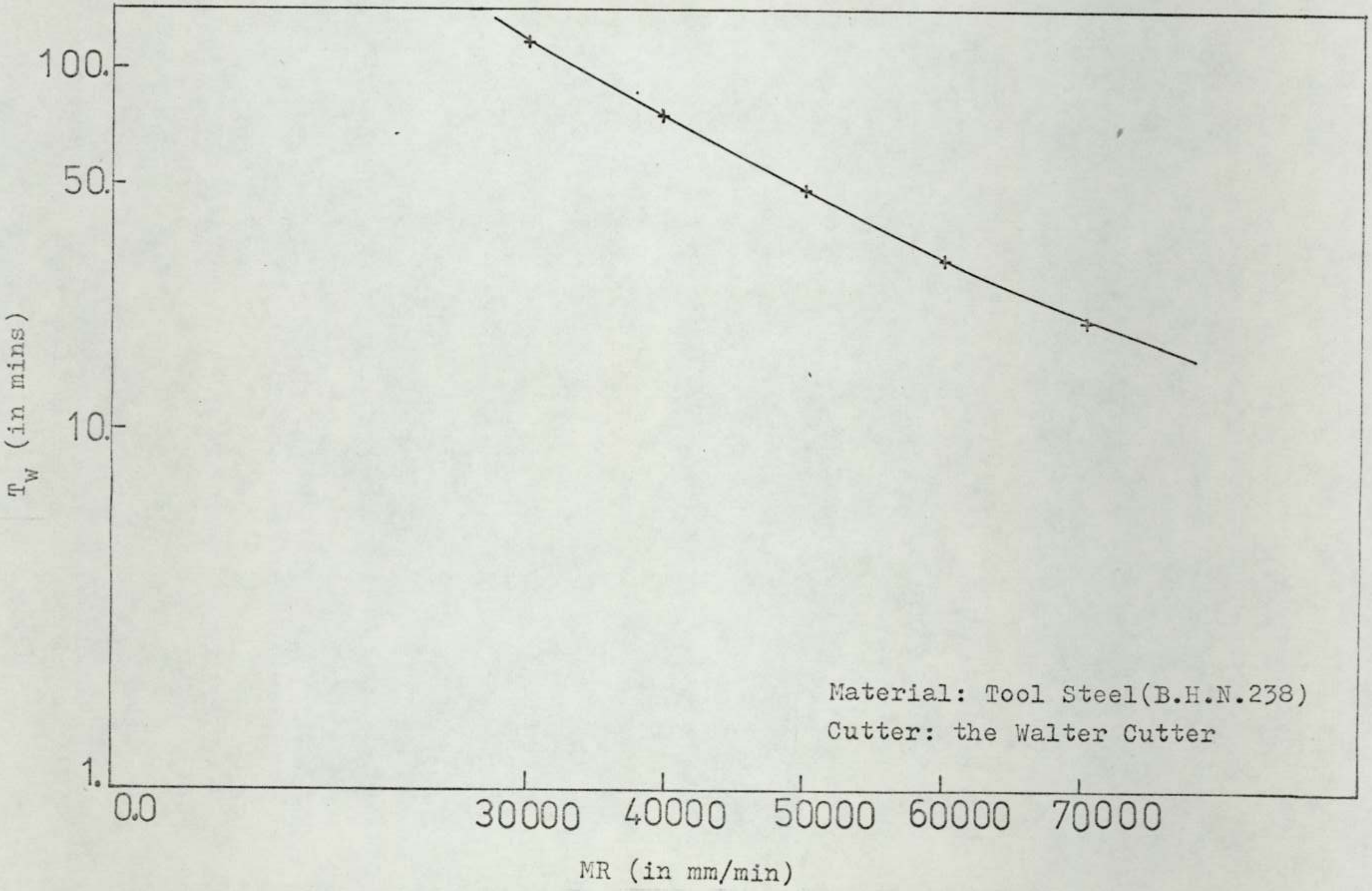


Fig.59 T_w-MR Characteristic Function in Down-Cut Milling

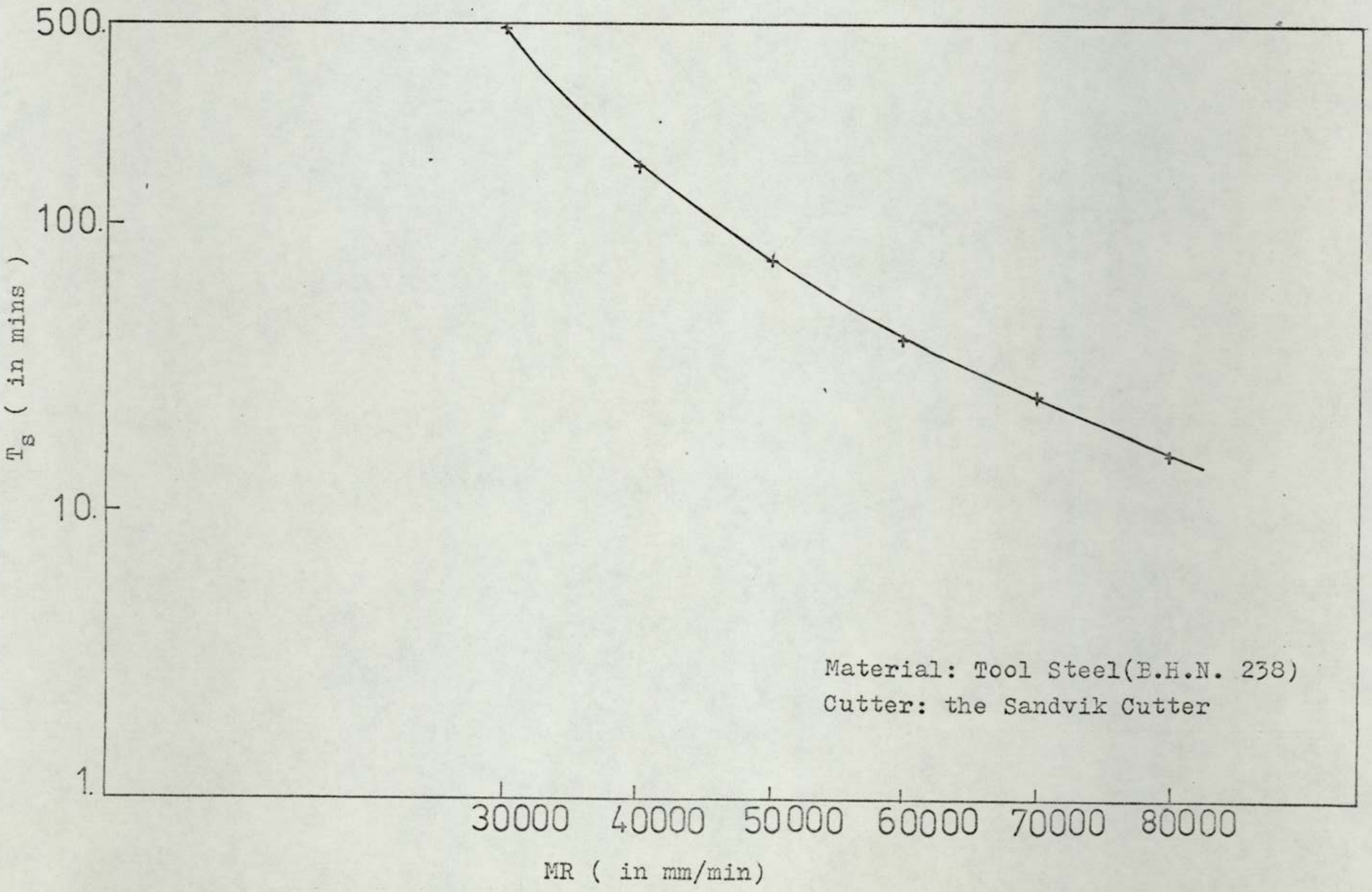


Fig.60 T_s-MR Characteristic Function in Down-Cut Milling