DRESSING OF GRINDING WHEELS FOR HIGH RATE OF METAL REMOVAL

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Summary

There is an increasing demand by industry for the utilisation of high rates of metal removal in the grinding process. Traditionally the grinding process has been considered as a finishing process following rough machining and hardening. If grinding is to be considered as a primary metal removal process, the dressing techniques used to prepare the wheel for grinding need to be modified. In recognising this need, the Science Research Council sponsored a co-ordinated grinding programme to examine the factors that contribute to the attainment of high rates of metal removal. The work reported here is part of that programme and deals with the preparation of grinding wheels using single and multi point dressing tools. The mode of grinding in all tests was cylindrical plunge grinding.

The test programme was designed to show the effect of different dressing tools, wheelspeed, metal removal rate and dress lead on the grinding ratio, surface finish and grinding forces. Consideration is also given to the effect on these measured results when the workspeed and hardness (or grade) of the wheel are varied. The results of the tests are detailed in Chapter 5 and recommendations regarding the settings of operating parameters are also given.

It is apparent from these results that various factors in the dressing and grinding operation influence the initial and subsequent levels of grinding force. These factors are discussed in Chapter 6 and empirical formulae developed to predict the levels of normal and tangential force during grinding. These formulae utilise commonly specified parameters in the grinding process. The ability to predict grinding forces is an essential tool for machine design or for developing adaptive control systems and the formulae presented here are more easily applied than those of other researchers which rely on measurements obtained during testing.

Keywords

Grinding, Wheel Dressing, Force Prediction

DECLARATION

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

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CONTENTS

Page No

Page No

CHAPTER 4

Page No

CHAPTER 5

LIST OF FIGURES

Page No

LIST OF APPENDICES

Page No

CHAPTER 1

INTRODUCTION

Traditionally the role of grinding in the manufacturing industries has been as a finishing process for components in a hardened state. Metal removal rates have been low when compared to the main metal removal processes of turning, shaping, planing and milling.

Recently however the grinding process has been the object of closer attention. If instead of grinding being purely used as a finishing process, the metal removal capability of the process could be increased, certain preliminary operations presently carried out on conventional machines could be transferred to grinding machines. In this way fewer machine set ups would be required, there would be reduction in factory handling and a reduction in the variety of machines leading to greater efficiency.

However, the grinding process is still to a certain extent, due to the nature and complexity of the tools used, shrouded in mystery and whereas most processes have been successfully harnessed to automatic control systems and adaptive control, it is only comparatively recently that the grinding process has experienced a degree of automation. In general grinding processes rely heavily on the experience of the operators and the knowledge gained through practical experience.

Latterly there has been a shortage of skilled personnel which it does not appear will be overcome in the near future. Also with the ever increasing costs of labour, strenuous efforts are being made to reduce the labour cost component of job prices. One area of possible cost reduction is the materials handling of a part in the machine shop. If a single machine could be used to perform a number of operations, this in addition to reducing the variety of machines employed, would also reduce the handling.

As the grinding process is in many cases the only process that can handle finishing operations it would seem sensible to investigate the possibility of utilising grinding as a major metal removal process.

The Science Research Council in recognising this need set up a co-ordinating committee to oversee and direct the current research in this country towards the broad aims of improving the knowledge of grinding and developing methods of increasing the metal removal capability of the grinding process using conventional wheels.

Initial research opened up two avenues of investigations; these were (a) using the conventional grinding process, and (b) the creep feed grinding process.

In the creep feed mode of grinding large amounts of infeed are applied allied with very low rates of workpiece velocity. The majority of creep feed research has been carried out using the surface grinding process, though the range of work is now being extended to encompass the cylindrical grinding process. Creep feed grinding is especially suited to grinding nimonic type alloys used to manufacture turbine blades, in which the material work hardens and hence the metal should be removed in the minimum number of passes. There are however a number of other applications for which the process can be used and it has been successfully used to grind tool steels with cubic boron nitride wheels and ceramics with diamond wheels. The range of machines offered by machine tool manufacturers has been considerably extended over recent years to cater for this type of grinding.

The creep feed grinding process presents problems in that it is desirable that the wheel should be kept as free cutting as possible during the length of the operation. Hence dressing methods such as continuous dressing are sometimes applied with this aim in mind. In many respects therefore the dressing problems associated with creep feed grinding are of a specialised nature and accordingly the work reported here is restricted to a consideration of those dressing processes used in conventional modes of grinding and their application to attain high rates of metal removal. A particular study has been made of the forces that arise as a consequence of the dressing conditions applied. The work reported here is a contribution to the current knowledge in these areas.

CHAPTER 2

DEFINITION OF THE PROBLEM

2.1 Grinding Wheels

The grinding wheel is defined as a bonded abrasive body consisting of a large number of abrasive particles held together by a bonding agent.

The main types of abrasive particle are classified as either conventional or semi-permanent abrasives. The conventional abrasives are aluminium oxide and silicon carbide and the semi-permanent abrasives are diamond (natural and synthetic) and cubic boron nitride. There are other abrasives but their use is relatively restricted and the abrasives listed cover a high percentage of all abrasives used. Each of the abrasives has its own particular sphere of application which may in certain circumstances overlap that of another abrasive. The majority of ferrous materials are ground using aluminium oxide wheels and these wheels are exclusively used for the test programme reported here.

The two major constituents of the wheel are the abrasive grit and the bond. These terms and the specification of wheel used are explained in the succeeding sections.

2.1.1 The Abrasive

Artificial abrasives were first perfected just over 100 years ago. Prior to that, the two minerals used as cutting agents were emery and corundum, both of which are impure forms of aluminium oxide. An important characteristic of the modern artificial abrasives is their purity, which has an important bearing on their efficiency.

Aluminium oxide is prepared in an electric furnace from bauxite (hydrated aluminium oxide). The furnace is provided with two electrodes for supplying the current. A layer of bauxite is placed in the furnace and the electrodes lowered until they make contact. A layer of graphite is then laid between the electrodes to initially induce a current. When the bauxite is molten, another layer is introduced and the electrodes raised, this process continues until the furnace is fully charged. No further graphite is required beyond that applied initially.

The whole process can take up to 36 hours and the furnace temperature is about 1800^{0}C. When the action is completed and the furnace cooled, the ingot is withdrawn, broken up, crushed and rolled into small grains. These grains are screened, graded, washed and dried.

The abrasive is graded by sieving through screens having holes or meshes graded in size. Grit sizes finer than 200 mesh are usually graded by flotation processes.

2.1.2 The Bond

The bond is the substance which when mixed with the abrasive grains holds them together and enables the mixture to be shaped into a wheel, which after a specified treatment will have sufficient mechanical strength for its work. The degree of hardness possessed by a bond is called the grade of the wheel and is an indication of the ability of the bond to hold the abrasive grit. A soft bond indicates that the abrasive grains will break away more readily than a hard one. In selecting the bond a soft bond would be specified for machining hard materials, when it is desirable to discard grains easily when they are worn. Conversely when grinding soft materials, it is desirable to retain the grain for longer periods in the bond and hence a harder bond is used.

The term hardness has no relation to the abrasive material used in its construction - a soft bonded wheel can contain the hardest of abrasives. The principle bonding materials are (a) Vitrified, (b) Silicate, (c) Shellac (d) Rubber, and (e) Resin. About 80% of all wheel bonds are vitrified bonds and all the wheels used on this project were vitrified bonded wheels.

Wheels made using this bond can be supplied in a wider range of grades than any other bonding material. The bonding materials consist of various kinds of fusible and refractory clays with which the grains are thoroughly mixed. Various other materials are added which in the firing process are burnt away leaving voids in the structure, in this way the porosity of the wheel is controlled. The entrapped gases escape through the voids.

There are two methods of forming wheels either by a puddling or a pressing process. The puddling process is akin to that used by potters, but is being rapidly superceded by the pressed product where the material is pressed into shape in a semi dry state. Better control of density can be maintained in the pressing process thereby giving a wider range of grades.

The grade is usually specified by letters of the alphabet. Bond hardness is graded from A (very soft) to Z (very hard) though the usual range of manufacture is covered by the range E (soft) to U (hard). Wheel manufacturers cannot manufacture wheel bonds to a closer tolerance than $\pm\frac{1}{2}$ grade. Hence a K wheel could be $\frac{1}{2}$ a grade harder than specification, and an L wheel $\frac{1}{2}$ a grade softer, so that in reality the two wheels are the same though differently specified.

The proportion of bond in the wheel can vary between 10% and 30% by volume. If this proportion is high the spacing between the abrasive grains will be high or open structured. If it is low a closely structured wheel will result. Even with identical bonds and abrasives the structure will influence the grinding action. The open structured wheel will tend to have the effect of a soft bond and vice-versa. Wheel structure is specified by numbers between 1 and 15, the low numbers referring to close structures and high numbers to open structures.

2.2 Methods of Dressing Grinding Wheels

2.2.1 The Dressing Process

The dressing process in essence satisfies a two fold function; initially the wheel is trued and then the wheel is prepared for a cutting operation.

Generally speaking when using conventional grinding wheels the two processes are carried out simultaneously and there is no reason to separate them. Indeed if they are separated extra costs will be added to the process. It is only when using diamond and cubic boron nitride abrasives that a distinct separation is made because separate tools are used for the two processes.

During the trueing process the dressing tool is used to remove the layer of worn and damaged grits, any loading that may have resulted during previous grinding and any contamination arising from coolant absorption. During this operation the wheel is returned to a concentric condition. In the latter half of the process the desired form, consistency and cutting qualities are applied to the wheel by the dressing tool.

However, in order that the results of all tests were consistent during the research programme, these two processes were distinctly separated. Following each grinding test the wheel was trued to a stable condition using a multi point diamond before the dressing condition was applied with the specified dressing tool.

2.2.2 Single Point Dressing Tools

The single point dressing tool is the most widely used tool for dressing operations. The cost of diamond has risen steadily over the years and this has meant that stones previously graded as industrial diamonds are now marketed as gem stones. The stones used for single point diamonds were previously drawn from this superior grade of industrial diamond and their continued use has lead to a sharp price rise in this grade of diamond. The alternative of using inferior stones gives a cheaper tool but usually results in a tool which gives a shorter life. Previously almost any size of diamond was used for dressing and frequently the size of diamond used was far larger than required. With increasing costs it therefore follows that the size of diamond must be more closely specified for the range of operations to be carried out and that in use, operational procedures should be practised that will ensure that the full potential of the diamond is realised.

In this report, the results obtained using the single point diamond were used to assess the potential of other modes of dressing and some measurements of diamond wear were made at enhanced wheel speeds.

2.2.3 Multi Point Dressing Tools

These tools take many forms; Figure 1 shows a range of tools offered by one manufacturer. The proliferation of configurations bears little relation to application but rather more to cosmetic appeal. The diamonds in the tool may be set in random or regular patterns.

Generally these tools are cheaper than single point tools. They utilise small sizes of diamond which are embedded in a sintered metal bond. Usually as one of the diamonds is exhausted other diamonds in the matrix become available for the dressing operation. In addition there may be a number of such points, at various stages of wear in operation at the same time. There can be no resetting with a tool of this type and when the dressing grits are exhausted the tool is discarded and another substituted.

Use of multi points reduces the cost of dressing, in that it uses the small sizes of diamond that are unsuitable for gem stones and certainly too small to be used for single point tools.

The blade dresser is a multi point dressing tool with a regular distribution of dressing points set in the form of a blade; in operation the blade is set vertically. Figure 2 shows the blade dresser used in the test programme. Although classed as a multi point dressing tool it has gained an identity of its own and has become widely used in recent years, particularly in Germany where it is known as a 'fliesche'. Accordingly in this series of tests, the blade dresser is treated separately.

2.2.4 Crush Dressing and Diamond Roller Dressing

In crush dressing, a hardened roll is pressed onto the wheel periphery under a high load. The wheel periphery rotates at slow speed and this rotation serves to drive the roller. As its name implies, the worn abrasive grains are crushed and new cutting points generated.

In diamond roller dressing, however, instead of a plain roll, a roll on which diamonds are set or plated is used. This roll is motor driven and used to dress the grinding wheel which rotates at normal operating speeds. Crush dressing and diamond roller dressing are particularly useful in generating complex shapes on the periphery of grinding wheels. By using this system, considerable time can be saved in generating these profiles over methods utilising single point diamonds and profiling mechanisms.

The use of these methods, though included in the investigations of the S.R.C. grinding programme, is beyond the scope of this thesis. It is only detailed here to complete the range of modern wheel dressing techniques.

2.3 Research Programme Specifications

As this work is part of an overall programme of grinding research sponsored by the Science Research Council (S.R.C.) at a number of research establishments, various factors have been specified to facilitate the interchange and comparison of results. These mainly relate to the type of wheels, workpiece materials, coolant and coolant application and are as follows:-

Grinding Wheels:	A 60 L,	A 60 K
Workpiece Materials:	EN 9,	EN 31
Coolant:	Meteor Oil	OSOL:EH

The coolant application nozzle is detailed in Figure 3 and described in Chapter 4.

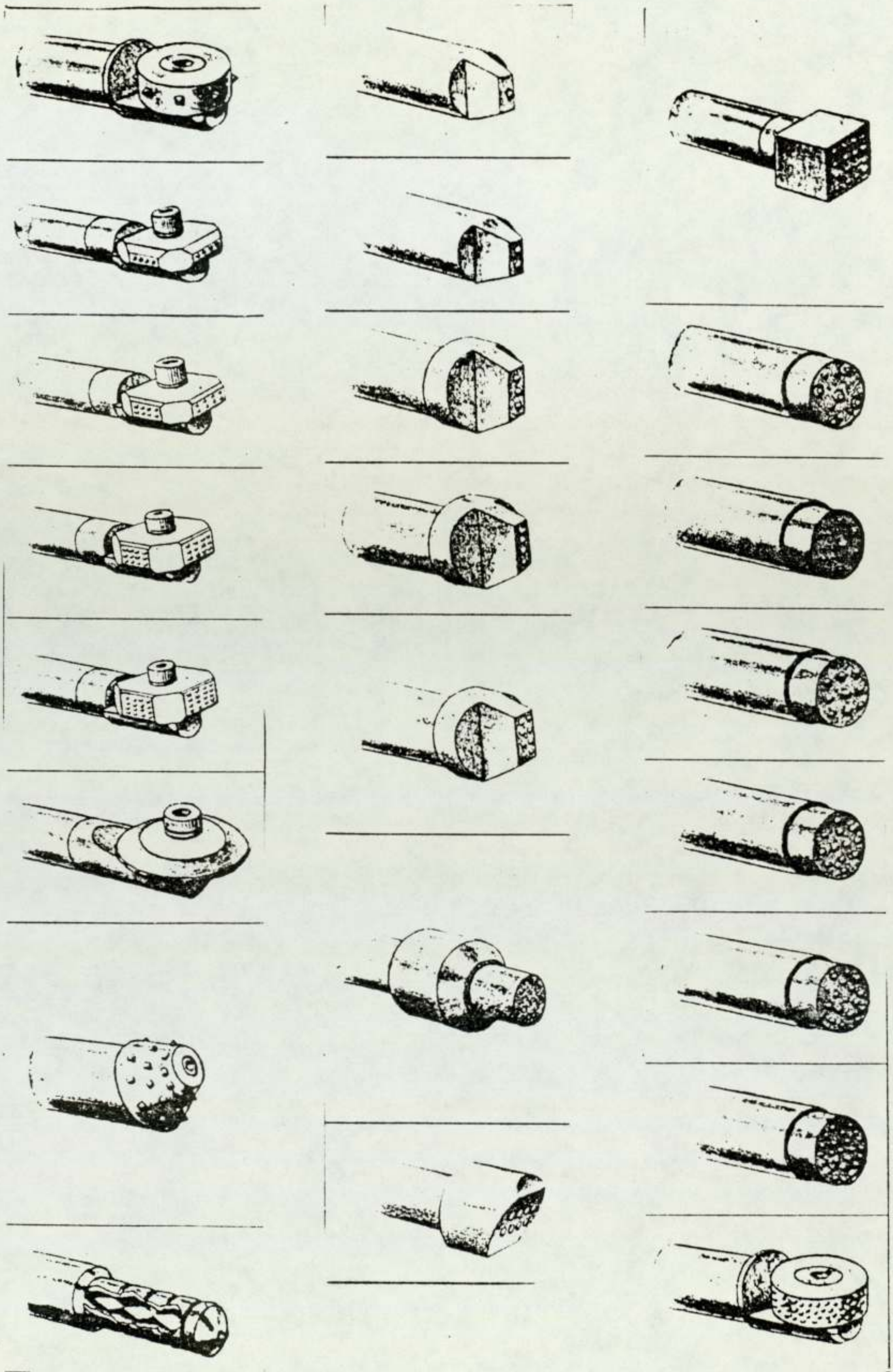
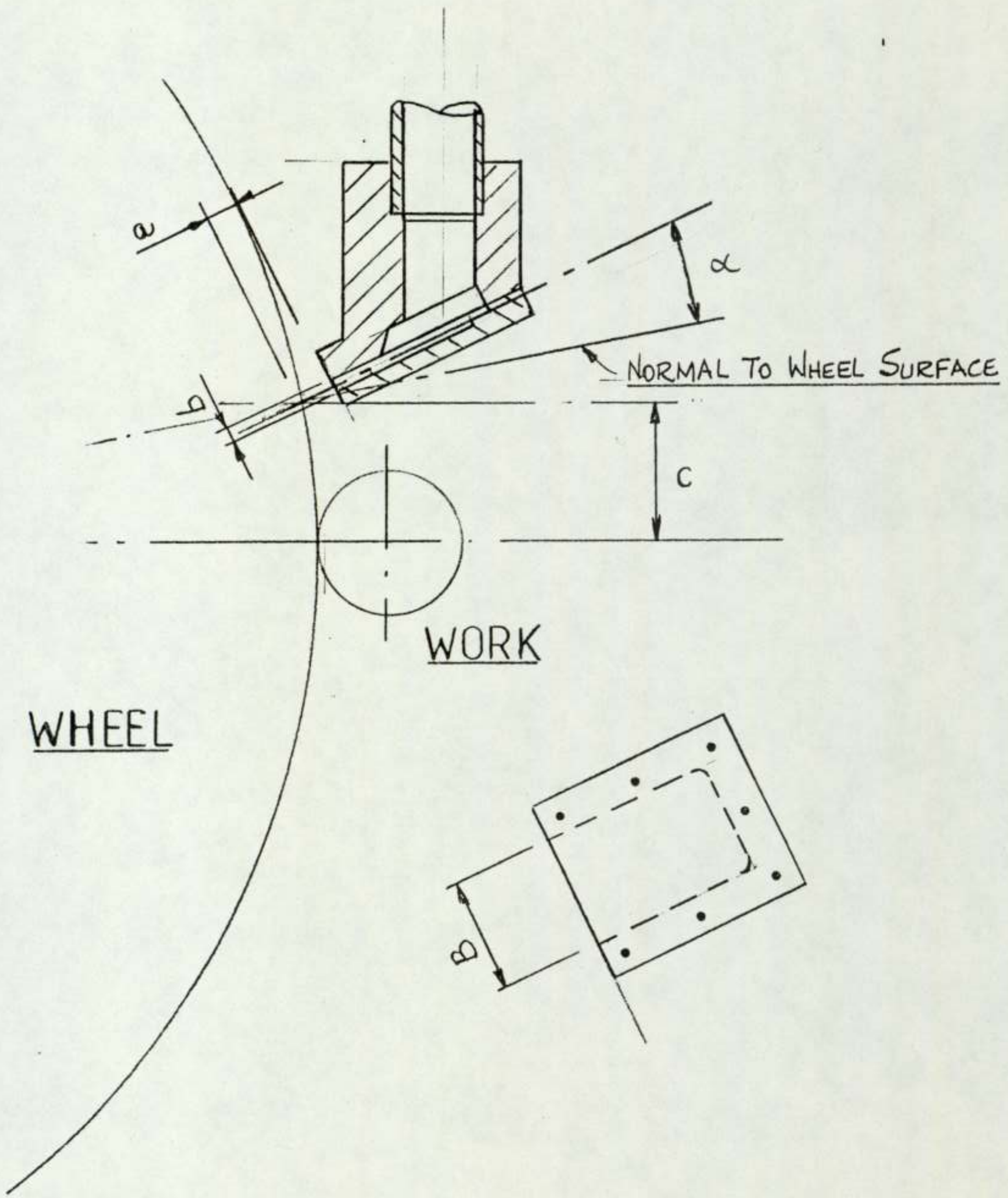


Fig.1 Range of Multi-Point Dressing Tools

FIGURE 2

THE BLADE DRESSER



NOZZLE GAP	b	4 MM
NOZZLE WIDTH	B	50 MM
ANGLE OF APPLICATION	α	15°
NOZZLE STAND OFF DISTANCE	a	5 MM
NOZZLE HEIGHT	c	70 MM

FIG 3 COOLANT NOZZLE

CHAPTER 3

A Review of previous work concerning Dressing of Grinding Wheels and their subsequent performance

3.1 Introduction

The success of a grinding wheel, once it is selected, will depend on the manner in which it is dressed. The dressing parameters establish the cutting capability of the wheel. Major variations in grinding wheel performance can be obtained by variation of the mechanical finishing of the face of the wheel with the selected dressing tool.

The selection of the dressing method will, to a large extent, be determined by the geometry of the part being produced. The use of single point diamonds as dressing tools predominates in industry as they can be used to generate either plain or contoured surfaces. Accurate contour or form dressing can also be accomplished using crush and rotary diamond dressing rolls, which because of their speed and convenience are favoured when components are mass produced. Multi point diamond dressing tools are finding increasing use due to their ability to give predictable results and their cheapness in relation to single point tools.

3.2 Single Point Diamond Dressing Tools

Prior to the advent of single point dressing tools dressing of grinding wheels was achieved by various mechanical dressing tools which are still used today on certain occasions. With an increasing demand for a full system of interchangeable manufacture, better and more consistent methods of dressing grinding wheels were required. The requirement for consistency was initially fulfilled by the use of the single point diamond dresser.

Initially the tool holders were crude affairs, generally made of steel with copper inserts. The diamond point was selected by the grinder operator who then placed the diamond in its holder and peened over the edges of the copper insert. Diamonds selected tended to be large and the Ford Co are cited (1)* as rarely using anything less than 20 carats and in one instance, a stone of 125 carats. This state of affairs compares with the present trend of using stones of about 2 carats or less and a maximum size of 4 carats.

With the advent of powder metallurgy techniques, it became possible to hold diamonds firmly in their shanks and to make use of smaller sizes of diamond. Single point dressers comprise three elements; the holder, the diamond in the correct orientation, and the powder matrix.

3.2.1 Selection of the Diamond

The ideal diamond (1) for a single point diamond dresser is quoted as having at least 5 clean, sharp and well defined points which by judicious use can all be used for dressing operations following resetting operations. The octahedron, with eight plane faces, and the dodecahedron with twelve faces, are the most widely used diamond shapes for single point dressers.

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* Figures in brackets refer to the list of references given in Chapter 9

The importance of taking crystalline structure into consideration when using the tool is emphasised by both Busch (2) and Merlyn and Drukker (3). In normal practice, a diamond will initially be set to show its strongest face.

There are several methods of selecting the size of diamond to be used, the most common being the points system (4). In this system, points up to a value of 10 are awarded on the basis of various factors:-

i) Grinding wheel dimensions (diameter and width)
ii) Type of abrasive
iii) Grit size
iv) Grade
v) Bond

The total aggregate points are then divided by 6 to give the required size of diamond in carats. This system has various modifications, one of which (5) gives a range of sizes between a minimum and maximum size of diamond required.

3.2.2 Mode of use of single point diamonds

There is general agreement by various authors (1, 4, 5) that the following procedures should be adopted to prolong diamond tool life:-

i) As temperatures of 1500^{0}C can be experienced during the dressing operation, it is essential that a copious supply of coolant is applied to both the wheel and dressing tool. This ensures lower temperatures as burning of diamond is instantaneous at high temperatures.

ii) If grinding wheels are to be dressed dry, it should be borne in mind that graphitisation of diamond will take place at 700^0C in air and time should be allowed for the diamond to cool between passes.

iii) Coolant flow should always be started prior to the commencement of the dressing pass as a diamond can shatter under the influence of a high temperature gradient.

iv) Single point diamond tools should always be inclined at an angle of $10\text{-}15^0$, pointing in the direction of rotation of the grinding wheel, as shown in Figure 4. This reduces the possibility of cleavage or fracture due to shock. In addition it helps to maintain a sharp point.

v) Under ideal conditions, the tool should be inclined between 10^0 and 20^0 to the direction of tool traverse. However, this is seldom done on production grinders as this restriction would require that dressing operations are only carried out in one direction. Research by PERA (4) showed that in rough grinding, an inclination of 30^0 to the traverse direction gave lower power consumption while at a

0^0 inclination, wheel wear was lower. There was no significant difference on surface finish or wheel loading. In finish grinding, it was found that an inclination of 0^0 gave least wheel loading while there was no significant difference in the results for power consumption, wheel wear and surface finish when using inclinations of 0^0 and 30^0. However, Pahlitzsch (6) states that the effective height of roughness increases with decreasing tool angles of inclination.

vi) The diamond should be rotated frequently. The amount of rotation specified varies between authors but the general concensus is not less than 15^0 (2) and between 20^0 and 40^0 (5).

3.2.3 The effect of dressing parameters on wheel performance

3.2.3.1 Depth of cut

The two extremes of dressing using single point dressing tools have been clearly specified (7). For fast metal removal, use large downfeeds per dressing pass and fast (cross) feed rates. Downfeeds should be about 0.025 mm and feed should be about 500 mm/min; only one pass should be made for each downfeed increment. At the other extreme when dressing for a smooth finish, a small dressing feed should be applied of 0.005 mm per pass and a (cross) feed of 50 mm/min. At the conclusion of dressing, one or two passes should be made without infeed.

However, Vickerstaff (8) concluded that the depth of diamond infeed was probably not significant on values for surface finish over the range of infeeds of 0.0075 mm to 0.033 mm and that assuming a constant dresser profile surface finish results are controlled by the traverse rate of the dressing tool. This conclusion is also substantiated by Pahlitzsch and Appun (9) and Pahlitzsch and Thoeing (10) when studying the effect of dressing operations on the surface roughness of the grinding wheel peripheral face. They concluded that the feed rate of the diamond dressing tool across the wheel face had a greater effect on wheel surface roughness than had the depth of cut of the diamond tool. Kaliszer and Trmal (11) postulated that the depth of penetration could be determined as follows:-

$$R_T = \frac{S_d^{\,2}}{8r_d}$$

where R_T = depth of penetration

S_d = dress lead

r_d = radius of diamond tip

It was further stated that the depth of penetration should not exceed 2.5 µm or 20% of applied infeed, and that the normally selected dressing depth of cut of 0.015 mm had little or no effect upon the profile generated on the wheel.

Pacitti and Rubenstein (12), however, showed that as the dressing depth of cut increases, the rate of increase in force which is a measure of plateau area per grit, and the rate of wheel wear, both decrease and their published results showed that the greatest increase in grinding force corresponded with the greatest wheel wear rate. This is in direct contrast to the conclusions of Pattinson and Chisholm (13) who concluded that the wheel wear in the secondary stage to be only slightly dependent on dressing severity. The reasons for this and other discrepancies will be reviewed following the sections dealing with dressing lead and diamond shape.

Tsuwa (14) showed that the effective grain spacing was influenced by the depth of cut applied to the dresser but that after a short period of grinding, the sharp edges wear and the spacing becomes smaller.

Lindsay (15) advanced the following formula derived by analysis:-

$$\Lambda^*_K = B(V_L)\left(\frac{C_o}{L}\right)^{\frac{1}{4}}(L)^{\frac{1}{2}}\left(1 \pm \frac{D_L}{D_K}\right)^{\frac{1}{2}}$$

where Λ^*_K = metal removal parameter

B = constant

V_L = wheel speed

C_o = Dresser infeed x 2

L = dress lead

D_L = diameter of wheel

D_K = diameter of hole ground

From the above, it was concluded that increasing the infeed of the diamond dressing tool had the effect of increasing the metal removal rate by a $\frac{1}{4}$ power.

3.2.3.2 Dressing Lead

Whereas the effect of varying the dresser infeed does not appear to have produced uniform conclusions, the effects of varying dress lead do give a general uniformity of opinion among researchers.

Lindsay (15) concluded that by increasing dress lead the metal removal capability would be increased by a $\frac{1}{2}$ power. Pande and Lal (16), however, stated that the metal removal capability of a grinding wheel remains almost constant and is not affected by variation in dress feed and dress lead. Pattinson and Chisholm (13) concluded that coarse dressing produced a wheel surface having a relatively low density of active cutting edges and a large amount of initial wheel wear. It was thought that this coarse dressing not only produced a rough surface but led to considerable sub surface damage to the active grits causing them to fracture more easily. Following this initial wear it was postulated that as the active grits were mainly wearing on their flank surfaces and were relatively stable, the rate of radial wheel wear would be relatively stable and unaffected by the severity of dressing. It was pointed out that the coarsely dressed wheel with a more open structure gives adequate chip clearance and lower grinding forces and that severe dressing does not necessarily decrease the amount of material which can be ground between dressings.

Tsuwa (14), however, concluded that an optimum dressing feed with regard to grinding volume occurred when the dress lead was equal to the breadth of the dresser point as shown in Figure 5. Under these conditions, it was found that this gave the most favourable condition for the distribution of cutting edges while if the feed were higher, the cutting edges became less than those necessary. Conversely a finer feed produced more cutting edges than was necessary. These results should, however, be treated with some caution as grinding times were extremely short.

Merlijn and Drukker (3) related the dress lead to the wheel grit size and concluded that in order to obtain individual grits in as sharp a state as possible and thereby attain a wheel of maximum efficiency, each grit of the wheel surface should not be 'attacked' by the diamond point more than twice. As a result of this, the feed per wheel revolution should be slightly less than the grit size.

3.2.3.3 Diamond Wear and Shape

Tests show (5, 17) that the area of wear flat of the diamond can be considerably affected by the dressing parameters (dressing depth of cut and feed rate) and grit size of the dressed wheel.

The wear pattern of the diamond is similar to that of most tooling in that there is a rapid initial wear phase which then falls away to a much steadier, almost linear rate. The linear wear rate will depend not only on the dressing parameters selected but also on the orientation of the stone selected. The parameter which has the greatest effect on diamond wear is feed rate. Increasing the dressing depth of cut alone has very little effect but if this is increased in conjunction with an increased feed rate, the wear rate will accelerate.

Thorn (17) showed that the rate of wear did not increase with increasing wheelspeed though Merlijn and Drukker (3) indicated that for wheelspeeds of 60 m/s diamond sizes should be doubled over those selected for operation at 30 m/s. No reason was advanced for this increase in size though it may be concluded that the larger diamond with its increased surface area would be more efficient in dissipating the extra heat generated.

All researchers (5, 8, 18, 19, 20) are in broad agreement that the shape of the diamond will have a significant effect on the performance of the wheel and that at a given traverse rate the wheel profile will become progressively smoother as the wear flat increases in size. It is generally accepted that if the wear flat is allowed to exceed 1 mm^2 it is impossible to produce a free cutting wheel which could lead to possible damage to the workpiece. In addition it becomes increasingly difficult to reset the diamond in its holder and thereby to take advantage of other useable points. The progression of the wear flat can be arrested to a degree by regularly turning the diamond in its holder.

3.2.3.4 The interactions of the dressing parameters

It will be noted that there have been instances when the conclusions of the researchers have differed. Pacitti and Rubenstein (12) using infeeds from 0 to 0.025 mm concluded that beneficial effects were derived by using infeeds at the high end of the range. This is in contrast to other researchers (11, 13, 20) who suggest lower infeeds or find no significant difference for results over a range of infeeds. The reason this discrepancy may have arisen is due to the diamond shape used by Pacitti and Rubenstein. In their tests, the diamond had a 0.635 mm x 0.635 mm wear flat and was traversed across the wheel at a rate of 0.38 mm per wheel revolution.

In conditions such as these at small infeeds a glazed wheel will result; if a higher infeed is applied the wheel rim will be unstable. Consequently the forces in grinding would dislodge or fracture some grits and some sharp cutting edges would be produced. Fisher (20) recommends a sharp diamond and states that as the diamond wears the traverse rate must be increased to maintain a similar wheel performance. Reference to the expression for depth of penetration given by Kaliszer and Trmal (11) confirms that approach.

Though no details of the dressing diamond are given by Pande and Lal (16) one can only conclude that an appreciable wear flat had developed in their programme to lead them to the conclusion that neither dress lead or infeed had any effect on the metal removal capability of the grinding wheel.

The discrepancy between researchers conclusions serves to underline the importance of considering all parameters in dressing and reference to Figure 5 shows the interactions between diamond traverse rate, infeed and shape.

3.2.4 The effect of dressing conditions on wheel wear

Research and testing by Grisbrook et al (21) shows that the greatest wheel loss is due to trueing and dressing of the wheel and by comparison the loss during grinding is minimal. Therefore an important objective of any grinding programme is the reduction of the need for excessive trueing.

During grinding the pattern of wheel wear has been shown to fall into three distinct phases (13, 21, 22, 23).

Phase A: consisting of intensive wheel wear which is non linear and related to dressing technique

Phase B: a linear rate of wear which will remain constant for long periods under 'good' conditions

Phase C: results when the wheel is overloaded and stalls or excessive vibrations occur; wheel wear occurs due to bond post rupture and whole grits are dislodged

This pattern of wheel wear is illustrated in Figure 6. In the second phase, two types of wear may occur, attritious wear or fracture wear of grits, and both these types are accommodated within very small amounts of radial wheel wear. Rubenstein (22) concludes that though the wear in the primary stage reflects the severity of the dressing techniques, the wear in the secondary stage is a function of wheel and workpiece properties and grinding conditions and is not a function of dressing techniques. This is at variance with Pande and Lal (16) who state that metal removal rate is not influenced by dressing parameters but that variations in grinding ratio (ie wear rate) are due to dressing conditions applied.

Pacitti and Rubenstein (12) in addition to recognising the three stages of wear previously mentioned added a fourth stage (Phase D) in which there is a decrease in grinding force and when there could be either an increase or decrease in wheel wear rate. In practice grinding would be terminated just before or at the onset of Phase C because at this point vibration levels increase and lobing of the wheel may occur. If grinding is carried out in the 'C' region increased quantities of the wheel will have to be removed in order to regain concentricity.

Malkin (24) showed that the size of wear particles was virtually unaffected by wheel dressing conditions and wear rate. 50 - 85% of total wheel wear consisted of bond fracture, almost all the rest of the wear was by grit fracture, but that 5% of wear was by attritious wear. This amount of attritious wear, though small, is nevertheless directly related to the grinding forces and thermal affects in the workpiece.

3.2.5 The effect of dressing conditions on the forces generated during grinding

Bhateja, Pattinson and Chisholm (25) studied the effect of fine and coarse dressing on the performance of the grinding wheel. They stated that when grinding commences with a freshly dressed wheel, the partially damaged grits are quickly removed, the active grit density decreases and the grinding force components increase from small initial values. For the finely dressed wheel, the grinding force components continue to increase to very high values and then subsequently decrease as grinding proceeds. These high values were thought to be caused by the high density of active undamaged grits which produce a large number of grinding chips which associated with insufficient chip clearance, leads to the high force levels. As wear proceeds the number of active grits decrease, the chip clearance increases and the force levels decrease. In the coarsely dressed wheel, this settling in period is achieved without high forces being experienced probably being due to the small number of active grits and the greater degree of initial damage caused by dressing.

After the initial phase of wear and during the secondary wear stage, the wear and force levels show less tendency to change though the rate of change for normal force is greater for the coarsely dressed wheel than for the finely dressed wheel. It would therefore appear that the dressing treatment imparts particular characteristics to a grinding wheel which are retained throughout its useful life.

Grisbrook, Hollier and Varley (21) recognised two distinct patterns of forces within the Phase B region of wear. The first pattern occurs immediately after the settling in period and during this time, the total cutting force 'R' remains constant where $R = \sqrt{(F_T^2 + F_N^2)}$, F_T = tangential force and F_N = normal force. This region is characterised by the term 'self dressing'. Following this period both the tangential force and the normal force are shown to increase, the normal force at a faster rate than the tangential force. The increase in normal force is associated with the increase of area of contact between the grit and the workpiece. It was therefore deduced that the area of the rubbing end grit was proportional to the radial wheel wear and the grinding force was proportional to the area of rubbing end grit in the following manner:-

$$A \propto W^k \qquad \text{and} \qquad F \propto A \text{ and therefore } F \propto W^k$$

where k = a constant dependent upon grinding conditions

A = area, rubbing end grit

W = radial wheel wear

F = grinding force

Pacitti and Rubenstein (12) recognised only a secondary stage in the force pattern during which the plateau area increases together with an increase in the number of active grits and this is reflected in a slow but steady increase in grinding forces.

Marshall and Shaw (26) considered that the ratio of tangential forces to normal forces in grinding was a measure of grinding efficiency and that this ratio will decrease as the forces increase with the pattern of normal forces increasing faster than tangential forces. However, Pacitti and Rubenstein (12) state that with the wheel in a stabilised condition (ie Phase B), the ratio of ploughing to cutting grits is constant with time and providing the apparent area of contact between wheel and work is also constant, then normal force is linearly related to tangential force despite both components varying with grinding time. The normal force is a function of the plateau area/grit and the tangential force is a function of the number of grits in contact. It was therefore postulated that the forces are related in the following manner:-

$$F_N = \left(\frac{1}{\mu}\right) F_T + C$$

where μ = coefficient of friction

and C is a complex function of grinding speed, wheel geometry and workpiece properties. For fixed geometries etc, C will be constant. It was deduced from considerations of other tooling that the relationship between normal and tangential forces, (ie $\frac{1}{\mu}$) would be lower in Phase C than in Phase B. Practical testing in fact showed this to be so and yielded consistent values of $\mu = 0.4$ during Phase B and 0.22 during Phase C.

Yoshikawa (27) found that after the initial settling in period, grinding force remained almost constant for some time. There then followed an abrupt increase in forces (2-3 fold for tangential force and 7-8 fold for normal force) and after reaching its highest value, the force level remained constant. The change in force levels was found to correspond to changes in the rate of increase in plateau area but in the second stage, during which there is progressing attritious wear and occasional fracture, only a small increase in plateau area occurs. In the third stage, there is a large increase in this area which coincides with a rapid rise in force levels. Yoshikawa's data gave the critical value for plateau area as 8% of total wheel surface. Malkin (24) reported that this critical value was 3.6% of total wear by weight but stated that according to the material being ground and the grinding conditions, variations were reported between 2% and 10% of total wear weight.

Tsuwa (28) and Malkin (24) initially adopted a common approach to the characterisation of grinding forces. They reasoned that the tangential and normal forces each consist of two components as follows:-

$$F_T = F_{TC} + F_{TF}$$

$$F_N = F_{NC} + F_{NF}$$

where the term 'C' indicated the cutting component and the term 'F' the friction component. This system is illustrated in Figure 7.

Malkin further developed his formula to take into account values for coefficient of friction (μ), average contact pressure ($\overline{P}$) and wear flat area (a_r) in the following manner:-

$$F_N = F_{NC} + \overline{P}a_r$$

$$F_T = F_{TC} + \mu\overline{P}a_r$$

When the grinding force was plotted against the wear flat area F_{TC} and F_{NC} were determined graphically as the values at $a_r = 0$. It was possible to measure wear flat area and hence values for $\overline{P}$ and μ were obtained. The values obtained by Malkin were:-

F_{TC} = 5.785 Newtons $\quad$ F_{NC} = 5.92 Newtons

$\overline{P}$ = 2.09 kg/mm^2 $\quad$ μ = 0.61

This value of coefficient of friction is rather high when compared with the results of other researchers:-

Tsuwa (28) 0.3 - 0.5 and Pacitti and Rubenstein (12) 0.41

Tsuwa (28) developed empirical formulae as follows:-

$$F_T = K_T V^{-0.75} v^{0.75} t^{0.83} B^{1.0} + \mu K_{NF} l_s B\varepsilon$$

$$F_N = K_N V^{-0.78} v^{0.78} t^{0.78} B^{1.0} + K_{NF} l_s B\varepsilon$$

where K_T, K_N and K_{NF} are constants.

The term $l_s B\varepsilon$ represents the contact area A between the grit and workpiece, the frictional resistance of the grit being affected by this area.

l_s = length of arc

B = grinding width

ε = wear flat area %

Values obtained by Tsuwa were as follows:-

$K_T = 5.5$ $\quad K_N = 8.1$ $\quad K_{NF} = 130$ kg/mm^2 $\quad \mu = 0.4$

3.2.6 The effect of dressing conditions on surface finish

Surface finish in heavy stock removal operations is not generally specified to the same extent as it would be in finishing operations, where it should be remembered that the cost of the article is closely allied to the degree of finish specified. It would be an asset to be able to predict the level of surface finish that would be obtained as a result of the various dressing parameters applied. Most of the literature either deals with this matter or with the general results obtained in the applications of these parameters or the profile of the dressing tool.

Hahn and Lindsay (29) stated that two of the more important considerations in metal removal, ie wheel dressing and interface force, were key factors affecting surface finish and geometry.

Of the wheel dressing parameters, the dressing lead (ℓ) and the dressing depth of cut (C) were shown to be important.

By increasing the lead and the dressing ratio (C/ℓ) the metal removal capacity of the wheel was enhanced giving a wheel that was 'sharper' and 'cut faster'. However by increasing the parameters in this manner the surface deteriorates and this trend continues as the interface force rises, as shown in Figure 8.

Hahn and Lindsay showed that the effect of increasing wheelspeed over a range of metal removal rates was that the surface finish improved at each incremental increase of wheelspeed up to 90 m/s, as shown in Figure 9. However when this surface finish data is plotted against the induced force intensity, Figure 10, it was observed that the finish is a strong function of force intensity and is only slightly improved by higher wheelspeed. Thus there is a tendency as wheelspeed increases for the force to be lowered and a better finish to result.

Further work by Lindsay (30) produced the statement that the finish resulting during grinding is proportional to the average chip thickness and a semi empirical formula for 'Easy to Grind' materials was suggested:-

$$F = A \left(\frac{d\ell}{R_c} \right)^{\frac{1}{2}} . \left(\frac{C}{\ell} \right)^{0.3} . \frac{(F_N')^{0.3}}{(D_e)^{1/6} (VOL)^{0.13}}$$

for constant force grinding.

$$F = \frac{B\,(d\ell)^{16/54}\,(C/\ell)^{0.1}\,(Z_w')^{19/54}}{(V_s)^{16/54}\,(V_w)^{3/54}\,(D_e)^{8/54}}$$

for feed rate grinding.

where A, B = constants

d = grit diameter

ℓ = dress lead

C = dress infeed x 2

F_N' = normal force

R_C = workpiece hardness

D_e = equivalent diameter

VOL = wheel characteristic

Z_w' = metal removal rate

V_w = workspeed

V_s = wheelspeed

The results obtained show that the ratio of finish predicted to actual finish had a mean value of 1.008 with a standard deviation of 0.162. Thus for a predicted surface finish of 0.25 μm there is a 95% confidence that the actual results will be within the range of 0.17 to 0.33 μm. It is however noted that these results are all related to finish grinding with dress leads not in excess of 0.1 mm/rev corresponding to the lower range of dress leads used in this work.

At such low values it will be noted that the results show that surface finish values tend to be more constant and predictable than obtained at higher values of dress lead.

It should also be noted that as force levels rise initially, the force per grit will also rise which will lead to grit fracture or pull out, inevitably leading to a poorer surface finish. It therefore follows that superior finishes will be attained during the period when attritious wear is taking place.

Pahlitzsch and Appun (9) demonstrated the trends of surface finish for both coarse and fine dressing and showed that the surface roughness of the workpiece was always higher than that of the wheel. In the coarsely dressed wheel (infeed 0.020 mm, feed rate 2 m/min), the roughness of the wheel rapidly dropped from a value of 18 μm to 8 μm and then showed a steady fall to 6 μm at the end of the test. The workpiece roughness during this period showed that after the first passes the value quickly rose to 19 μm and then fell to a value of 9 μm. From this point the trend was for a slow general improvement paralleling the value of wheel roughness and always 1 μm higher. At the end of the test a value of 7 μm was recorded. The finely dressed wheel (infeed 2.5 μm, feed rate 0.25 m/min, plus 5 spark out passes) however showed the opposite trend with a value of wheel roughness increasing from an initial value of 2 μm to 4 μm after a third of the test and then remaining constant. The value of workpiece roughness parallels this trend but was always 2 μm higher than the wheel roughness with a final value of 6 μm. It is thus seen that even though widely different dressing treatments were used and initially widely differing results for surface finish obtained the final values of surface finish are similar and this trend is confirmed by the results of this work.

Vickerstaff (8) showed that the factors that were highly significant in determining surface finish were:-

(a) Diamond shape - a blunt diamond will give a smoother surface.

(b) Traverse rate - reducing the rate will give a smoother surface

(c) Traverse rate and shape combination - effect of increasing the rate is reduced when blunt diamond is used

(d) Traverse rate, shape and spark out combination - spark out shown to be effective for fine finish when a blunt diamond and high traverse rate used

(e) Grinding time - increased grinding leads to a smoother surface

Over the range of dresser infeed of 0.0075 mm to 0.03 mm it was concluded that the dresser infeed was probably not significant in reducing surface finish and the effect of wheelspeed in the range 12.5 m/sec to 30 m/sec was also probably not significant in affecting surface finish.

The conclusions drawn by Vickerstaff are in broad agreement with other researchers. In a later work, Vickerstaff (31) demonstrated that there was a good correlation between a composite wheel profile built up of individual peaks and valleys of a number of wheel profiles and the workpiece profile. This conclusion is in contradiction to previous research (9, 15) where it was concluded that a form was machined onto the wheel grit and then transferred to the workpiece.

From the foregoing it is apparent that the manner of wheel preparation will have a significant effect on the quality of the wheel and work surface. If consistent values of surface finish throughout the wheel life are required together with high values of metal removal capability, it is essential that careful thought be given to selecting the dressing parameters.

3.3 Multi Point Dressing Tools

3.3.1 Introduction

With the price of industrial diamonds steadily rising and the availability of good quality stones becoming scarce due to their being of near gem quality, greater use is now being made of multi point diamond dressers. The caratage in multi points is usually greater than for the single point tool used for the equivalent operation but as stones of between 10 per carat and 80 per carat are used, the cost per carat is much less. However, in certain cases, the total cost of the tool may be higher than for the equivalent single point tool.

Selby (5) summarised the advantages of using multi point dressers as follows:-

i) Diamonds can be set in a variety of patterns

ii) Due to larger areas of diamond contact area, more rapid wheel removal is possible

iii) Less risk of diamond loss

iv) The tool is better suited to unskilled and semi-skilled workers

v) Tool wear is much slower and only occasional rotation is required

The main disadvantage is that precision is not as good as can be obtained with a single point tool.

3.3.2 Mode of Use

Anderson (1) points out that for efficient use of the multi point dresser all the diamonds must be in contact with the wheel, that is the face of the dressing tool must be square to the wheel face. Infeed should generally not exceed 0.025 mm. Traverse speed is then used to govern the type of wheelface and surface finish required. In comparison with single points, it is possible to use faster traverse rates or dress leads thus saving time during the dressing cycle.

Several researchers, notably Pahlitzsch (6) and Busch (2) point out that as a result of several superimposed or neighbouring diamonds contacting the wheel, the number of score marks on the cutting surface is multiplied and a more even peak to valley height achieved, at a reduced depth of scoring. The more particles a dresser contains, the greater will be this reduction in surface roughness within the range of higher dress leads and dresser infeeds in comparison with single point tools.

3.3.3 Effect of use of multi point tools on grinding performance

Use of the multi point dresser shows that the final performance of the wheel in a number of ways resembles that achieved by the finely dressed wheel using a single point tool (1). The surface of the wheel is smooth giving rise to low surface finish values, grinding forces tend to be high and the metal removal capacity of the wheel is restricted.

3.3.4 Selection of multi point tools

Selby (5) lists three main types of multi point tool in addition to the blade dresser or fleische:-

i) Layer tool: in which the diamonds are set in layers at various depths and as one set becomes worn another set of points is presented. Elongated stones are ideal for this application

ii) Magazine or wheel type tool: which has rows of stones on indexable faces - usually used for small wheels

iii) Impregnated multi point dresser: uses a blocky grit bonded in a hard matrix, mainly used for light dressing. The grit size must be 2-3 times larger than the wheel grit size. The bond and matrix have to be matched to maintain diamond protrusion.

In general, for most multi point tools, the diamonds must be smaller than wheel grit size and therefore they are not often used for rough work. Their main application is for dressing of the circumference of the wheel and the plane sides of the wheel.

Very little research has been carried out using multi points but in a survey by Herbert (32) it was shown that the dressing costs were reduced from £0.50 per hour to £0.12 per hour on a cylindrical grinding operation when single point tooling was replaced by multi point tooling.

3.4 The Effect of Process Variables on Grinding Operations

3.4.1 The effect of wheelspeed on Grinding and Dressing Operations

3.4.1.1 The effect of wheelspeed in Grinding Operations

High speed grinding is frequently proposed as an effective means of improving part finish and tolerances or as a way of increasing productivity through faster metal removal rates (33, 34, 35, 36, 37, 38, 39).

The benefits of high speed grinding can accrue in one of two ways:-

(a) To improve quality. The workpiece is exposed to more revolutions of the wheel in a given time so a more accurate form is generated and the grinding forces are lowered. The metal removal rate is not increased over that achieved at lower speeds.

(b) Alternatively high speed grinding can be used to increase productivity. If the work speed and feed rate are increased in proportion to wheelspeed, the resulting increase in productivity is the most cost effective approach.

Brown, Schierloh and McMillan (33) report that in increasing the metal removal rate proportionately there was no significant change in grinding forces, specific energy, surface finish or residual stress. Associated with these results, however, were a slight decrease in grinding ratio and a small increase in surface roughness. While peak residual stresses were about the same, tensile stresses were experienced to a greater depth.

Mutsyanko (35) however reported that while increasing metal removal rate by a factor of 2-3 wheel wear was decreased by a factor of 5 thereby increasing wheel life by a factor of 4-6. The surface finish was improved by a factor of 3 and the cost of the operation halved.

However the higher cutting speeds, especially when operating at enhanced metal removal rates lead to increased heat production in the contact zone.

To minimise these effects the following measures are recommended:-

i) Use wheels of average grit size of soft more open structure, preferably self sharpening.

ii) Use increase component speed to wheelspeed ratio

$$\frac{V_s}{V_w} \leqslant 60$$

iii) Use a coolant with good lubricating properties or a neat oil.

iv) A coolant flow at high volume and pressure is required to overcome the air pressure barrier built up as the wheel rotates in the atmosphere.

v) Use of segmented wheels is recommended due to their inherent strength.

3.4.1.2 The effect of wheelspeed on dressing operations

The dressing operation is usually carried out at the operating speeds for the grinding operation. As the majority of grinding is carried out at wheelspeeds of approximately 30 - 45 m/s, this presents few problems. However, if wheelspeeds are significantly raised above this level, it necessarily follows that for speed of operation, the wheel should also be dressed at the higher speed.

There appears to be very little published on the effect of wheelspeed during the dressing operation and to some extent, the conclusions are contradictory. Merlijn and Drukker (3) recommend that trueing and dressing should be carried out at low speeds to save wear on the diamond but state that satisfactory results will be achieved in the range of 25 - 35 m/s if the speed cannot be reduced. They also state that at dressing wheelspeeds of 60 m/s, diamond sizes should be increased by a factor of 2.

Thorn (17) on the other hand states that the rate of wear of the diamond did not increase with increasing wheelspeed.

The effect of increasing peripheral speeds during trueing on the wheel surface is covered only by Pahlitzsch and Appun (9) who concluded that the effect on the effective roughness of the wheel at up to 45 m/s was relatively low.

3.4.2 The effect of workspeed on grinding operations

The component workspeed is often quoted as a ratio of the wheelspeed; Mutsyanko (35) stated that the ratio of wheelspeed to workspeed should be less than or equal to 60. Gindy and Vickerstaff (40) and Brough et al (41) found that there were substantial advantages to be gained in reducing the workspeed and hence increasing the wheel/workspeed ratio to a value of 130.

Krabacher (42) listed the advantages of reducing workspeed as follows:-

(a) increased grinding ratios and in consequence lower wheel wear

(b) an improvement in surface finish

(c) a decrease in the power drawn for grinding

These advantages were, it was concluded, due to the reduction of the size of chip per active grit.

In a review of grinding fundamentals, Peklenick (43) listed the following equations that had been developed to determine the chip thickness in grinding:-

i) $$t = 2\lambda_K \frac{V_w}{V_s} \sqrt{a\left[\frac{d_w + d_s}{d_w \circ d_w}\right]}$$ µm developed by Pahlitzsch (44)

ii) $$t = \left[\frac{4\ V_w}{r.C.V_s} \sqrt{a\left[\frac{d_w + d_s}{d_w . d_s}\right]}\right]^{\frac{1}{2}}$$ µm developed by Reichenbach (45)

iii) $$t = a \frac{V_w}{V_s} \cdot \frac{L_{ZE}}{\ell_e}$$ µm developed by Peklenik (43)

where a = depth of cut

λ_K = structural distance between grains

V_w = workspeed

V_s = wheelspeed

C = number of cutting edges per unit area

L_{ZE} = effective cutting distance between cutting edges

ℓ_e = contact length

d_w = diameter of workpiece

d_s = diameter of grinding wheel

Comparison with practical results showed that expression (i) gave results which were too small while the results from expression (ii) gave too large a value at high rates of infeed. Expression (iii) which required practical measurements of the effective distance between cutting points to be made, gave the best correlation with practical results.

All the expressions show a similar relationship between workspeed and wheelspeed in determining the chip thickness, that is that the chip thickness will increase as workspeed is increased and decrease as wheelspeed is increased.

3.4.3 The effect of wheel grade on grinding operations

Grade measures the relative hardness or softness of the wheel, the harder the wheel, the more securely the grains are held and the greater the force required to break them out of the wheel. The grade of the wheel is then a measure of the amount of bond supporting the grits and is therefore a measure of bond post strength (46). It follows then that a harder grade wheel will allow the grits to become duller before they are dislodged due to bond post rupture. In this manner, a less free cutting wheel results in comparison with a wheel of a softer grade. A wheel that is too hard in operation will tend to glaze and will eventually cause chatter while a wheel that it too soft will break down rapidly. Fisher (20) states that in addition a wheel of too soft a grade will in practice prove difficult to dress due to the weakness of the bond posts which even under very slow traverse conditions are broken during the passage of the dressing tool. A further problem of increased diamond wear is experienced as the hardness of the wheel is increased.

Kaliszer and Trmal (11) demonstrated that the selection of the dressing method can have a more pronounced effect upon the level of grinding forces than a large difference in wheel hardness.

A number of researchers (14, 24, 43, 47) investigated the topography of the wheel in relation to the hardness of the wheel: Malkin in analysing the patterns of wheel wear found that for harder wheels as the grits were more firmly held, a greater amount of grit fracture was experienced. Peklenik (43) using a thermocouple device found that the effective distance between cutting points was smaller for harder wheels due to the less elastic nature of the harder wheel. He also found that an increase in wheelspeed led to an increase of the effective distance between cutting points. This confirms the statement by Shaw (47) and confirms grinding practice that to make a wheel 'act' softer, the wheelspeed should be reduced.

Tsuwa (14) in addition to a study of the distance between cutting points showed that the rate of increase of wear flats per unit area increases with an increase in wheel hardness. For harder wheels, as grinding proceeds, the effective distance between cutting points becomes smaller leading to a decrease in the grit depth of cut. Under these conditions, rubbing increases and therefore the amount of wear increases more rapidly.

It is apparent therefore that although the differences in grinding forces due to grade variation may be smaller than those due to the selection of dressing method, the initial rise in forces with a hard wheel will be much more rapid than with a soft wheel. An examination of Kaliszer and Trmal's data shows that this divergence is apparent even before 10,000 mm^3

of material have been removed.

In addition to the above, economic disadvantages occur in that if the wheel is too hard the stock will not be removed efficiently and the depreciation costs of dressing tools will increase. The selection of the correct grade is therefore critical to the optimisation of the grinding operation.

3.5 Review of relevant points and their effect on the test programme

It is evident from a survey of the literature that the parameters, dressing infeed and dressing lead, in single point diamond dressing have a significant effect on the subsequent performance of the wheel in grinding. It must be stressed however that these factors cannot be considered in isolation from each other. The conclusion that can be drawn from the survey is that dressing lead is the most significant parameter but different research workers have observed varying influences due to dressing infeed. As explained earlier in section 3.2.3.4, this is probably due to variations in the diamond shape used.

Various researchers have shown that both the initial and subsequent forces in grinding are determined by the dressing conditions applied. These forces can be separated into two components, a friction component and a cutting component, the levels of which depend on the grit and chip geometry. From an analysis of the forces it can be concluded that there is a direct relationship between the normal and tangential forces based on the coefficient of friction between the wheel grit and the workpiece. From consideration of these factors, empirical formulae have been advanced predicting both normal and tangential forces.

Wheel wear has been shown in the literature to follow a pattern wherein three distinct phases of wear can be discerned. Of these, only the primary and secondary phases of wear are of interest to the production engineer, as grinding in the tertiary phase is impracticable. The wear pattern in the secondary phase is of profound interest, as during this phase, the rate of change of attritious wear, though small by comparison with other wear mechanisms, determines both the onset of the tertiary phase of wear and the force levels experienced in the grinding operation.

The grinding process has been traditionally regarded as a finishing operation and the majority of research as a consequence has been carried out at low metal removal rates. This thesis will investigate the dressing parameters that are required to obtain high metal removal rates and the effect these parameters will have on the process variables.

An investigation will also be undertaken into the factors which determine the levels of grinding force. All researchers are agreed that the level of normal force is directly related to the grit wear flat area; it will be demonstrated that the applied dress lead will determine the grinding characteristics throughout the useful life of the wheel. Thus the dress lead will determine the initial force, at the selected metal removal rate and wheelspeed, and also the rate of attritious wear and hence the wear flat area. The necessity of making experimental readings to determine wear flat area is consequently removed when computing predicted forces. It will also be confirmed that the relationship between normal and tangential force is governed by the coefficient of friction between the wheel grit and the workpiece.

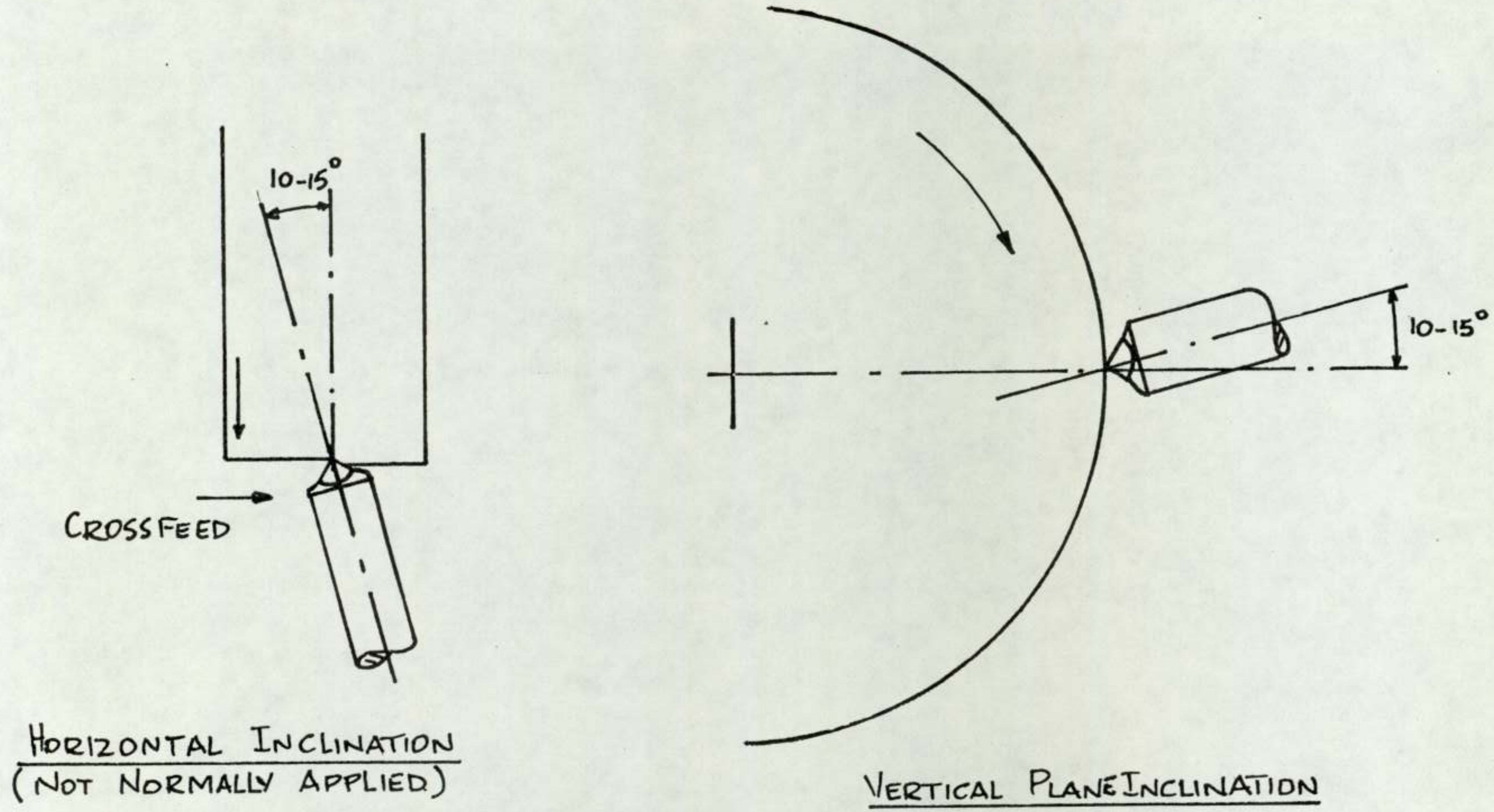


Fig 4 Setting Angles for Single Point Diamonds

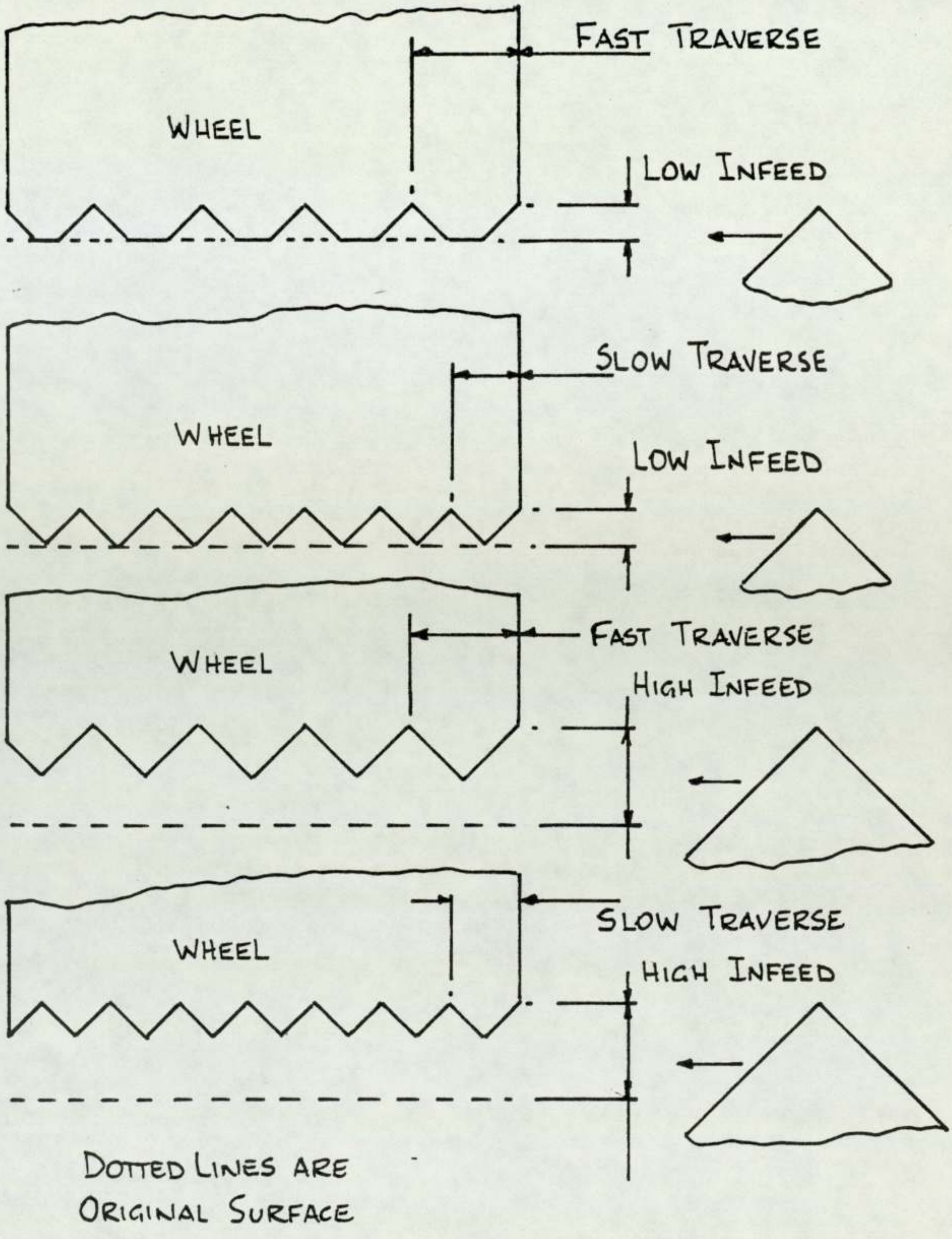


Fig 5 Influence of Diamond Shape, Traverse Rate and Infeed on the Wheel Surface (31)

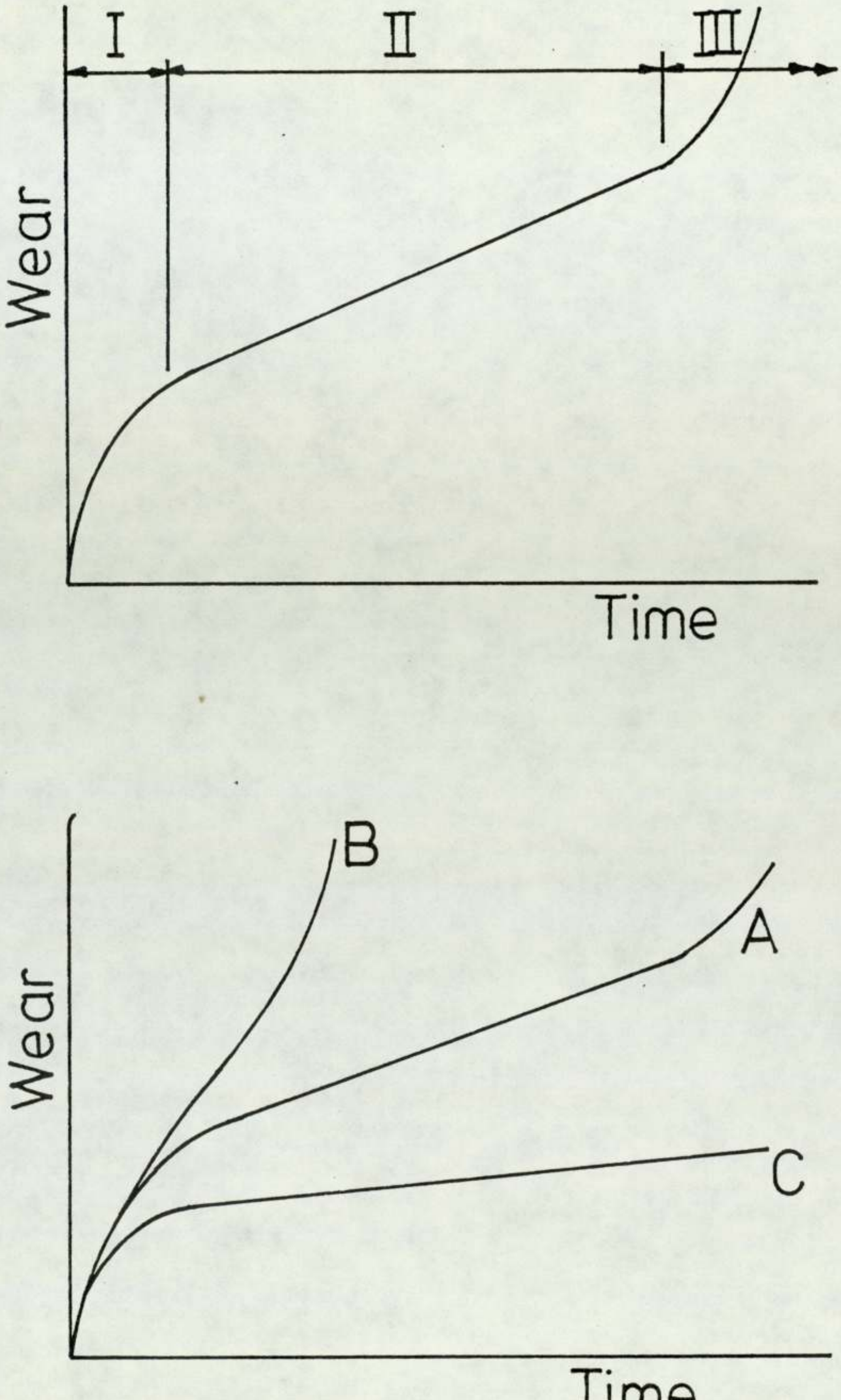


Fig. 6 Patterns of Wheelwear during Grinding (31)

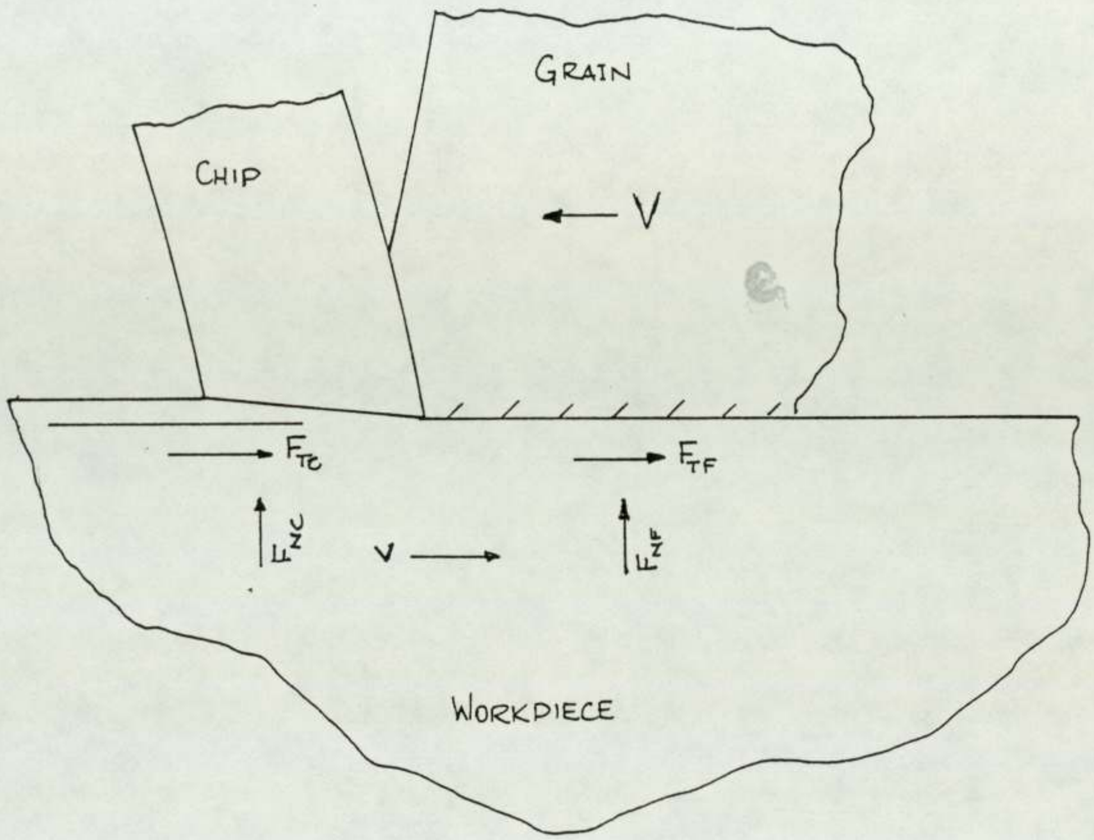


Fig 7 Distribution of Force Components(24)

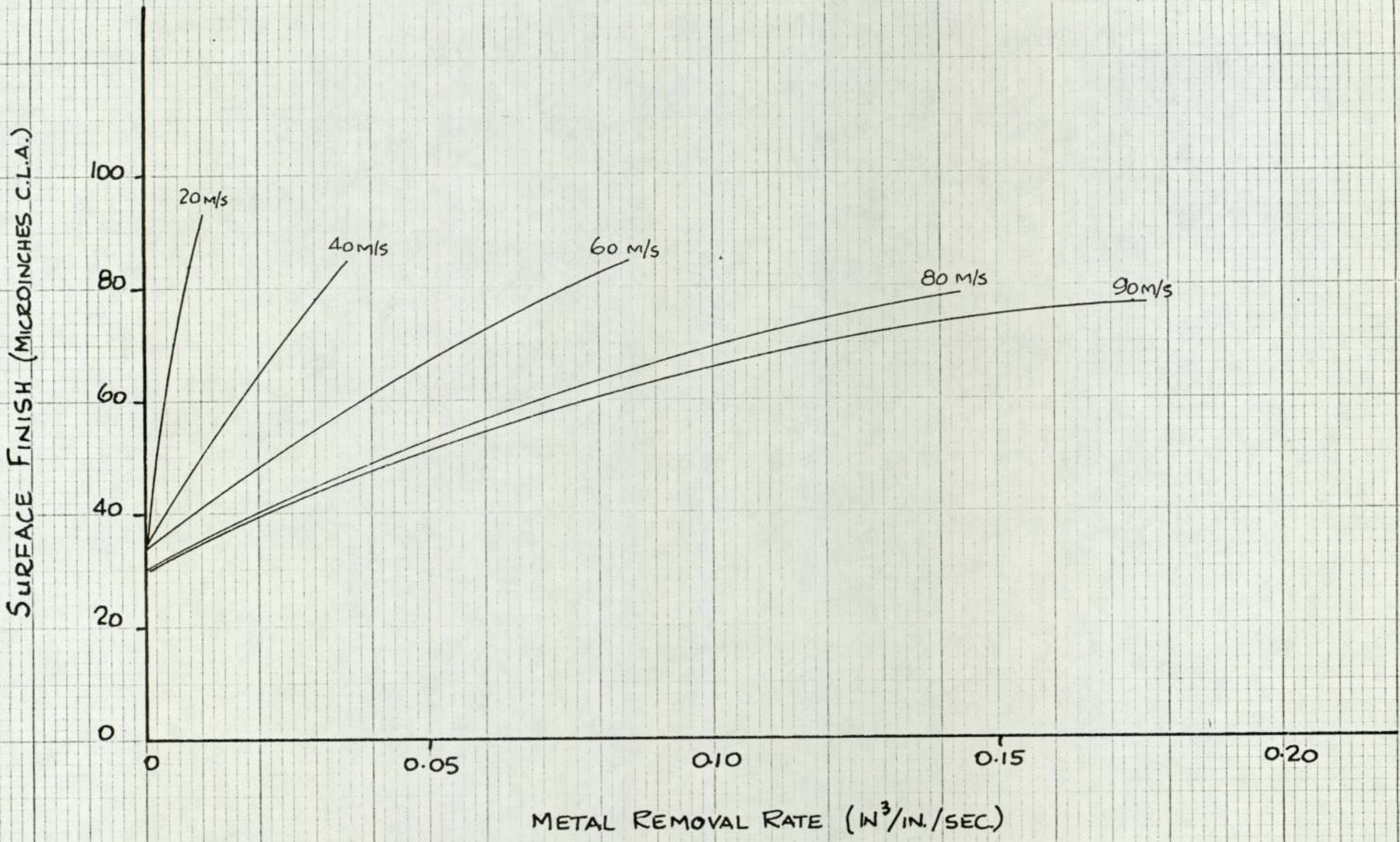


Figure 8 Effect of Wheelspeed on Surface Finish (30)

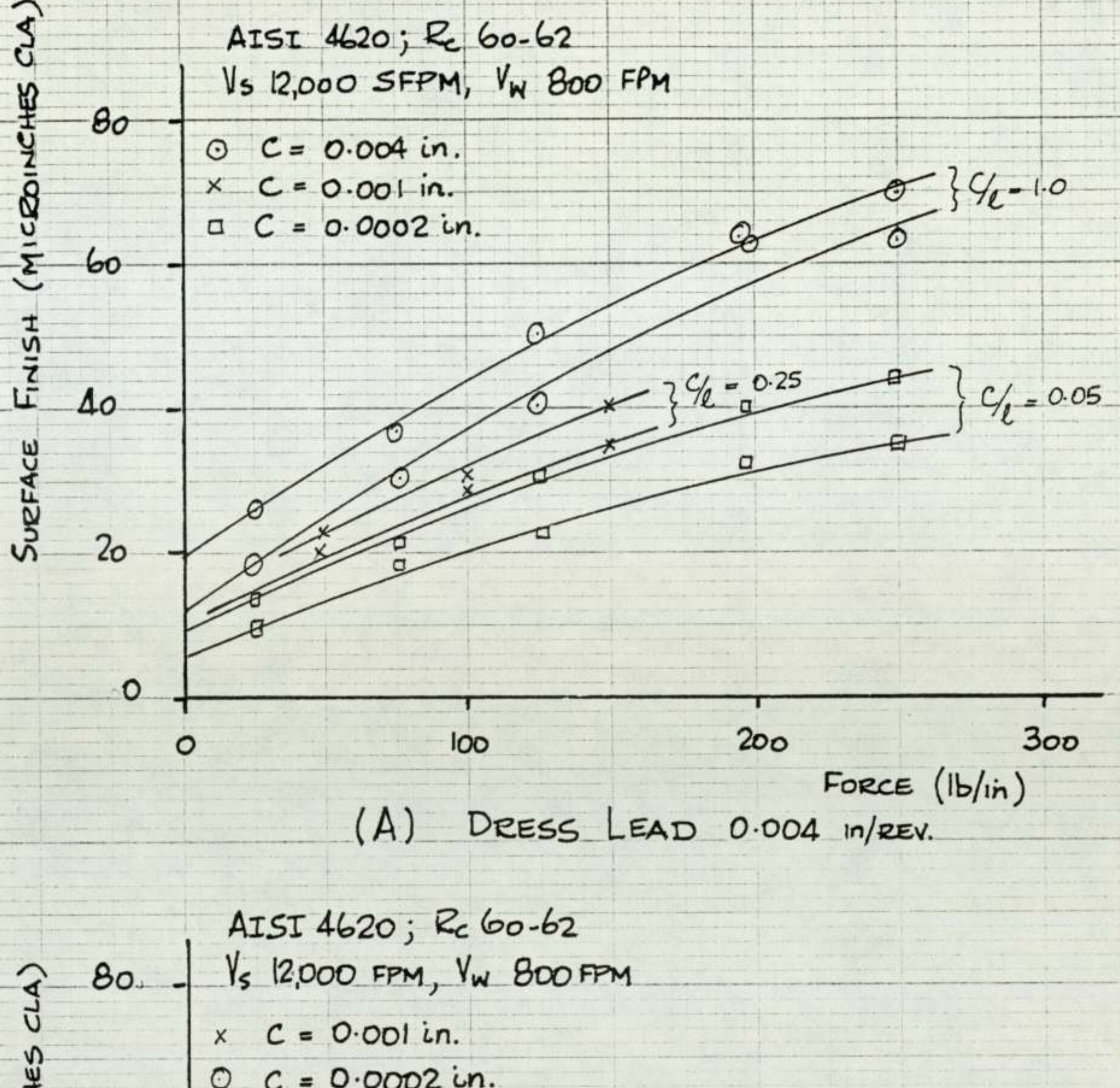


Figure 9 Effect of Dress Lead & Feed on Surface Finish (30)

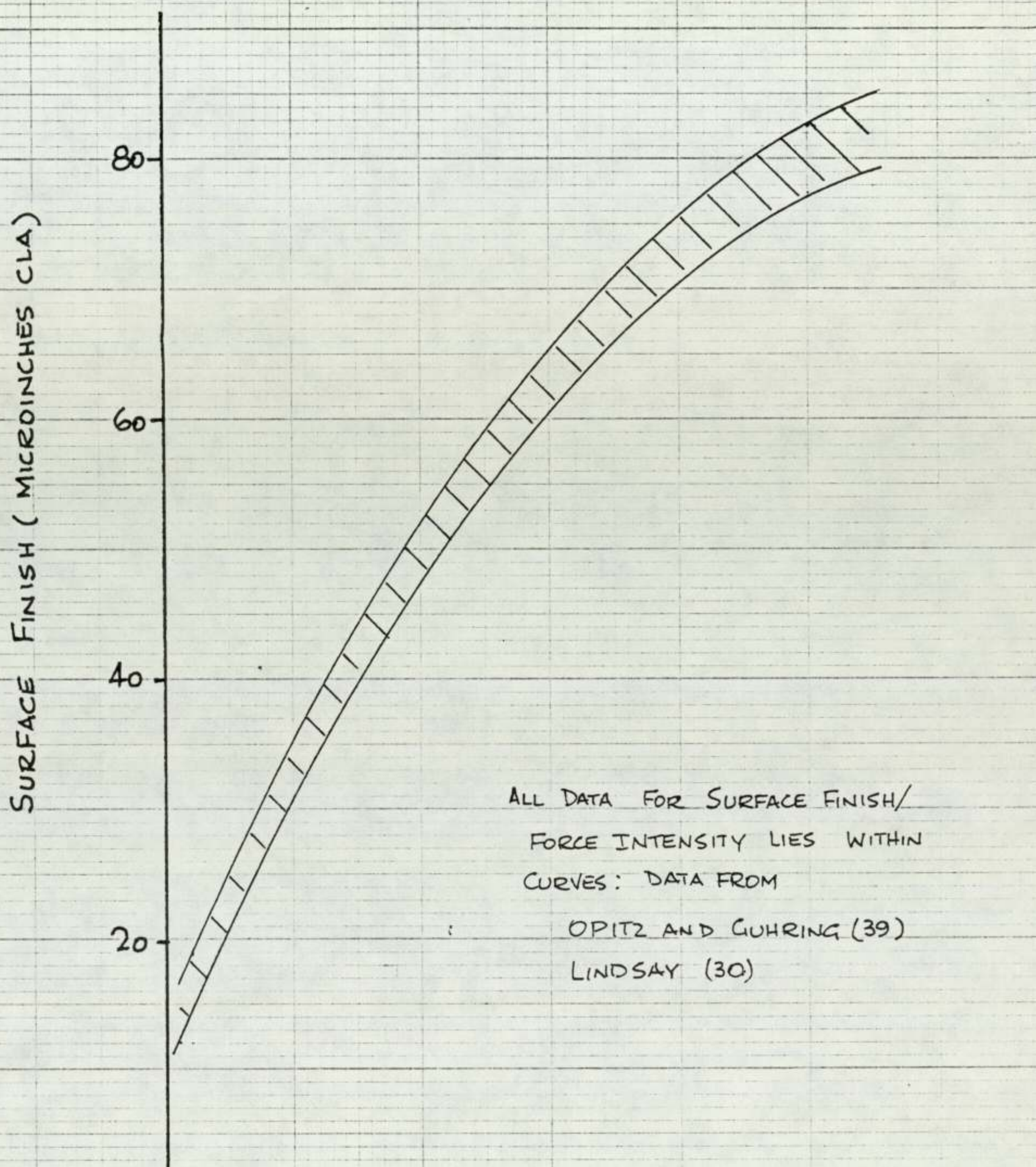


Figure 10 Effect of Force Intensity on Surface Finish (30)

CHAPTER 4

EXPERIMENTAL EQUIPMENT AND TEST PROCEDURE

4.1 The Grinding Machine

The basic machine used was a Jones and Shipman 1051 Type E cylindrical grinding machine. The machine was extensively modified to enable higher wheelspeeds to be obtained. The following modifications were carried out by the manufacturers:-

i) Fitting of a new wheelhead with slow speed drive (to facilitate crushing operations) to spindle, 10 H.P. motor, 15 H.P. Danfoss speed convertor giving infinitely variable wheelspeed up to 60 m/s

ii) New tailstock and dead centre workhead

iii) Replacement of coolant system with Darenth Universal Clarifier, Type 1040 equipped with two pumps, one capable of delivering 90 litres/min at 6 metres head and the other 45 litres/min at 10 metres head with tank capacity of 450 litres

The modified machine is shown in Figure 11 and details of the machine specification in Appendix I.

The following modifications were carried out to facilitate testing:-

i) Motorisation of the table traverse, shown in Figure 12, in order to achieve consistent dress leads

ii) Incorporation of Kistler load cells in the work centres to measure grinding force; a schematic of the system is shown in Figure 13

iii) Take off from the wheelhead power supply in order to monitor power supply as shown in Figure 14

iv) Modified coolant nozzle as shown in Figure 3

v) Modified drive system for workpiece; the components for the drive system are detailed in Figure 15

All testing was carried out by plunge grinding. In this mode, two types of operation were possible on the test machine. The machine allows for a basic stock removal of 0.5 mm on diameter for each cycle either by removing 0.45 mm at a rough grinding rate followed by 0.05 mm at a finishing rate, or alternatively by removing all the material at a fixed rate. Roughing and finishing rates can be preselected by adjustments to hydraulic pressures. In the testing carried out all material was removed at a single selected metal removal rate because the main concern was with the influence of heavy metal removal rates of the magnitude that may be applied in conventional metal cutting processes.

Facilities were available at the end of the grinding cycle to incorporate varying lengths of spark out time. This time was consistently maintained at 5 seconds throughout testing.

4.2 Calibration of table traverse rates

The table traverse was only used for dressing purposes. At slow rates of traverse the movement of the hydraulic table was not consistent and 'stick-slip' conditions were experienced, plus possibly some turbulence of the hydraulic fluid due to the small valve opening.

The fine adjustment to the table traverse was accordingly modified by removing the micrometer dial and directly coupling a 1/3 H.P. D.C. electric motor to the worm drive for the traverse. A potentiometer was then used to vary the power supply to the motor and hence the revs per minute of the motor. In this way, consistent table traverse rates at slow speeds were obtained in both directions. Figure 12 shows the modification to the table traverse.

4.3 Force Measuring System

The schematic diagram of the system is shown in Figure 13. In this system both centres incorporated Kistler type 9251 DE quartz force transducers for measuring the three components of the force. The signals from the transducers were fed via coaxial cables to charge amplifiers where the signals from both transducers were summed. From the charge amplifiers, the signals were passed to a Medelec fibre optic recorder which also displayed the forces on an oscilloscope screen, a recording of the forces was obtained on U.V. paper.

4.3.1 Modified Centres

Figure 16 shows the modified tailstock centre incorporating the load cell and mounting washer. The assembly was completed by an 8 mm dia x 100 cap screw which was tightened using a torque spanner to give the necessary preload of 2500 kp. In operation it was found to be essential that the overhang from the load cell to the end of the centre was as small as possible as otherwise there was too much compliance in the system. The headstock centre was similar in most respects except that the transducer cables were taken back through the headstock. Hence a channel to take these leads had to be milled for the length of the taper shank. When the connections were made to the load cell these had to be sealed using heat shrink sleeving to prevent any ingress of the coolant into the connectors. If this was not done, the signal did not maintain a steady base and drifting occurred.

With the load cell being incorporated into the headstock and the drive for the workpiece being through the headstock, some interference of the signal was experienced due to the normal type of drive, ie through a dog and carrier, and modifications to the drive system were required. These are detailed in Section 4.5.2.

4.3.2 Quartz Force Transducer

The quartz force transducer is designed to resolve a dynamic or quasistatic force into three perpendicular components. It combines high resolution and high rigidity with small dimensions. Details of the transducers are given in Appendix II and the layout and dimensions in Figure 17.

The unit consists of three quartz disc pairs hermetically welded in a stainless steel housing. One pair is sensitive to compression in the transducer axis (Z direction) and the two others to shear in two perpendicular directions of the transducer plane (ie in the X and Y directions). The connectors corresponding to the disc pairs are hermetically welded to the housing. Thus a force acting on the transducer is measured in its three components, X, Y and Z. As the grinding machine is only operating in the plunge grinding mode, no force is induced in the horizontal axis, and only the X and Y components were monitored as normal and tangential forces.

4.3.3 Charge Amplifier

The charge amplifiers used are Kistler type 5001 charge amplifiers, technical details of which are given in Appendix 3.

The charge amplifier is a mains operated d.c. amplifier of very high input impedance with capacitive negative feedback, intended to convert the electric charge from a piezoelectric transducer into a proportional voltage on the low impedance amplifier output.

The calibration factor setting which is the adjustment of the transducer sensitivity, gives a range of standardised amplifier sensitivities calibrated in mv/mechanical unit. The calculating disc enables the reciprocal value of the sensitivity to be shown directly as a measuring range (eg 100 Newtons/Volt). In combination with the Medelec with a deflection of 1 volt/cm on the oscilloscope screen and the fibre optic recorder, the measuring range is transformed to 100 Newtons/cm. However, the calibration figures were also checked by statically loading the system in both the normal and tangential directions as shown in Figure 18.

4.4 Modification of Coolant Nozzle

With increasing wheel speeds there is a tendency for an air barrier (35) to be formed, due to the rotational speed of the wheel, close to the wheel surface. The presence of this barrier is sufficient to prevent coolant reaching the wheel surface. It is necessary to either use scraper blades to break up the air flow, or to modify the coolant nozzle to increase the coolant flow pressure sufficiently to penetrate the air barrier, or alternatively to employ both methods. In this case, the method selected was to employ a modified coolant nozzle as shown in Figure 3, similar in design to that proposed for the S.R.C. co-ordinated grinding programme.

4.5 Workholding and Drive Arrangements

4.5.1 Details of Workpiece

The material used for all the tests reported was EN9 hardened and tempered to 30 R_c (Rockwell C scale). All test pieces were manufactured from a single bar. The specification for EN9 is given in Appendix 4. The blanks were machined leaving a surplus of material on the bore and width. Following hardening these blanks were ground to width to give parallel faces and the bore finally honed to size. Dimensional details of the workpiece are given in Figure 19.

From an initial outside diameter of 125 mm, grinding tests were carried out until the diameter was reduced to 100 mm. The limiting factor was the size of the workpiece holder.

4.5.2 Workpiece Holding Fixture

The workpieces were manufactured as discs, 125 mm OD x 25 mm ID x 25 mm thick to conserve material and consequently a mandrel was required to hold them. The mandrel, Figure 19, was designed to combine lightness and rigidity such that it did not sag or distort under its own weight. It was essential that the workpiece was held securely and that it was neither strained nor distorted. To ensure that the workpiece surface finish was not affected in any way by the fixture, the fixture was balanced after manufacture. In manufacturing the mandrel, the locating surfaces were finish machined and ground to close tolerances. The workpiece blanks were also ground to give parallel faces, perpendicular to the bore which was honed following hardening to give a close fit on the mandrel shank. The centres of the mandrel were lapped to minimise runout.

4.5.3 Workpiece Drive Features

When using the normal carrier and peg system for the workpiece drive the force trace showed a pronounced cyclic variation. It was therefore decided to try to minimise this variation by modifying the drive system. The original design for the drive system was as shown in Figures 20 and 21.

In this system, the drive plate was mounted on the front plate of the workhead and the driving dog was located in the two slots of the drive plate. The mating condition of the two parts was a close slide fit.

In practice the exact fit up was difficult to achieve and interference effects led to greater cyclic variations under certain conditions.

Accordingly certain modifications were made to reduce the bearing area of the mating parts. These modifications are indicated on Figures 20 and 21 and with these modifications, the amount of cyclic variation was considerably reduced. The variation in cyclic effects is illustrated in Figure 22.

4.6 Wear measurement and Calculation of Grinding Ratio

Several methods of measuring wheel wear were tried. These included the use of pneumatic comparators, dial gauges and the use of shim blades as described by Grisbrook, Hollier and Varley (21). Due to irregularities in the wheel surface, the readings obtained by both the pneumatic comparator and by direct reading dial gauge were extremely difficult to interpret with any degree of certainty. Therefore all readings of wheel wear were made using the shim blade technique to obtain replicas of the wheel surface after grinding.

The technique comprises using a measuring blade carrier which is held between the centres when taking an impression. The fixture is illustrated in Figure 23. The blade was held between jaws on the centre line of the fixture. Following dressing and plunge grinding operations, the workpiece was unloaded from the machine and the measuring fixture substituted in its place. With the wheel rotating at its normal speed, the measuring blade was brought into contact with the grinding wheel and then slowly rotated by hand. In this manner the measuring blade became a replica of the rotating wheel as shown in Figure 23. The wheel wear while grinding the measuring blade was very small in comparison with that experienced when grinding the workpiece and can be ignored when calculating grinding ratios.

The measuring blade was manufactured from half hard shim steel, a press tool being used to manufacture blanks 60 mm long x 12.7 mm wide x 0.4 mm thick.

The step on the shim blade replica was measured using a Talysurf 4 surface measuring machine in conjunction with a Talytron S150 air traversing table and the reversing stylus. The combined arrangement of equipment is shown in Figure 24.

4.6.1 Talysurf 4 Surface Measuring Machine

The Talysurf 4 is similar in most respects to the Talysurf 3, which is described in Section 4.7, except that additional magnifications of 500 x and 100,000 x are provided.

4.6.2 Air Traversing Table

The Talytron S150 is an air supported measuring carriage which enables the workpiece to be traversed under a stylus. Over the full length of travel of 150 mm the carriage deviation does not exceed 0.1 micron.

The carriage is driven by a synchronous motor at speeds varying from 0.3 mm/min to 300 mm/min. The movement is claimed to be free of friction and vibration. When linked with a linear recorder which has a maximum paper speed of 300 mm/min the range of speeds give horizontal magnifications of between 1 and 10,000 x in 10 steps.

The measuring fixture complete with the shim blade was located on a flat plate with a locating jib on the carriage which is adjustable in three directions, swivelling about the vertical axis (± 3 mm), tilting about the horizontal axis (±1 mm) and adjustment crosswise to the measuring direction (15 mm). Initially these controls were manipulated to give a horizontal trace on the two datum faces produced. Following this the complete profile of the shim blade was traced using the reversing stylus.

4.6.3 Reversing Stylus

The reversing stylus, with the aid of a bias unit, can alter the direction of the stylus force from positive to negative enabling the unit when fitted with a double tipped stylus to trace the upper and lower profile of a bore without having to alter the pickup height. However, when fitted with a chisel shaped stylus, the reversing stylus is much quicker in operation for tracing the shim blades than the standard Talysurf pick-ups due to its greater width of contact.

The stylus arm used throughout the tests had a magnification factor of 0.7. This was checked using gauge blocks of 0.0001" difference at 20,000 x magnification. Figure 25 shows the calibration check trace and the resulting step measurement of 0.000107". Figure 24 shows the combined set up of the Talysurf 4, air traversing table and reversing stylus.

4.6.4 Measurement of Material Ground from the Workpiece

Measurements of metal removed were taken using micrometers. Initially tests were made to check the roundness of the workpiece, from these results it was determined that the roundness was within normally acceptable limits for the machine and process and as these tests were time consuming they were not carried out for the full test programme. The machine was also set to ensure that parallelism was maintained over the width of the workpiece and this feature was regularly checked when monitoring workpiece diameter.

4.6.5 Determination of Grinding Ratio

The grinding ratio is a comparison between the volume of metal removed and the volumetric grinding wheel wear and is given by:-

$$\text{Grinding Ratio} = \frac{\text{Metal Removed}}{\text{Wheel Wear}}$$

The methods of obtaining measurements of metal removed and wheel wear have already been discussed. However, the wheel wear pattern follows three distinct phases as previously mentioned (11, 21, 22, 23). Initially there is a stage of very rapid wheel wear, the amount of which is influenced by the dressing technique. This is followed by a period during which there is a linear relationship between wheel wear and metal removed and finally wheel wear again increases at a rapid rate. The majority of the tests carried out only exhibited the characteristics of the first two phases and the grinding ratio is calculated on the basis of the rate of wheel wear in the second phase as shown in Figure 26.

4.7 The Measurement of Surface Finish

The Talysurf 3 was used for all measurements of surface finish carried out on the test pieces. The Talysurf 3 is a triple cut-off average meter with three cut off values:-

i) 0.01" (0.25 mm) cut off which is used for short surfaces on which the crests are always close together and less than 0.01" apart

ii) 0.03" (0.75 mm) cut off is used for ordinary well finished surfaces on which the crests are less than 0.03" apart

iii) 0.1" (2.5 mm) cut off is used for rougher surfaces with chatter marks up to 0.1" apart

There are six standard ranges of magnification available and details of the chart scales and centre line average (CLA) index scales are given in Appendix 5.

All records of surface finish were taken using the average meter. The average meter is designed so that pointer fluctuations are avoided by the use of an integrating meter. The integrating meter is connected to the output from the amplifier for a predetermined time of operation, which is controlled by contacts in the gear box. These contacts operate after the start of the stroke and just before completion of the stroke. The meter sums the fluctuations of current which the instrument receives as the stylus traverses the work and shows the average directly on the scale. The reading is maintained until the pick-up is moved forward to the start position.

In order that a representative reading is obtained, the operative length of the traverse is several times longer than the meter cut off being used. Details of the traverse lengths for the various cut offs are given in Appendix 5. On this instrument, the stroke length and meter cut off are changed in pairs and interlocks prevent mismatching.

In this series of tests, the surface finish readings were made using the 0.03" (0.75 mm) cut off. A number of readings were taken each time and although the full range of results was reported, only an average value was used when plotting the graphs of results.

4.8 Test Procedure

4.8.1 Wheel Balancing Procedure

The grinding wheel was mounted on flanges complete with blotters and then using a standard static balancing fixture, the wheel was initially balanced. Following this, the wheel was trued using a commercial multi point dressing tool. The wheel was then rebalanced statically on the balancing fixture and finally trued on the grinding machine. Following this a component was ground and a check made to ensure that the set up was free of vibration. Following this procedure, it was not found necessary to dynamically balance the wheel though facilities were available to have done this if required.

4.8.2 Wheel Dressing Procedure

The wheel dressing process consisted of three distinct operations:-

i) Deloading, during which all traces of the previous grinding operation were removed, trueing and elimination of any eccentricity of the wheel

ii) Stabilisation of the wheel, to give a true wheel face for the final dressing pass

iii) Dressing of the wheel as required by the test programme. This part of the process used the test dressing tool for a single pass of the wheel at a specific traverse rate across the wheel surface

Three types of dressing tool were used:-

i) 2.5 carat single point diamond

ii) Multi point diamond

iii) Blade dressing tool

The tools used are shown in Figure 27 and details of the size of the single point diamond in Appendix 6.

Each dressing tool was mounted in the tailstock of the grinding machine and hence no trail angle of application was given. This is in accordance with normal production engineering practice and allows for dressing in both directions of traverse.

Stages (i) and (ii) of the dressing process were accomplished using a commercial multi point diamond dressing tool of suitable size. Following the removal of all grinding debris from the wheel, the stabilisation process was carried out in the following manner:-

i) Make 3 passes at 0.05 mm infeed

ii) Make 2 passes at 0.025 mm infeed

iii) Make 2 passes at 0.01 mm infeed

iv) Make 2 passes at 0.002 mm infeed

v) Make 2 passes at zero infeed (ie spark out)

This series of passes to stabilise the wheel was carried out at 30 m/s wheelspeed at a traverse rate of 0.25 mm/rev.

Following the stabilisation process, the wheel was given it's final form by one pass across the wheel at a dressing infeed of 0.04 mm at the traverse rate and wheelspeed specified in the test programme given in Section 4.8.3.

4.8.3 Test Programme

The test programme was divided into two series of tests. The first, Test Series I, was designed to determine the effects of using a range of dressing tools and dressing leads for a range of grinding conditions. During the second test series, the range of conditions was restricted and the effects of altering the wheel grade and workpiece speed were observed.

The grinding tests were carried out in the plunge grinding mode. The appropriate plunge grinding rate for the selected metal removal rate was set using a stop watch. During testing, wheel wear measurements were normally taken following the removal of 0.5 mm on diameter but initially readings were taken at 0.125 mm intervals to determine the rate of initial wear. Surface finish of the workpiece was measured at the same time as wheel wear. Normal and tangential forces were monitored continuously using a Medelec fibre optic recorders and the values recorded in the data tables are the maximum readings during an individual test run. A minimum of 6 mm on diameter (25,000 mm^3 approximately) was removed during a test unless grinding conditions did not allow this amount to be removed.

4.8.3.1 Test Series I

During this test series, a complete set of results for a single point dressing tool was compiled so that a total picture could be obtained for all selected conditions. Comparisons were then made using the different dressing tools.

During this test programme the following variables of the grinding process were investigated and considered:-

i) The dressing tool

ii) The dressing tool traverse rate

iii) The wheelspeed during grinding

iv) The metal removal rate

The following factors were kept constant:-

v) The workspeed

vi) The wheel specification

vii) The workpiece specification

viii) The coolant specification and delivery rate

The effect of grinding under the above conditions was observed and recorded on the following variables:-

ix) The wheel wear rate and grinding ratio

x) The workpiece surface finish and roundness

xi) The normal force

xii) The tangential force

The wheel used for test series I was

Wheel size 450 mm OD x 200 mm ID x 50 mm thick

Wheel specifications WA 60 LV

The range of testing in this series of tests is detailed in Tables 1, 2 and 3 in Appendix 11.

4.8.3.2 Test Series II

During the second phase of testing, the following variables were investigated and considered:-

i) The wheel grade or hardness

ii) The grinding workspeed

iii) The dressing tool traverse rate

The following factors were kept constant:-

iv) The dressing tool

v) The wheelspeed during grinding

vi) The metal removal rate

vii) The workpiece specification

viii) The coolant specification and delivery rate

The effects of altering the designated parameters was observed during grinding on the following variables:-

ix) The wheel wear rate and grinding ratio

x) The workpiece surface finish

xi) The normal force

xii) The tangential force

The specification for the L grade wheel was identical to that used for Test Series I, in addition the following wheels were used:-

Wheel size 450 mm OD x 200 mm ID x 50 mm thick

Wheel specification (a) WA 60 JV

(b) WA 60 NV

Tests carried out in this series are detailed in Tables 4, 5 and 6, and Appendix 11.

FIGURE 11

THE GRINDING MACHINE

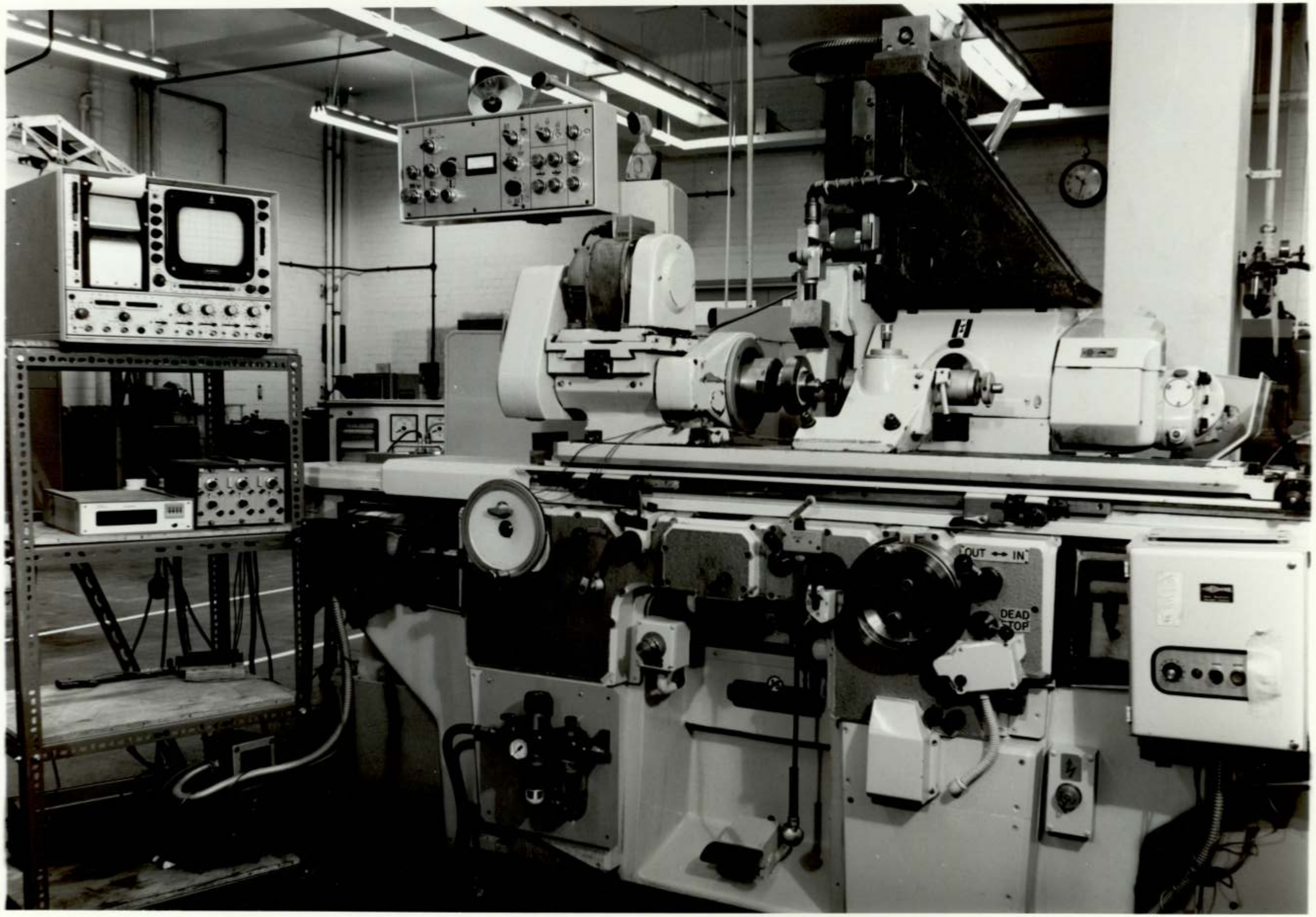
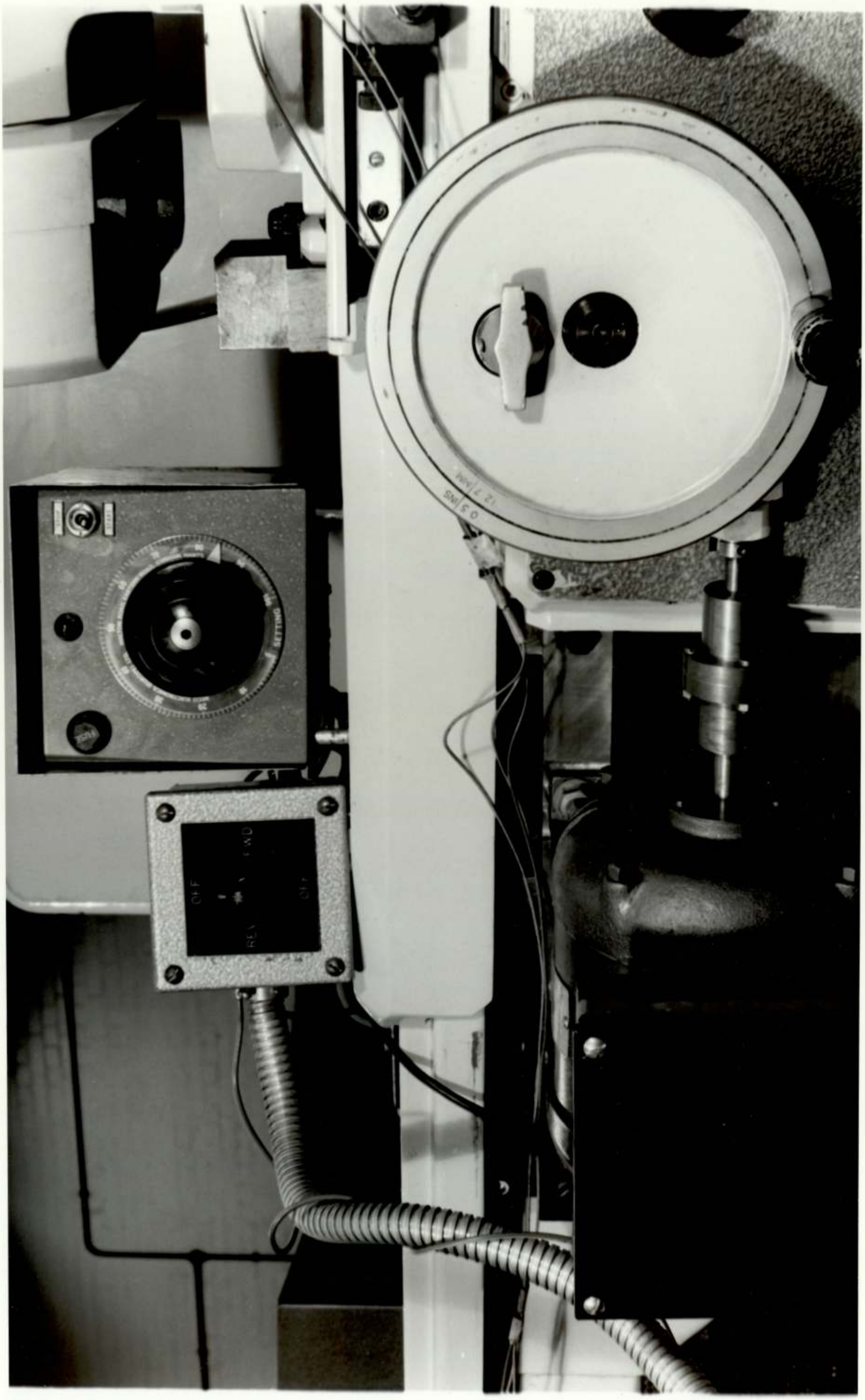

OUT ↔ IN
DEAD STOP

FIGURE 12

TABLE TRAVERSING MECHANISM



OFF
REV
FWD
OFF
SETTING

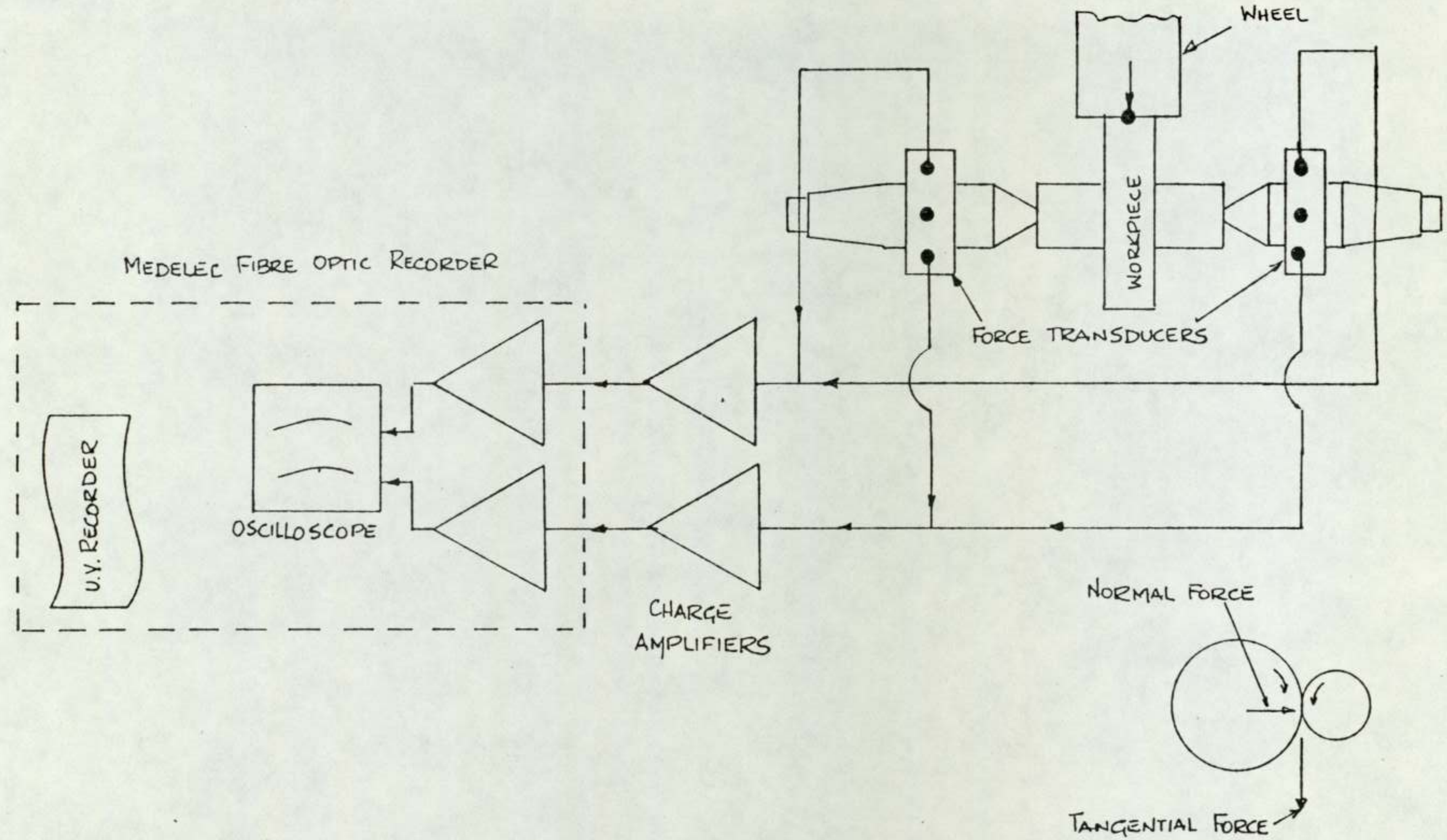
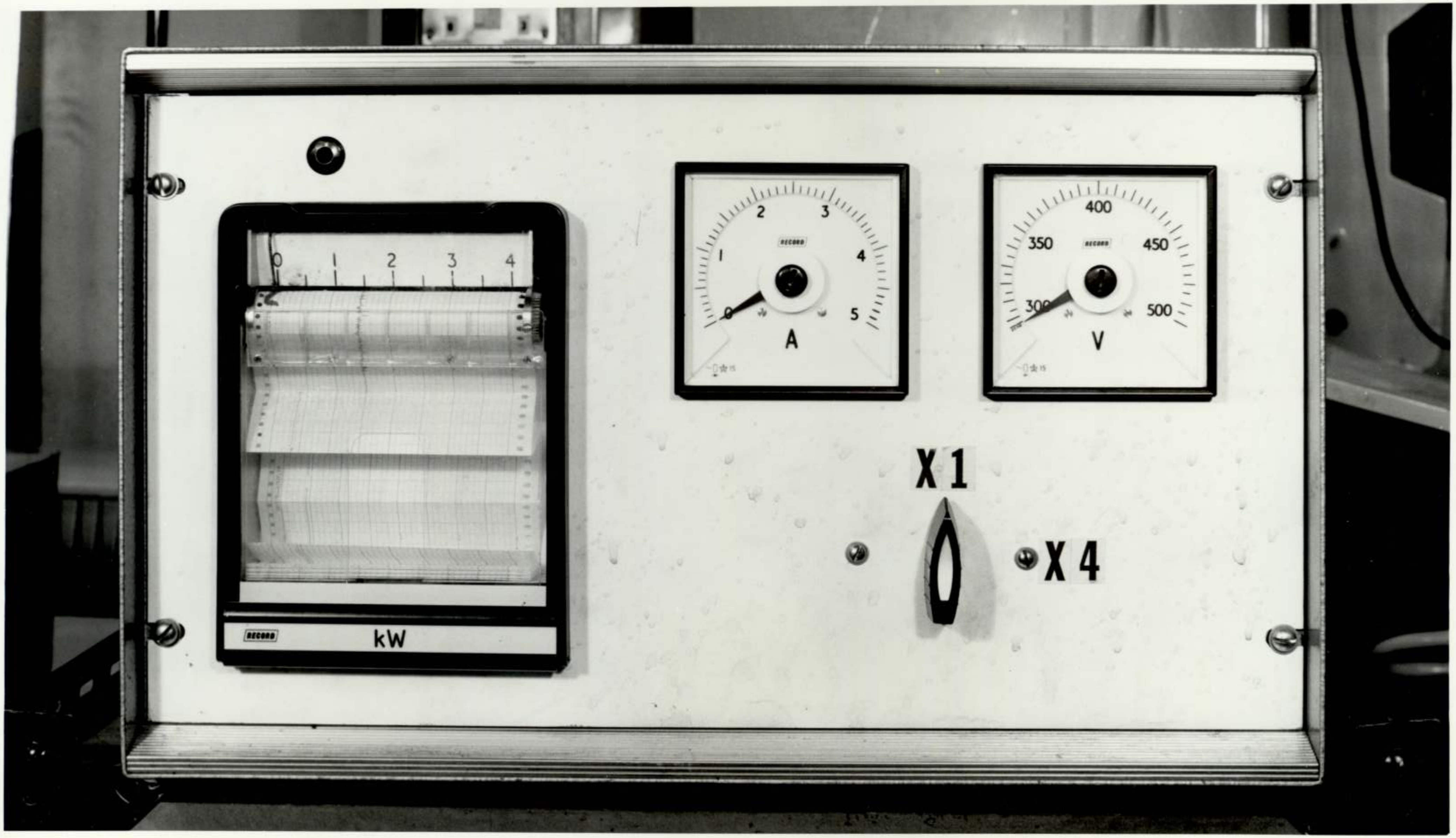


Fig13 Schematic of Force Measuring System

FIGURE 14

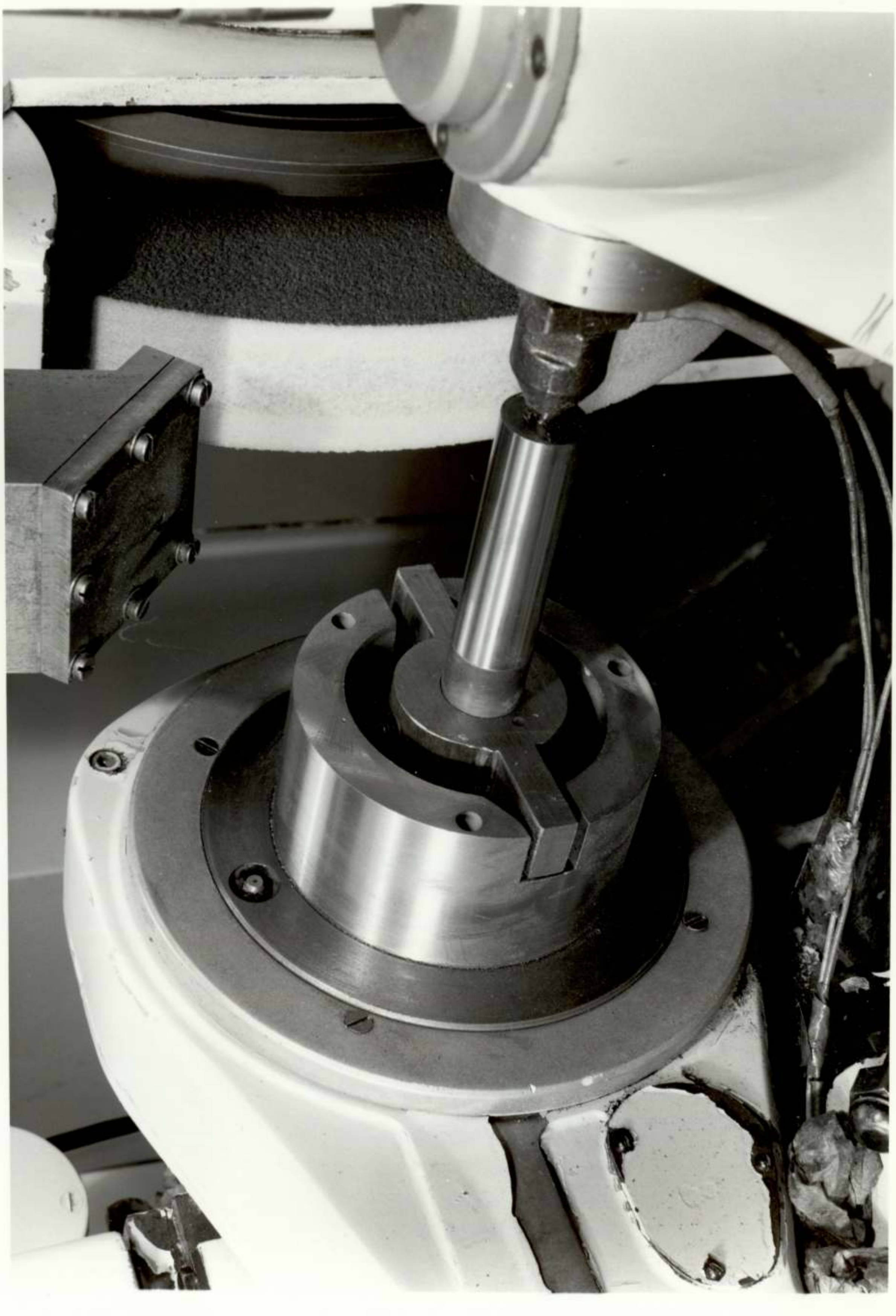
WHEELHEAD POWER RECORDER



A
V
X 1
X 4
kW
RECORD

FIGURE 15

WORKPIECE DRIVE ARRANGEMENT



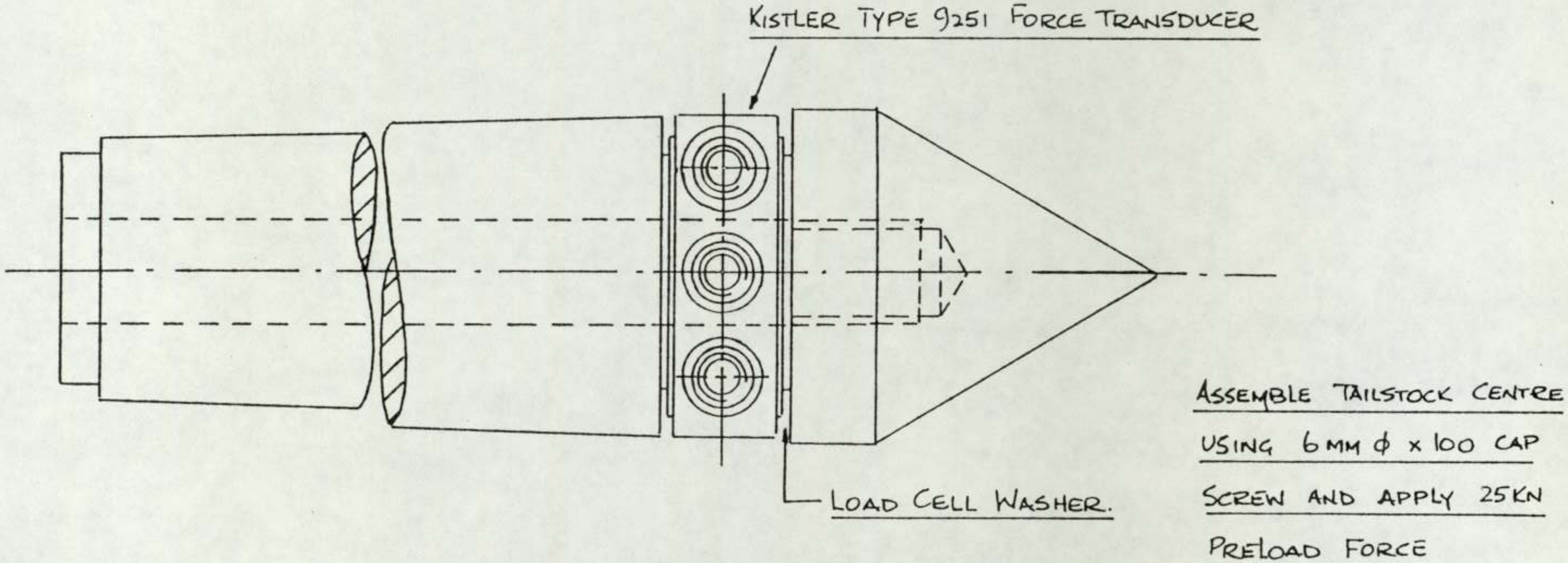


Fig 16 Tailstock Centre with Force Transducer

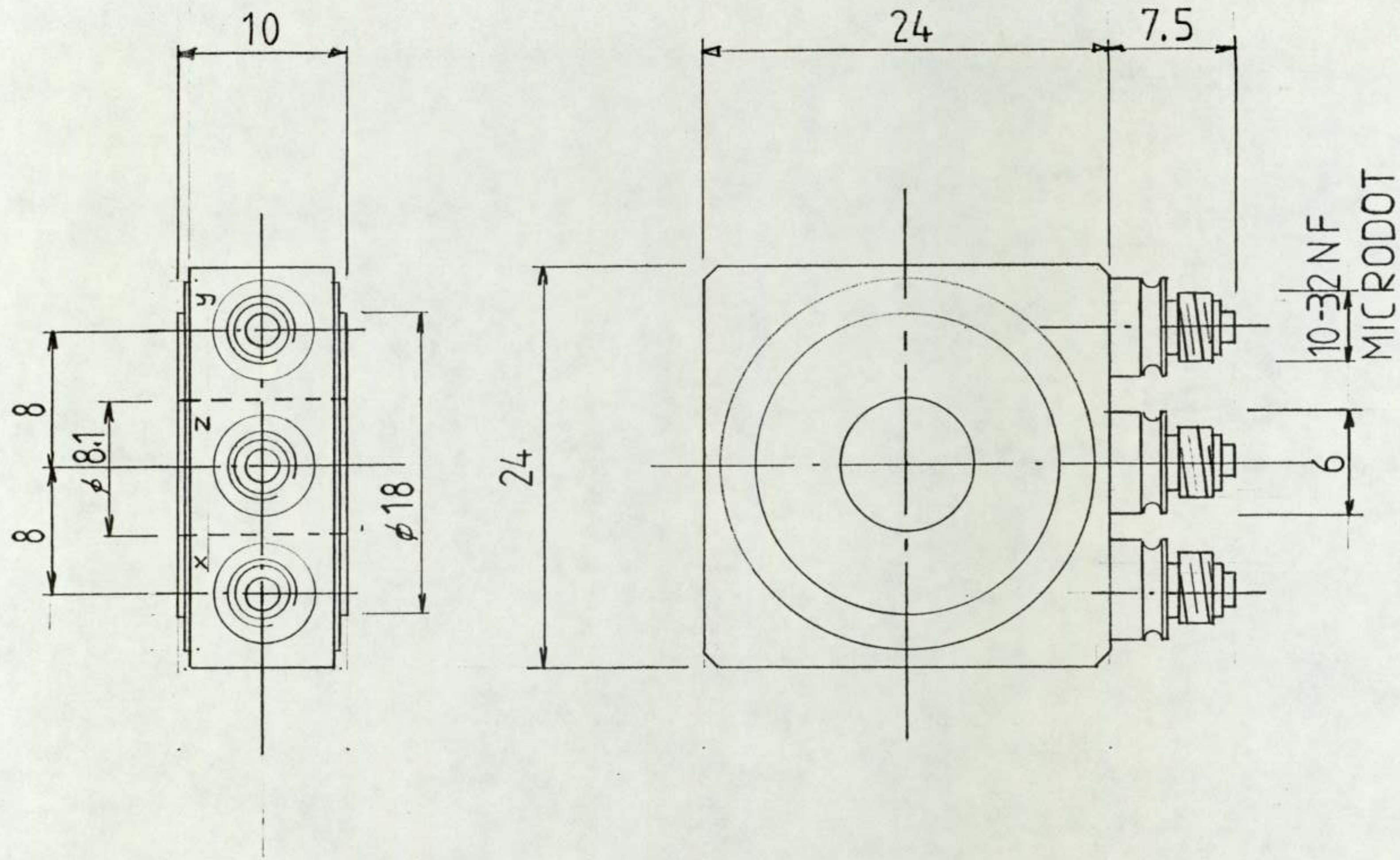
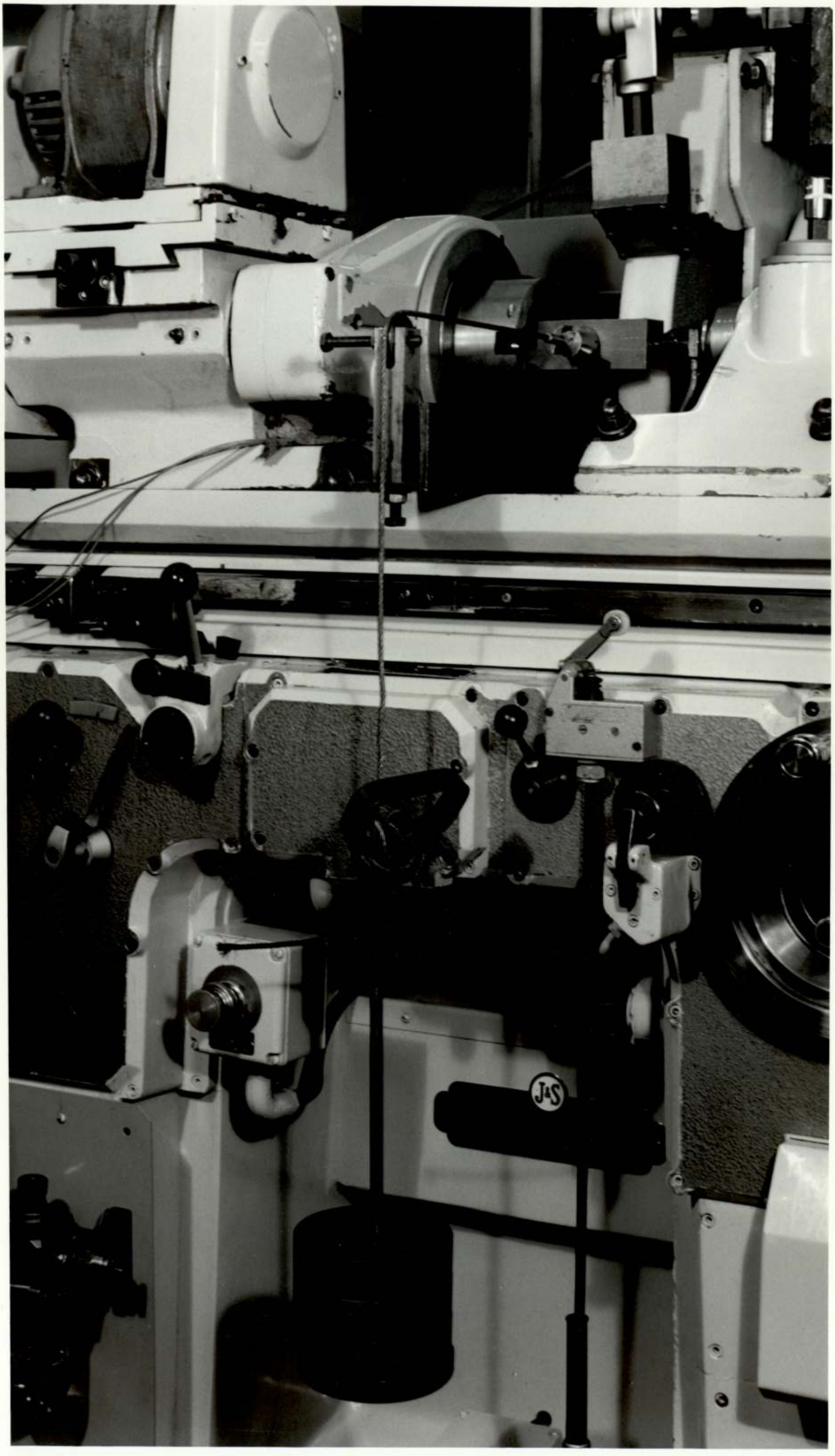
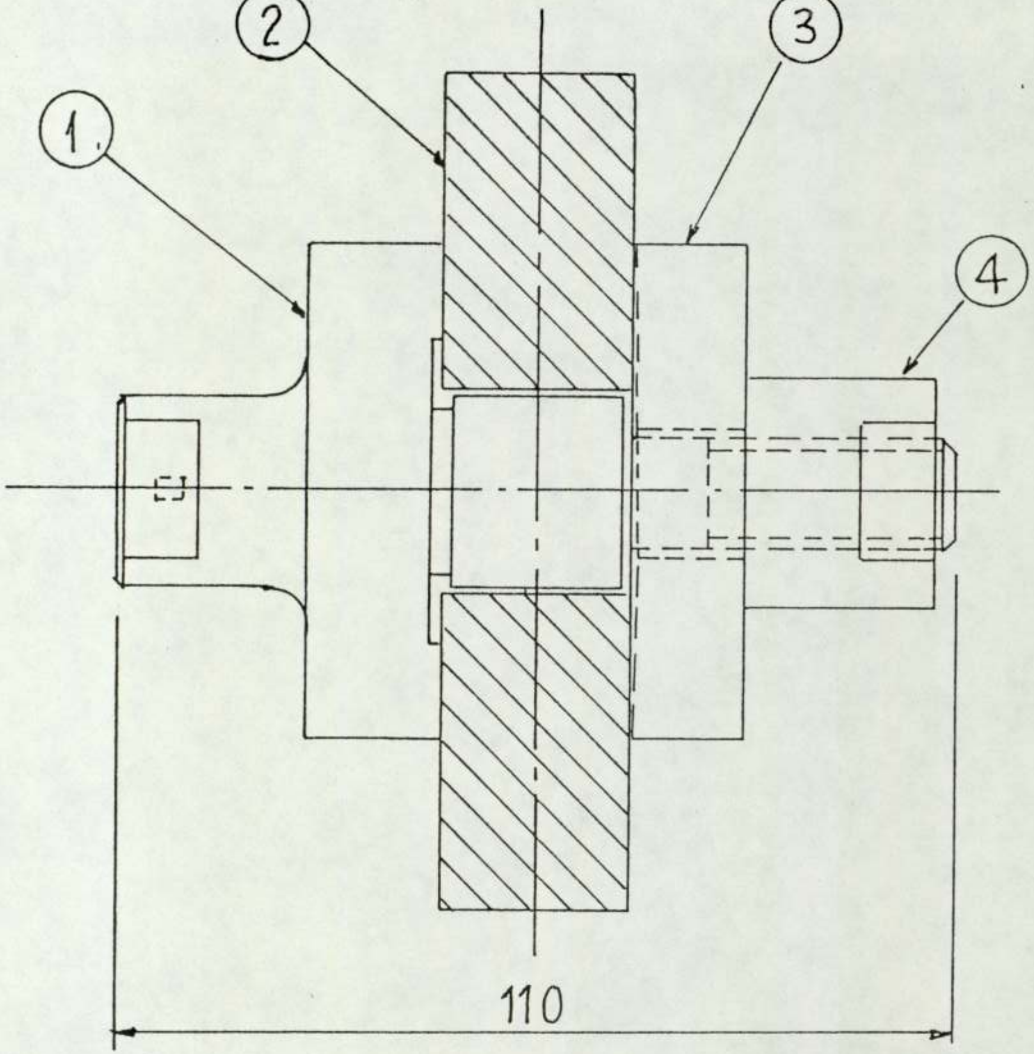


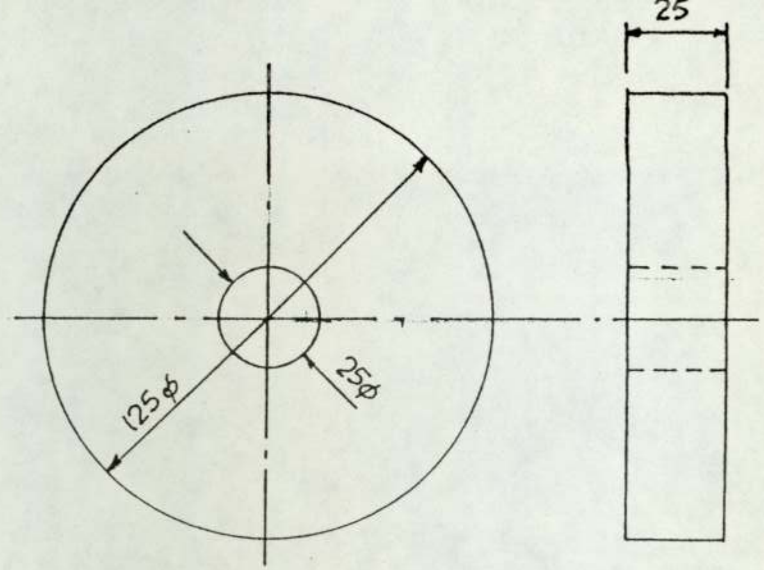
FIG17 QUARZ FORCE TRANSDUCER

FIGURE 18

STATIC CALIBRATION OF FORCE MEASURING SYSTEM







DETAIL OF WORKPIECE

No.	DESCRIPTION
1	MAIN BODY
2	WORKPIECE
3	WASHER
4	LOCK NUT

Fig 19 DETAILS OF MANDREL AND WORKPIECE

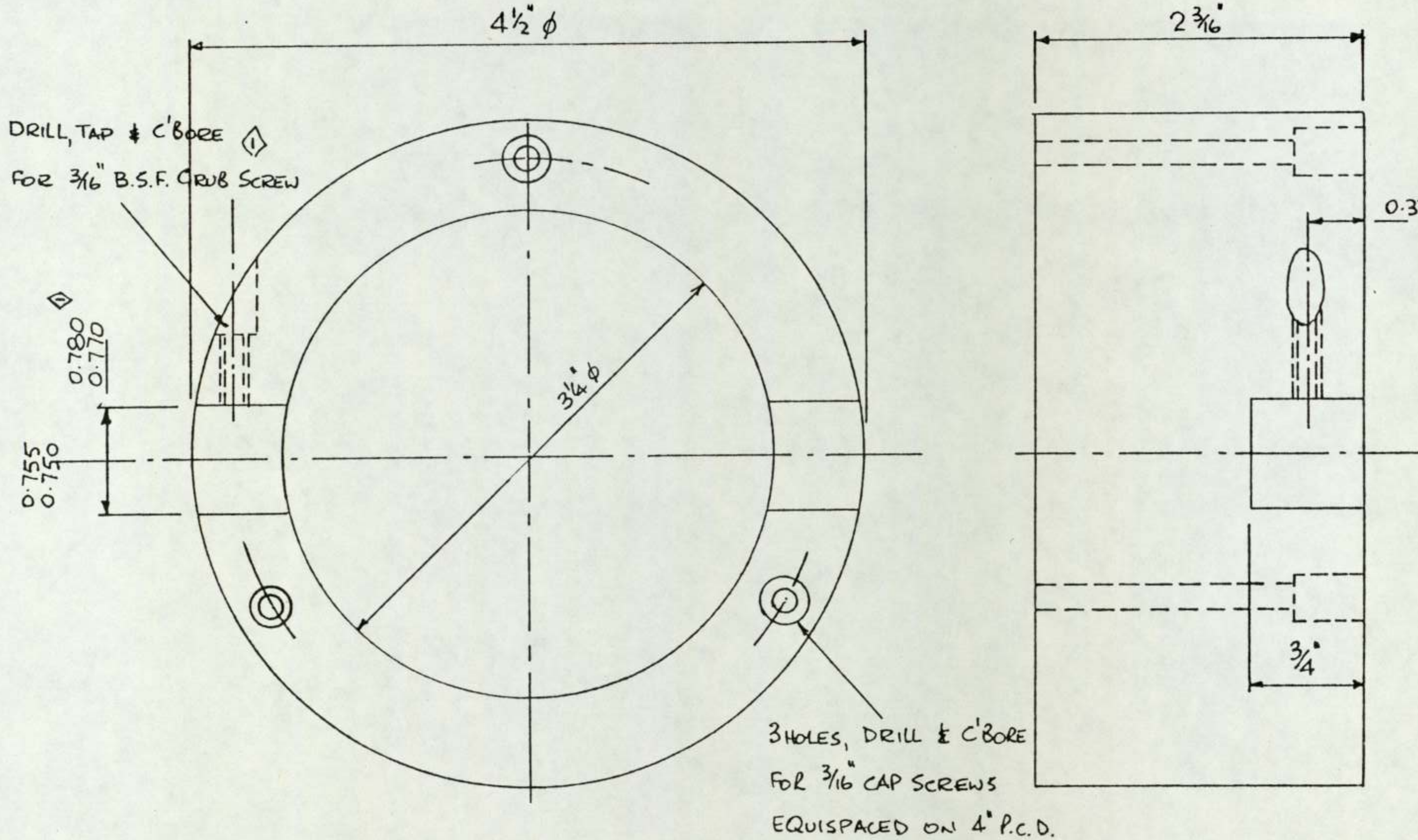


Fig 20 Workpiece Drive Plate

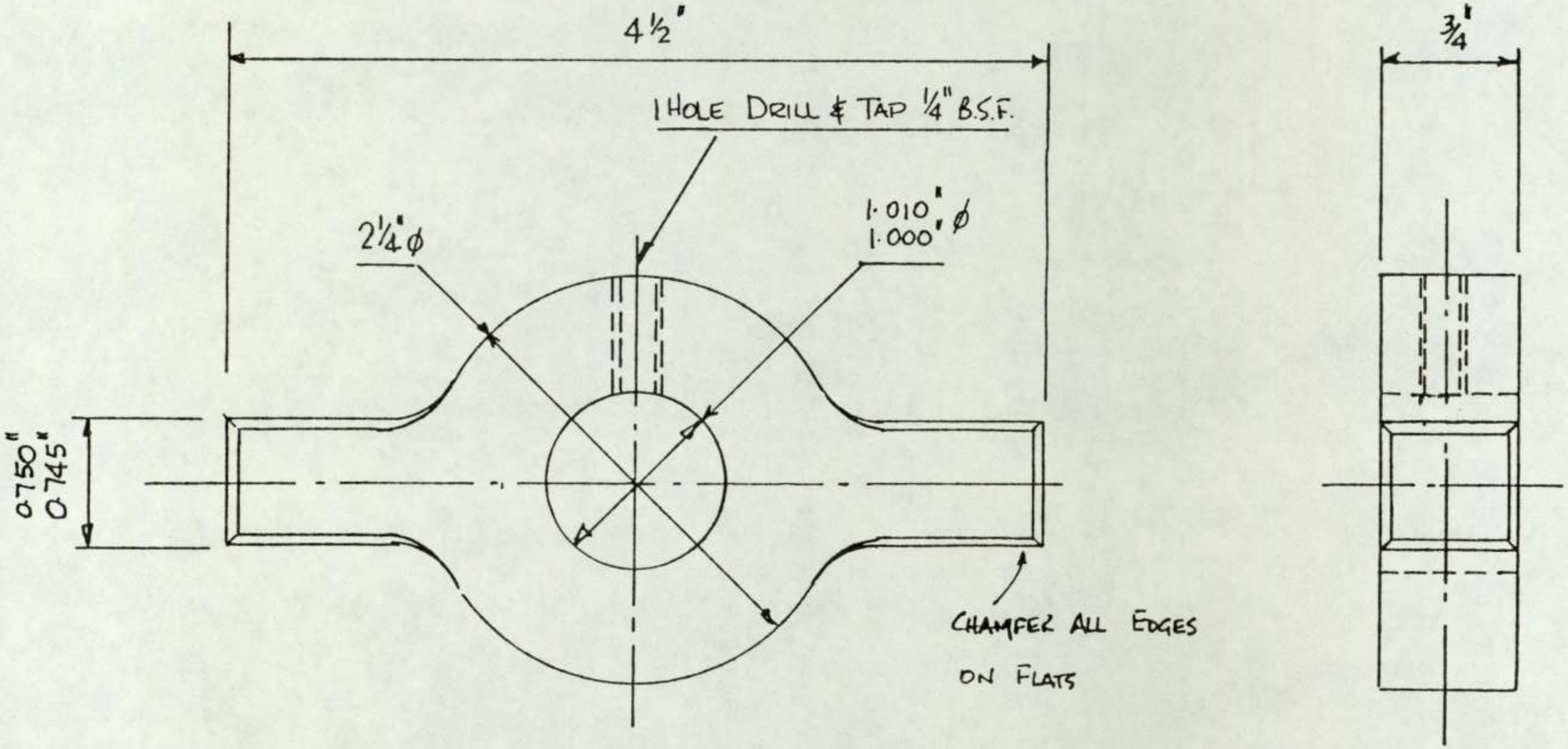


Fig 21 Workpiece Drive Dog

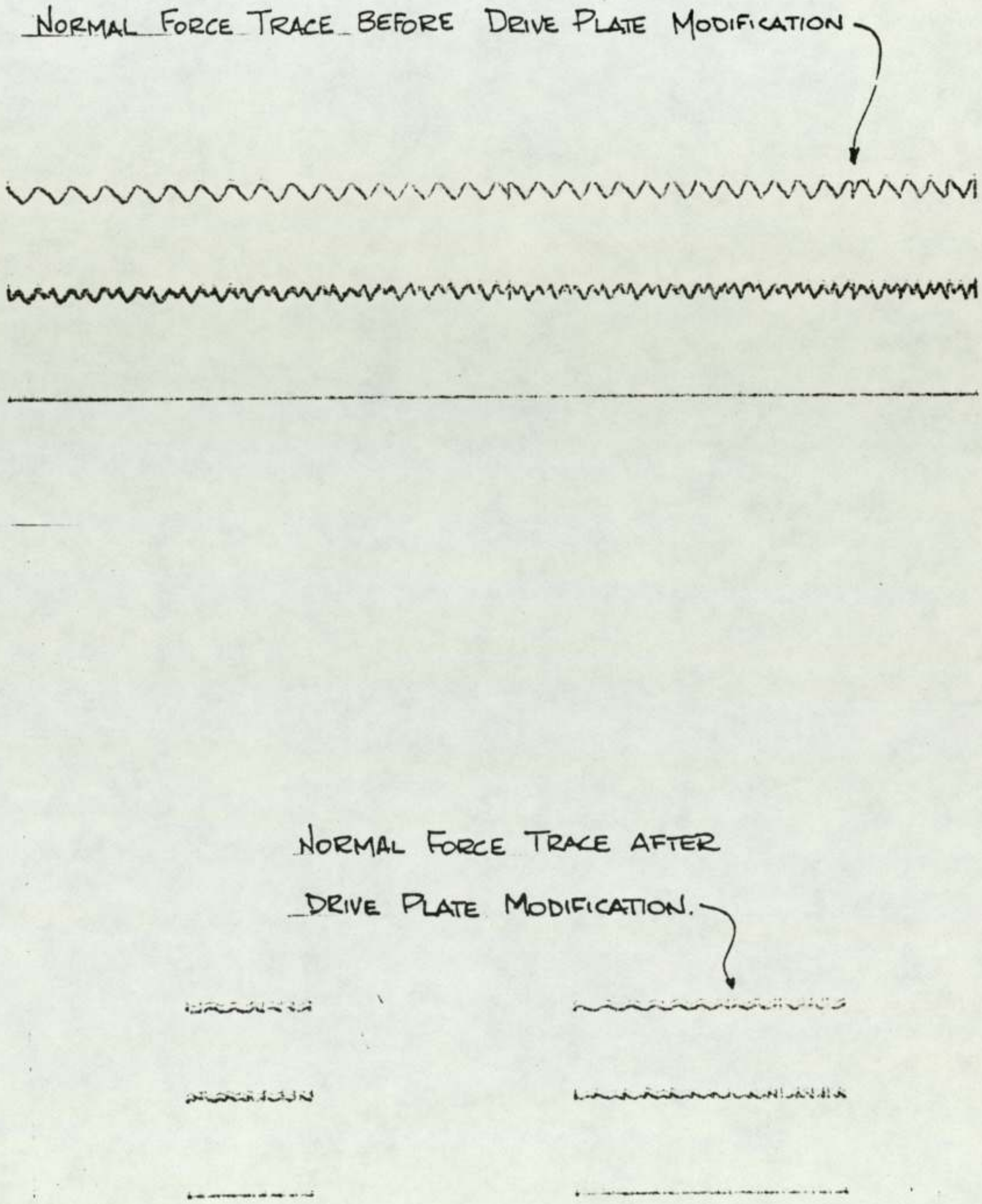


Fig 22 No-Load Force Traces

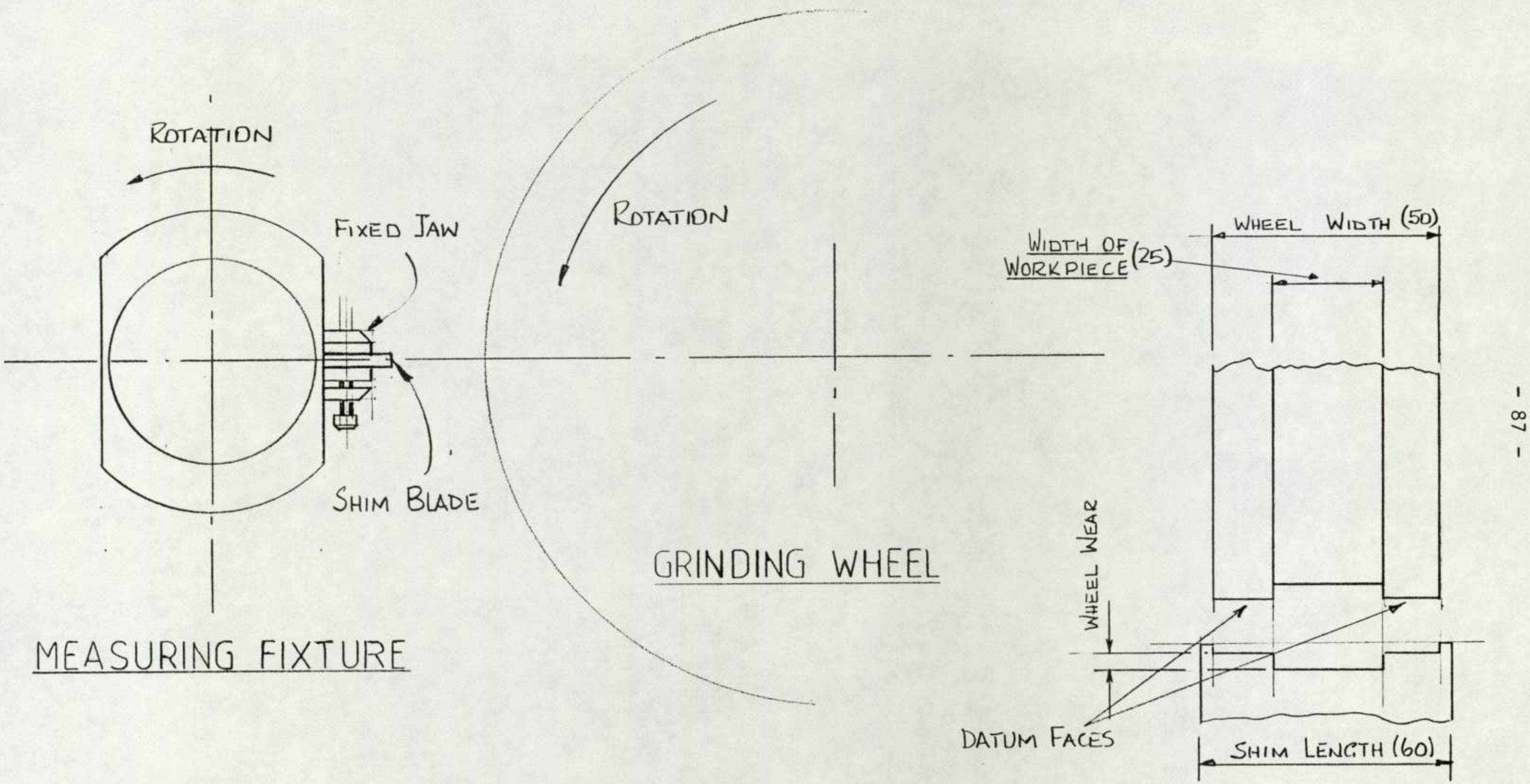
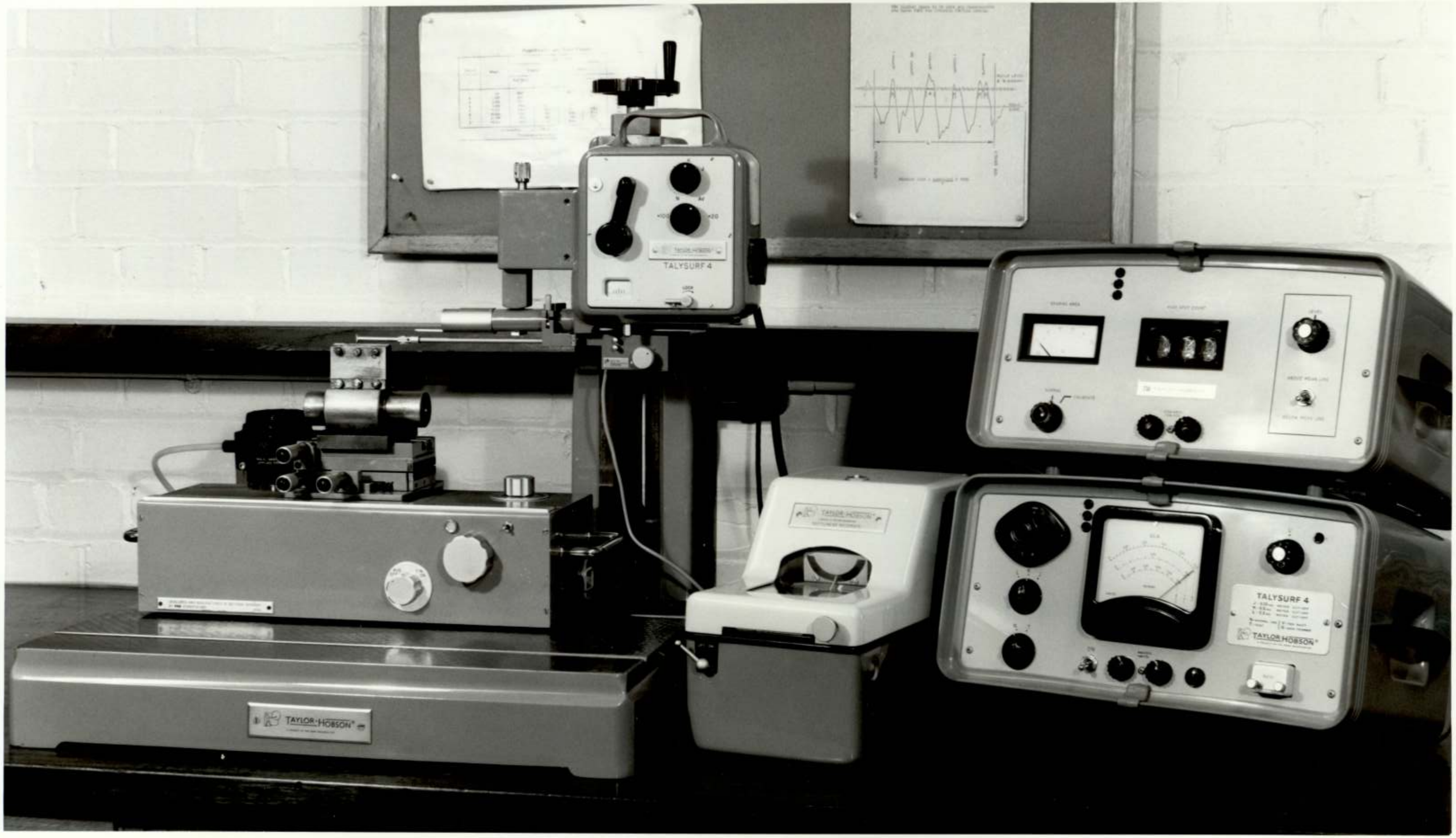


FIG 23 WEAR MEASUREMENT FIXTURE

FIGURE 24

REPLICA BLADE MEASURING EQUIPMENT


TALYSURF 4
TAYLOR-HOBSON
TALYSURF 4
TAYLOR-HOBSON
TAYLOR-HOBSON

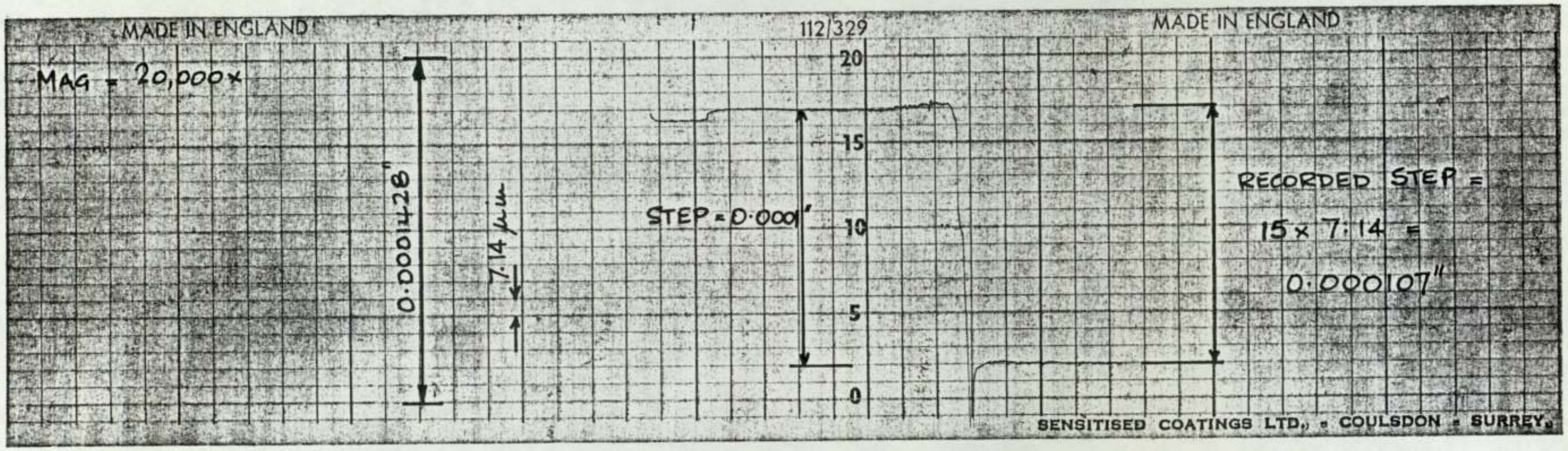


Fig25 Calibration Check : Air Traversing Table

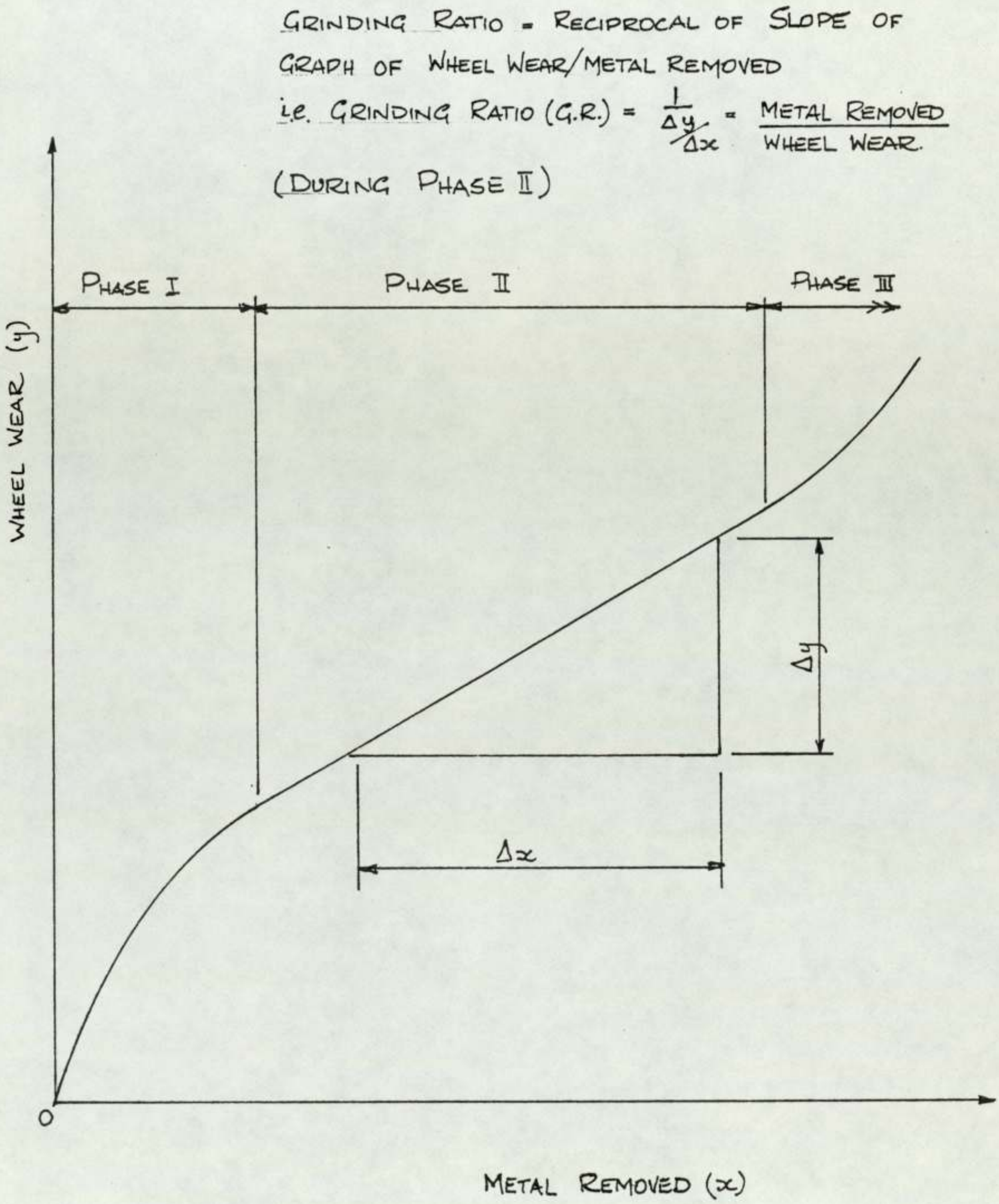


Fig 26 Determination of Grinding Ratio

FIGURE 27

GRINDING TEST DRESSING TOOLS

CHAPTER 5

ANALYSIS AND DISCUSSION OF RESULTS

From the results of the tests detailed in Table 1 to Table 6, Appendix 11, graphs for each test of wheel wear, surface finish and grinding forces were prepared. A typical set of results and graphs for test No. 87 in Table 3 are given in Table 7 and Figures 28, 29 and 30. From these individual tests values for grinding ratio on the basis of wear in the second phase of wheel wear were calculated. Values for surface finish, normal force and tangential force at 15000 mm^3 of metal removed were extracted. These values are given in Table 8 to Table 16, Appendix 11.

In addition to the tabular presentation of results, composite graphs were prepared from the individual test data showing the effects of the variation of dress lead, wheelspeed, workspeed, wheel grade and metal removed on wheel wear, surface finish and grinding forces. The graphical presentation is given in Figure 31 to Figure 65.

During testing it was noted that as a result of the dressing treatment applied a wide range of results were obtained during the initial phase of wheel wear. Whilst these results are of great interest their real relevance in production is when the wheel is dressed after grinding each component or when continuous dressing is practised. Normally the production engineer is more interested in the grinding performance that will occur during the second phase of wheel wear.

Accordingly the statistical testing for the levels of surface finish and grinding force have been made both at the start of grinding and when 15000 mm^3 of metal were removed. This is after approximately 60% of the total metal has been removed in a test and is well within the second phase of wear. The results quoted for grinding ratio are on the basis of wear throughout this secondary phase of wear.

5.1 Statistical Analysis of Results

The paired t test was used to compare the results obtained using the different dressing tools and also to compare the predicted and actual force levels obtained using the analysis detailed in Chapter 6. Where a fully replicated test programme was utilised, an analysis of variance was carried out and the procedure for this is outlined in Section 5.1.2.

5.1.1 Paired t test

The values obtained in Table 8 to Table 11 were subjected to statistical analysis to determine those factors which had a significant effect on the measured parameters.

Given a set of paired observations from two normal populations with means μ_1 and μ_2 (unknown)

x_i	x_1,	x_2,	x_3 .... x_n
y_i	y_1,	y_2,	y_3 .... y_n

let $D_i = x_i - y_i$

then $$\overline{D} = \frac{1}{n} \sum_{i=1}^{n} D_i$$

the standard deviation

$$S_D = \sqrt{\frac{\Sigma D_i^{\,2} - \frac{1}{n} (\Sigma D_i)^2}{n - 1}}$$

and the standard error of the mean

$$S_{\overline{D}} = \frac{S_D}{\sqrt{n}}$$

Thus the test statistic is as follows:-

$$t = \frac{\overline{D}}{S_{\overline{D}}}$$

which has (n - 1) degrees of freedom and can be used to test the null hypothesis:-

$$H_o : \mu_1 = \mu_2$$

The values obtained are compared with the percentile values for the students t distribution with ν degrees of freedom given in Appendix 7 and a level of significance applied to the results. If the calculated value of 't' exceeds the value given by the 5% probability for the appropriate degrees of freedom, it is concluded that the result is probably significant; if the 1% probability level is exceeded the result is significant and if the 0.1% probability level is exceeded the result is highly significant.

In the testing carried out it was possible to pair a number of results in which only one parameter was varied, the minimum number of tests carried out being twelve for any set of data for a paired 't' statistic calculation.

5.1.2 Analysis of Variance

Analysis of Variance is a statistical technique that assesses the effects of one or more categorical independent variables, measured at any level upon a continuous dependent variable that is usually assumed to be measured at an interval level. Conceptually, the cases are divided into categories based on their values for each of the independent variables and the differences between the means tested for statistical significance. The relative effects upon the dependent variables of each of the independent variables, their combined effects and interactions may be assessed.

The basis of analysis of variance is the decomposition of variance or sums of squares corrected for the mean (SS). If a one way analysis of variance is considered with a dependent variable (Y) and a categorical independent variable, or Factor A, then the total sum of squares in Y, SS_Y can be decomposed into two independent components:

$$SS_Y = SS_{BETWEEN} + SS_{WITHIN} \tag{1}$$

where $SS_Y = \Sigma_j \Sigma_i (Y_{ji} - \overline{Y})^2$

in which $\overline{Y}$ is the mean of Y over the whole sample and the summations are over all individual cases i in each category j of the factor A.

$$SS_{BETWEEN} = \sum_j N_j (\overline{Y}_{j.} - \overline{Y})^2$$

In which $\overline{Y}_{j.}$ is the mean of Y in the category j and N_j is the number of cases in category j

$$SS_{WITHIN} = \sum_j \sum_i (Y_{ji} - \overline{Y}_{j.})^2$$

- $SS_{BETWEEN}$ is the portion of the sum of the squares in Y due to factor A, that is, due to the variation in the $\overline{Y}_{j.}$ means of the categories of factor A. Thus $SS_{BETWEEN}$ can be denoted as SS_A. SS_{WITHIN} is the portion of the sum of the squares in Y due to the variation within each of the categories of A. SS_{WITHIN} is the variation which is not accounted for by A and is often known as the error sum of squares.

Thus the statement (1) can be rewritten as:-

$$SS_Y = SS_A + SS_{ERROR} \tag{2}$$

The estimate of population variance based on the between category variations, $\frac{SS_A}{(k-1)}$ is equal to the mean square due to A or MS_A. The estimate of population variance based on the within category variations $\frac{SS_{WITHIN}}{(N-k)}$ is equal to the Mean Square of the error or residual. Both these estimations are independent estimates of the variance of the dependent variable Y. The F ratio is the ratio between these estimates and is given by:-

$$\frac{SS_A/(k - 1)}{SS_{ERROR}/(N-k)} = \frac{MS_A}{MS_{ERROR}} \tag{3}$$

and follows the F distribution with (k - 1), the number of categories in A less one, and (N - k) degrees of freedom.

The above principle can be extended to study the effects of further variables so that the total variation in Y can be partitioned into further independent components, consisting of main effects, both linear and quadratic and the interactive effects.

An example of an analysis of variance is given in Appendix 8 and an extract of the F distribution tables in Appendix 9. The same values of significance are applied for the 'F' test as were applied for the 't' test (Section 5.1.1).

5.2 Effects of using Different Dressing Tools

The dressing tools employed in this series of tests were a single point diamond, a multi point diamond dresser with a random distribution of grits and a blade dressing tool. The results of the statistical tests are summarised in Table 17.

5.2.1 The variation of grinding ratio due to differing tools

Significant increases in grinding ratio are obtained when using both the multi point and the blade dressing tools compared with the single point diamond. This general improvement in grinding ratios when using 'cluster' tools can be correlated with the effect described later in Section 5.3.1, that the grinding ratio improves as the dress lead decreases.

When using the cluster type of tool, the nature of contact between the dressing tool and wheel is changed from that which occurs when single point dressing. With a single point tool, each point on the wheel surface is contacted once and therefore any structural defects in the wheel surface caused by the impact of the tool remain when the wheel begins to grind. However, the multiple contacts achieved by cluster tools, illustrated in Figure 66 will tend to remove the damaged wheel structure and hence the wheel will be more stable when it is used for grinding. A stable wheel will wear at a slower rate and hence give an increase in grinding ratio.

5.2.2 The variation in surface finish due to different dressing tools

The statistical testing revealed that there was no significant difference between the surface finish obtained using the different dressing tools.

These results confirm the expected trend, as it was shown by Pahlitzsch and Appun (9) that the surface roughness of the wheel rapidly stabilises during the initial wear phase and that the results for the workpiece surface finish at the end of testing were comparable for a range of dressing treatments.

The measurements of surface finish in the series of tests reported here was taken at 15000 mm^3 of metal removed, ie after a considerable period of grinding in the secondary wear phase, at which time the stabilisation effects were well established.

5.2.3 The variation in grinding forces due to different dressing tools

Testing reveals that there were no significant differences in either the normal or tangential forces as a result of altering the dressing tool. The effect of altering dress lead will be shown to be a significant factor on the level of grinding forces in Section 5.3.1. However, if small changes in dress lead are considered, the level of significance is substantially reduced.

Figure 66 shows the effect of using multi point tools on the wheel profile generated. The main effect is seen to be that of reducing the peak to valley height of wheel roughness. In addition, a number of subsidiary points are generated at the root of the dressed profile. Thus the basic form of the wheel suffers only minor modifications in terms of dress lead, though the overall roughness of the wheel is reduced. This then being a minor change of dress lead would not affect the level of forces, although the smoother wheel with decreased chip clearance will not allow grinding for the same length of time as a wheel dressed with a single point diamond under the same conditions.

5.3 Effects due to Varying Dress Lead

The results for the statistical tests showing the effect of dress lead on grinding ratios, surface finish and grinding forces are shown in Table 18.

5.3.1 Variation of grinding ratio due to changing dress lead

Generally an increase in dressing lead will give a more open wheel, more suited to a heavier metal removal operation due to the greater chip clearance available. However, in providing this more open wheel, a greater amount of surface and sub surface structural damage results to the bond posts. Thus initially there is a far higher rate of wear and subsequently the rate of wear is higher during the steady state conditions.

These trends, shown in Figures 31, 34, 37, 40, 43, 44 and 45, are confirmed by the statistical testing which shows that for each incremental increase in dressing lead, there is a subsequent decrease in grinding ratio. Within the range of dress leads for which the tests were made, the factor of dress lead was found to be highly significant.

5.3.2 Variation in surface finish due to changing dress lead

Statistical testing shows that dress lead has a highly significant effect upon the quality of the surface finish. For each incremental increase in dress lead, there is a consequent reduction in the quality of surface finish. The reason for this is that an open wheel is of necessity a rougher wheel and the increased roughness is imparted to the workpiece.

It was noted in testing and shown in Figure 46, that when dress leads in excess of 0.50 mm/rev were applied, the initial values for surface finish could be very high. However, by the time the tests were concluded, the differences in value were considerably reduced. The sampling of surface finish was made at a point when 15000 mm^3 of metal had been removed during the test, that is at a point when the initial effects were no longer apparent. Even though the differences in surface finish are much less the effect of dress lead is still highly significant. It must be concluded therefore that if consistent levels of surface finish are required, dress leads of 0.50 mm/rev or less must be used. However, if a heavy metal removal rate is required, the surface finish is not usually a limiting factor and assumes relative unimportance.

The statistical testing shows that in addition to the highly significant effect of dress lead on surface finish, there is a further significant effect due to the interaction of metal removal rate and dress lead on surface finish. Metal removal rate itself does not have any significant effect on surface finish but the combination of high dress leads and high removal rates enhance the deterioration in surface finish because both effects tend to cause rapid breakdown of the wheel surface.

5.3.3 Variations in grinding force due to changing dress lead

The treatment of both the normal and tangential forces has been considered at two stages, (a) shortly after the commencement of grinding, and (b) when 15000 mm^3 of material had been removed during testing.

When the results of the grinding tests were analysed, it was noted that in some cases the forces increased consistently until a steady state condition was achieved, whilst at other times, an initial high peak was recorded before the forces decreased to the steady state. These conditions have been noted in the literature but no explanations as to the reasons were given by the authors (21, 25, 27). In succeeding sections, this pattern of forces will be analysed and reasons advanced for the variations in patterns of initial forces encountered in testing.

Sampling of these initial forces was made at a point when 500 mm^3 of metal had been removed. This would approximate to the amount of material removed from one component under the conditions used in these tests.

5.3.3.1 Variations in grinding force at the commencement of grinding due to changing dress lead

Statistical testing shows that dress lead has a significant effect on the values of both normal and tangential force at the commencement of grinding. As the dress lead is increased to give a more open wheel, the grinding forces are reduced.

In addition to the main effect of dress lead there is a quadratic interaction between the dress lead and the metal removal rate. The result of this interaction is that as metal removal rate is increased in combination with dress lead, the grinding forces will fall. The reason for this is that high metal removal rates quickly break down the surface of the wheel, producing sharp cutting edges and hence lower grinding forces.

5.3.3.2 Variation in grinding force during the steady state condition due to changing dress lead

After a wheel has been used to grind material for some time, it is apparent that dress lead has a less complex effect on forces. The main effect of dress lead is highly significant and an increase will give lower grinding forces due to the more open and sharper wheel.

The interaction between dress lead and metal removal rate, which was quadratic at the commencement of grinding, is by now however a simple linear relationship which tends to reduce the grinding forces. The reduction is very small when associated with low metal removal rates and small dress leads (approximately 1 Newton) but with high metal removal rates and high dress leads, the factors of reduction are of the order of 50 Newtons for normal force and 30 Newtons for tangential force for the tests reported here. These results indicate that a wheel dressed with a high lead has instability in its surface layers to a significant depth. The high metal removal rate will cause rapid wheel wear and hence maintain sharper cutting edges than would be obtained at lower wear rates. The effect of dress lead is shown in Figures 33, 36, 39, 42, 47, 48 and 49.

5.4 Effects due to Varying Grinding Wheelspeed

There were three wheelspeeds used during the grinding tests, 30, 45 and 60 m/s. The diameter of the grinding wheel was monitored throughout the tests and the rotational speed was adjusted so that the peripheral speed remained constant. The coolant system was modified as described in section 4.4 to counter the effects due to the additional heat generated at increased wheelspeeds.

5.4.1 Variation in grinding ratio due to changing wheelspeed

It will be seen from the statistical summary in Table 18, that the linear effect of wheelspeed is probably significant in increasing grinding ratios. In addition to this, there is a significant quadratic effect of wheelspeed on grinding ratio and a further significant quadratic effect in conjunction with metal removal rate.

From a consideration of previous work (33, 34, 35) it is to be expected that because of the reduced chip dimensions and lower grinding forces encountered when grinding speeds are increased, the wear of the wheel will be less. Chip thickness 't_{max}' can be calculated by using the equation (45):-

$$t_{max} = \left[\frac{4\ v}{VCr} \bigg/ \sqrt{\left(\frac{d}{D} + \frac{d}{Dw} \right)} \right]^{\frac{1}{2}} \qquad (4)$$

where v = workspeed
V = wheelspeed
C = number of effective grits
r = width to depth ratio
d = depth of cut
D = wheel diameter
Dw = workpiece diameter

It will be seen that the maximum chip thickness is inversely proportional to the square of wheelspeed, an effect illustrated in Figure 50. It is therefore logical to expect that the quadratic effects of wheelspeed will be more significant than the linear effects. Figures 43, 44 and 45 illustrate the effect of wheelspeed on wheel wear.

5.4.2 Variation in surface finish due to changing wheelspeed

The results of statistical testing show that there is a highly significant improvement in surface finish as wheelspeed is increased and in addition, there is a significant interaction between the metal removal rate and wheelspeed.

The improvement in surface finish when increasing wheelspeed is due to two effects:-

(a) the value of maximum chip thickness will decrease as the wheelspeed is increased as shown in Section 5.4.1. This will lead to a reduction in the depth of penetration of the grit and hence a lower value of peak to valley height on the workpiece

(b) by increasing the wheelspeed, an increased number of grits will be presented to the workpiece per unit time. This is in effect a reduction in the value of feed per grit and again leads to improvements in surface finish

Figure 51 shows the effects of wheelspeed on surface finish. It should be noted that statistical testing was carried out on the results obtained at the point when 15000 mm^3 of metal had been removed.

5.4.3 Variation of grinding force due to the variation of wheelspeed

The analysis of the results for both normal and tangential forces show that for each increase in wheelspeed there is a subsequent reduction in force level. The patterns of significance are very similar for the normal and tangential force.

The reason for the reduction in force levels is due to the effect of wheelspeed on the maximum chip thickness as demonstrated in Section 5.4.1. A reduction in the maximum chip thickness will lead to a reduction in the load per grit and hence lower tangential forces and reduced power drawn. The reduction of maximum chip thickness will also lead to a lower contact area and hence a lower normal force.

The main effect of wheelspeed on tangential forces is highly significant during grinding and significant at the commencement of grinding. In addition, there is a probably significant two factor interaction between wheelspeed and metal removal rate that also tends to reduce tangential force.

The effect of wheelspeed on normal forces is significant in reducing the force levels during the steady state phase of grinding. However, due to the unpredictability of wear in the initial phase of grinding, it is not prominant in these early stages.

These results are in agreement with the findings of other researchers, and wheelspeed therefore can be seen to be one of the major factors in determining both the normal and tangential forces in grinding. This point will be dealt with in more detail in Chapter 6 which deals with the prediction of force levels in grinding.

Figures 47, 48 and 49 show the effects of wheelspeed on both normal and tangential forces.

5.5 The Effect of Increasing Metal Removal Rate

5.5.1 The effect of increasing metal removal rate on grinding ratios

As an increase in metal removal rate will probably lead to an acceleration in the wear rate because of the increased load per grit, it is to be expected that an increase in metal removal rate will lead to a drop in the grinding ratio. Referring to Table 18, it is seen that the main effect is highly significant. There is in addition a significant two factor interaction of metal removal rate and wheelspeed which will tend to modify the decrease in grinding ratio as the factor of wheelspeed will reduce the maximum chip thickness (see also section 5.4.1).

5.5.2 The effect of increasing metal removal rate on surface finish

There is no evidence of direct significant effects of metal removal rate on surface finish. Trends are apparent from the graphical presentation of the results, see Figure 52, and these trends are the result of significant interactions of metal removal rate and wheelspeed and metal removal rate and dress lead. Both these two factor interactions tend to lead to an improvement in surface finish, though of the two the relationship between metal removal rate and wheelspeed gives the highest values when substituted in a regression equation. The values for the metal removal rate and dress lead interaction are of a lower order of magnitude.

5.5.3 The effect of increasing metal removal rate on grinding forces

From an examination of the table of significance (Table 18) metal removal rate is seen to be a highly significant factor in determining the levels of grinding force. The levels of grinding force rise as metal removal rate increases. This trend is to be expected from a consideration of metal cutting theory, and as metal removal rate is of prime importance in determining the level of both normal and tangential force, its' effect will be discussed in greater depth in Chapter 6.

5.6 The Effect of Changing Workspeed

A summary of the statistical tests is given in Table 19. This series of tests was carried out at 60 m/s wheelspeed and at a metal removal rate of 16 mm^3/mm/sec and was designed to investigate the effects of workspeed and wheel grade on grinding force, surface finish and grinding ratio. The tests were limited to this combination of wheelspeed and metal removal rate because the project is mainly concerned with grinding conditions at high metal removal rates and best results were obtained at 60m/s.

Three workspeeds were used 90, 140 and 210 RPM; on average these correspond to 0.51, 0.80 and 1.20 m/s respectively.

5.6.1 <u>The effect of workspeed on grinding ratio</u>

Statistical testing shows in Table 19 that there is no significant effect of workspeed on grinding ratio. Considering the equation for maximum chip thickness (45):-

$$t_{max} = \left[\frac{4\ v}{VCr} \left[\frac{d}{D} + \frac{d}{Dw} \right]^{\frac{1}{2}} \right]^{\frac{1}{2}}$$

it might have been expected that the quadratic effect of workspeed would be of significance.

The following calculations show for the range of workspeeds tested the effect of workspeed is greater in percentage terms than the effect of wheelspeed.

at 0.51 m/s $(\sqrt{0.51}) = 0.71$

at 1.2 m/s $(\sqrt{1.2}) = 1.09$ ie a 53.5% increase in chip thickness

at 60 m/s $(\sqrt{\frac{1}{60}}) = 0.129$

at 30 m/s $(\sqrt{\frac{1}{30}}) = 0.182$ ie a 41% increase in chip thickness

Though these results are roughly comparable, they ignore the effect of the relative change in infeed, the consequent change in chip length and the change in relative speed between wheel and workpiece. Although the maximum chip thickness is greater at 1.2 m/s workspeed due to the reduction of infeed, the length of the chip is reduced. In addition the relative speed of the wheel is increased leading to a greater amount of heat being generated. This as will be shown later will lead to a reduction of the coefficient of friction between the grit and the workpiece. These factors would tend to lower the rate of wear (G Ratio) at the higher workspeed. However, examination of the figures for overall wear reveal that the value of signficance for the quadratic effect of workspeed at 3.20 is only just below the 5% significance level. The range of testing in the second series of tests was very much more restricted than in the first series of tests and as this factor may be possibly significant, further testing would be required to determine the level of significance.

There is, however, a two factor interaction between workspeed and dress lead that is possibly significant. If the expression for chip thickness (45) is examined, it will be seen that the term C, the effective number of grits, will be affected by the dress lead. A more open wheel will lead to a reduction of the effective number of grits and thereby lead to an increase in the maximum chip thickness. Figure 53 shows the effects of workspeed on maximum chip thickness, Figures 54 and 55 show the effects of workspeed on wheel wear.

5.6.2 The effect of workspeed on surface finish

Statistical testing shows that there are no significant effects of workspeed on surface finish. The sampling of surface finish was carried out when 15000 mm^3 of metal had been removed. At this time, the effects that influence surface finish tend to have diminished and this result should not be unexpected. Figures 56 and 57 show the effect of workspeed on surface finish.

5.6.3 The effect of workspeed on grinding force

The effects of workspeed on both normal and tangential force are complex. Reference to Table 19 shows that there are significant main effects of both linear and quadratic forms effecting the normal force and in the linear form for the tangential force. In addition, there are significant quadratic two factor interactions between workspeed and dress lead and workspeed and wheel grade affecting the level of grinding force.

The interactions affect forces in opposing ways. As workspeed is reduced the grinding forces are reduced due to the reduction in the maximum chip thickness. A softer wheel will promote lower grinding forces because blunted grits will be released faster from the wheel while a more open wheel, due to the reduction in active cutting points, will lead to an increase in the maximum chip thickness. Thus the wheel grade workspeed interaction will lead to an overall reduction of 40 Newtons in normal force and 10 Newtons in tangential force for the extremes of a J wheel at 90 RPM and an N wheel at 210 RPM. The interaction of workspeed and dress lead may similarly be quantified as 46 Newtons for normal force and

10.5 Newtons for tangential force between the extremes of a J wheel at 0.25 mm/rev dress lead and an N wheel at 0.75 mm/rev dress lead.

The overall effect of workspeed is that as workspeed is reduced and hence the ratio of $\frac{V_s}{V_w}$ is increased from 50 to 110 the grinding forces are seen to be significantly lowered. The effect of workspeed on grinding forces is shown in Figures 58 and 59.

5.7 The Effect of Wheel Grade

In addition to the L grade wheels used in the series I tests, wheels of the same grit size but of J and N grade were tested to demonstrate the effects of wheel grade on grinding ratio, surface finish and grinding forces. The summary of statistical testing results are shown in Table 19.

5.7.1 The effects of wheel grade on grinding ratio

Statistical testing showed that there was no significant effects of wheel grade on grinding ratio. However, if the results for overall wear are examined, it will be seen that the wheel grade has a significant effect on wheel wear. The conclusion that can be drawn is that once the initial wear phase is concluded, the wear of the wheels will be approximately the same and yield very similar results for grinding ratio. In general, the N grade wheels will give lower wear.

The two factor interaction between workspeed and dress lead that was analysed in section 5.6.1 modifies the trend where the harder wheels wear more slowly and at low wheel speeds and high dress leads this trend is reversed. This in part confirms the findings of Mutsyanko (35) who recommended that softer, more open wheels should be used for grinding at high wheelspeeds. However, the use of higher workspeeds was recommended to minimise the heat produced in the grinding zone. The use of these higher workspeeds would appear to lead to greater wear. Referring again to equation (4) for the maximum chip thickness it is apparent that by reducing the workspeed the maximum chip thickness will be reduced and this should reduce the wear of the wheel.

The influence of wheel grade on wheel wear is shown in Figures 60 and 61.

5.7.2 The effect of wheel grade on surface finish

The interaction between wheel grade and surface finish is shown in Figures 62 and 63. These figures show consistently similar results for surface finish once the initial effects are overcome and grinding is in a 'steady state' condition. Statistical testing confirms this result, there is no statistical difference in the results of surface finish due to wheel grade.

5.7.3 The effect of wheel grade on grinding forces

Table 19 shows that both the normal force and the tangential force are significantly affected by wheel grade in both the linear and quadratic mode. In addition there is a significant two factor interaction between wheel grade and work speed, this has already been examined in section 5.7.3. The overall effect is that the forces will be lowered as a softer grade of wheel is selected. This is because the individual grinding grits will be released from the wheel sooner than they would with a harder wheel, thus the wear flat area will always be less with a softer wheel and hence a lower normal force and as there is a tendency for fewer active grits the tangential forces will also be lower with a softer grade wheel. The effect of wheel grade on grinding force is illustrated in Figures 64 and 65.

The factors of wheelspeed, dress lead and metal removal rate have all been shown to have highly significant or significant effects on the level of grinding force. These factors are further modified by the variation of wheel grade and workspeed. All these factors will be considered in the prediction of grinding force and the interaction between normal and tangential forces that are made in Chapter 6.

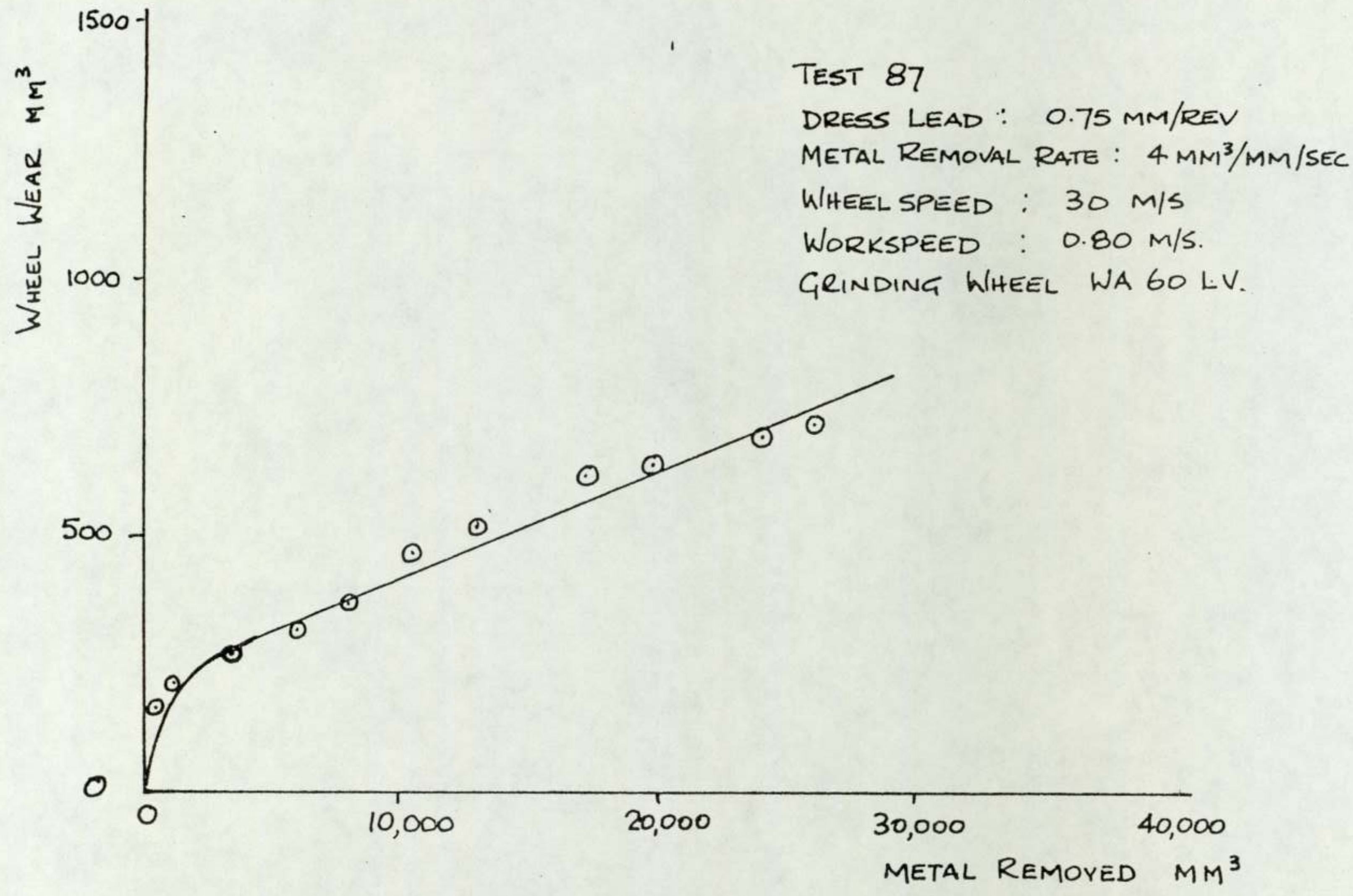


Fig 28 WHEEL WEAR, TEST NO. 87

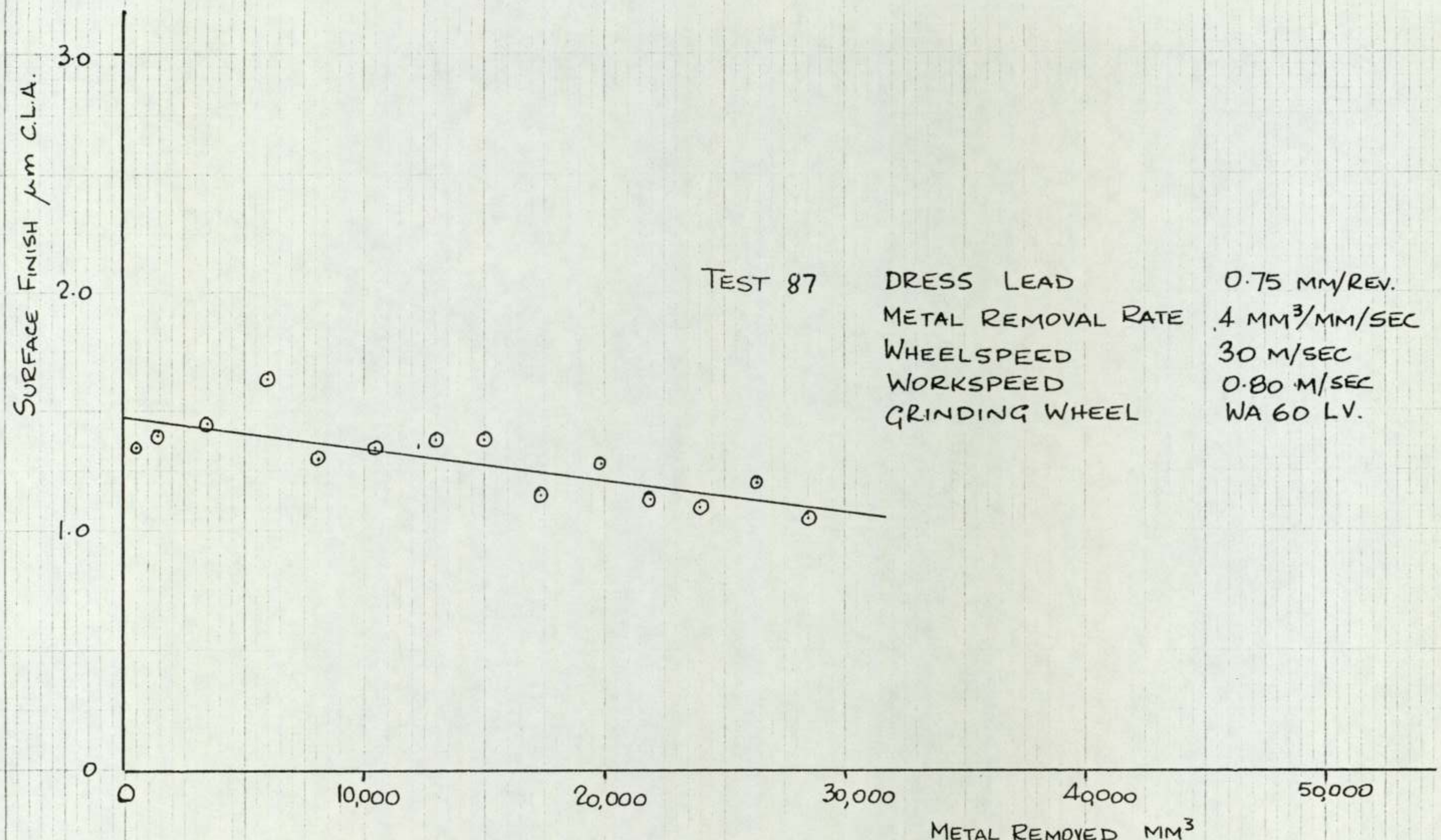


Fig 29 SURFACE FINISH, TEST NO. 87

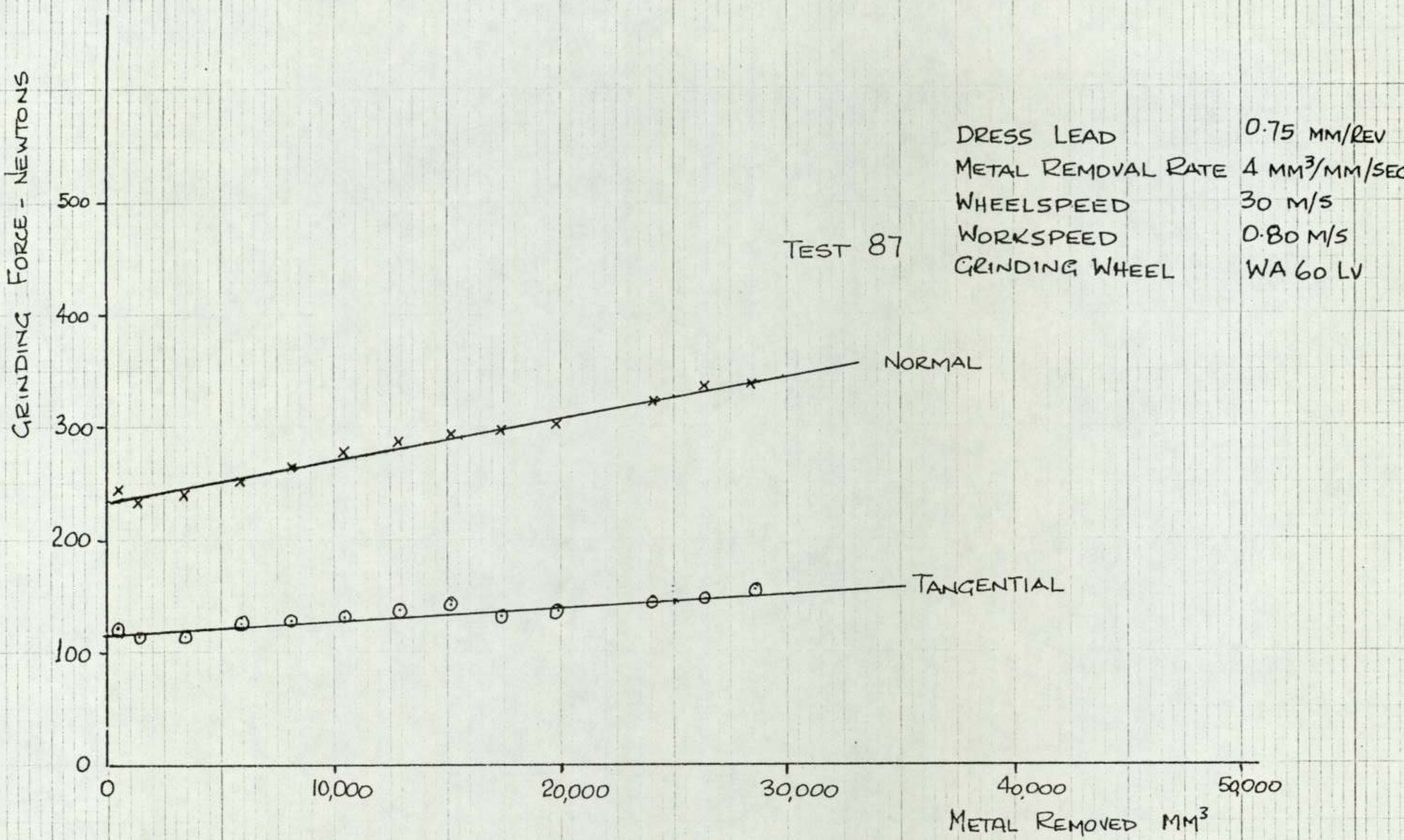


Fig 30 GRINDING FORCES, TEST NO. 87

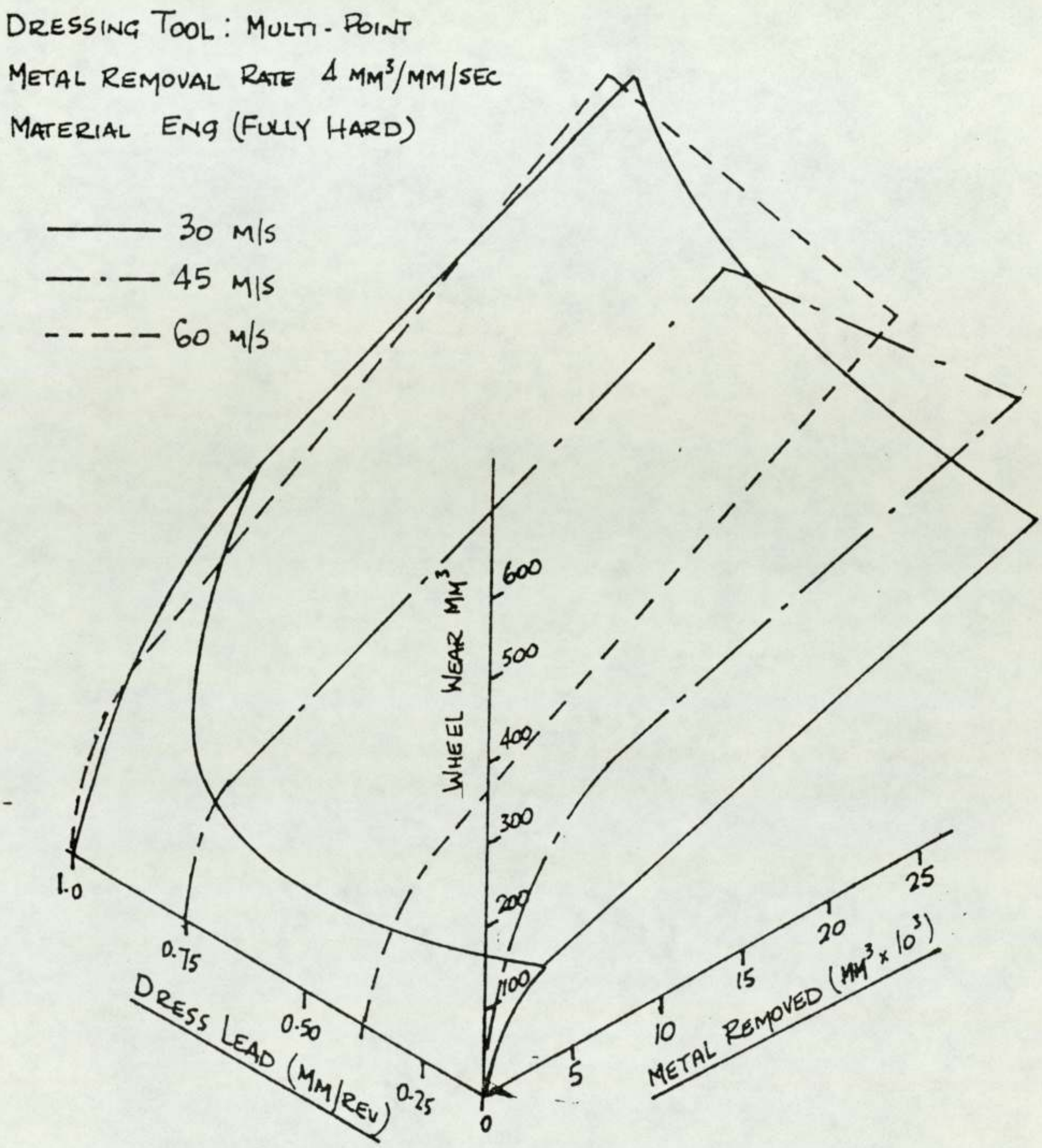


Fig 31 Wheel Wear

DRESSING TOOL MULTI POINT
METAL REMOVAL RATE 4 MM³/MM/SEC
WHEELSPEED 30 M/S
MATERIAL EN9 (FULLY HARD)

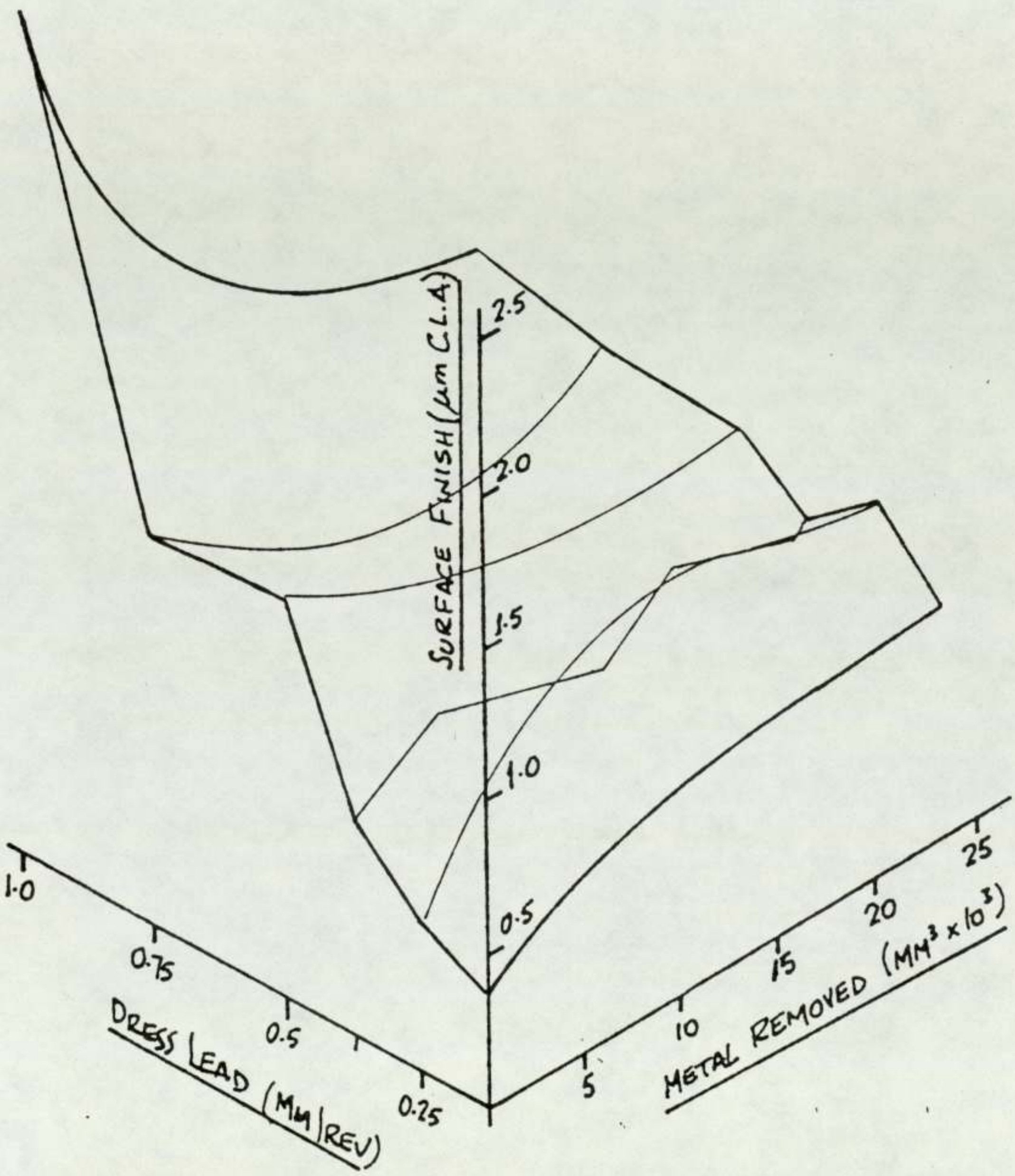
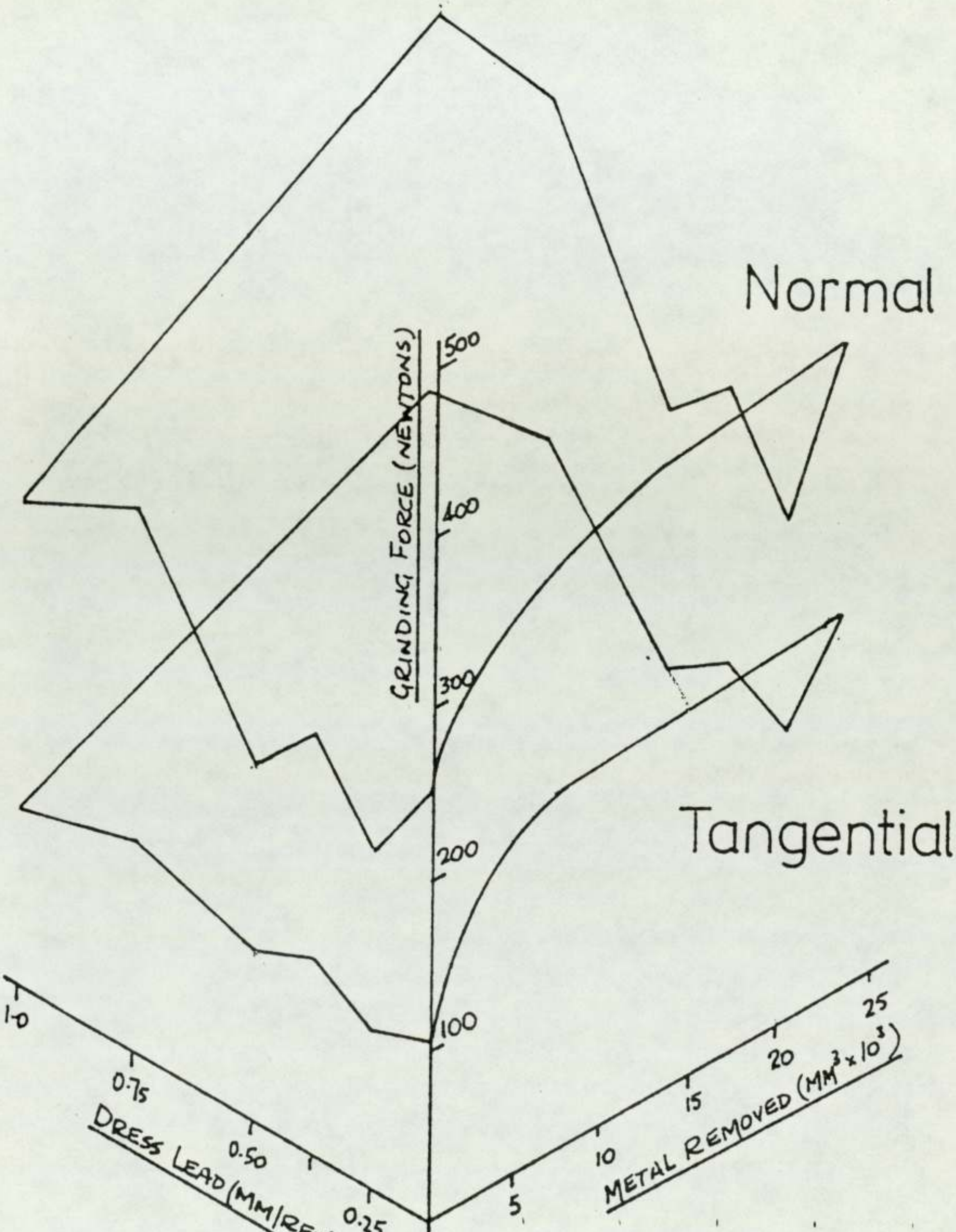


Fig 32 Surface Finish



DRESSING TOOL MULTI POINT
METAL REMOVAL RATE :
4 MM^3/MM/SEC
WHEELSPEED 30 M/S
MATERIAL EN9 (FULLY HARD)

Fig 33 Grinding Forces

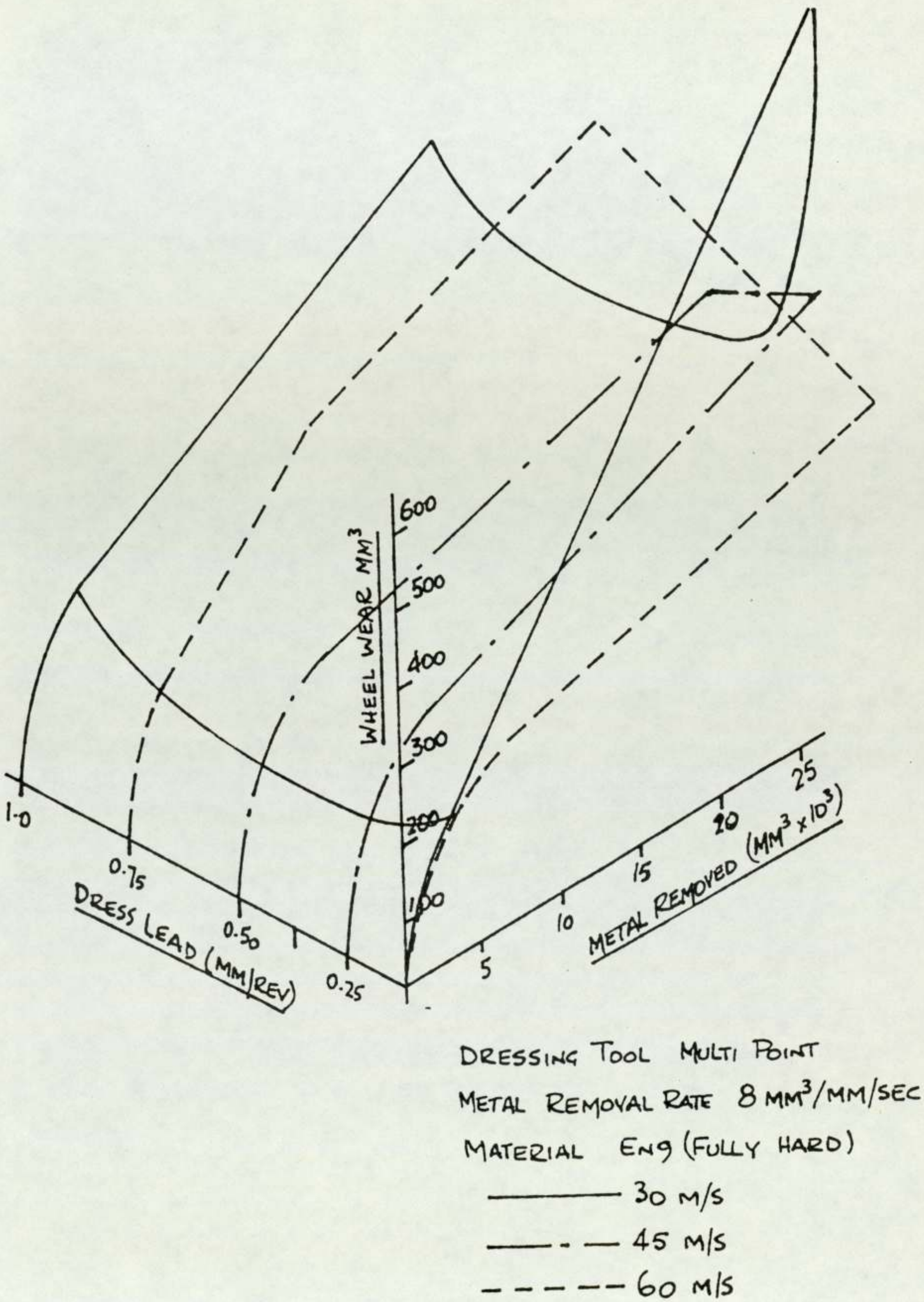


Fig 34 Wheel Wear

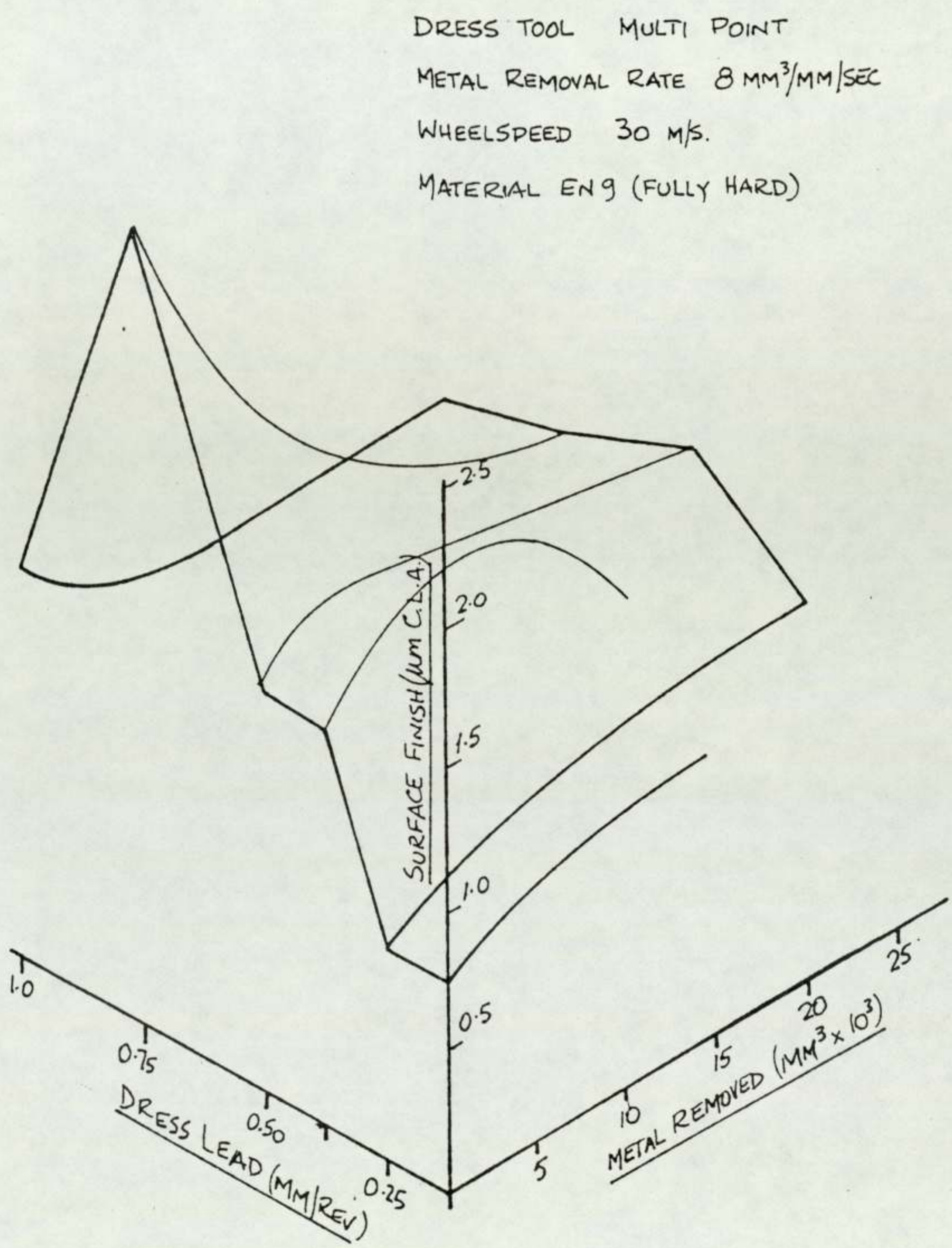


Fig 35 Surface Finish

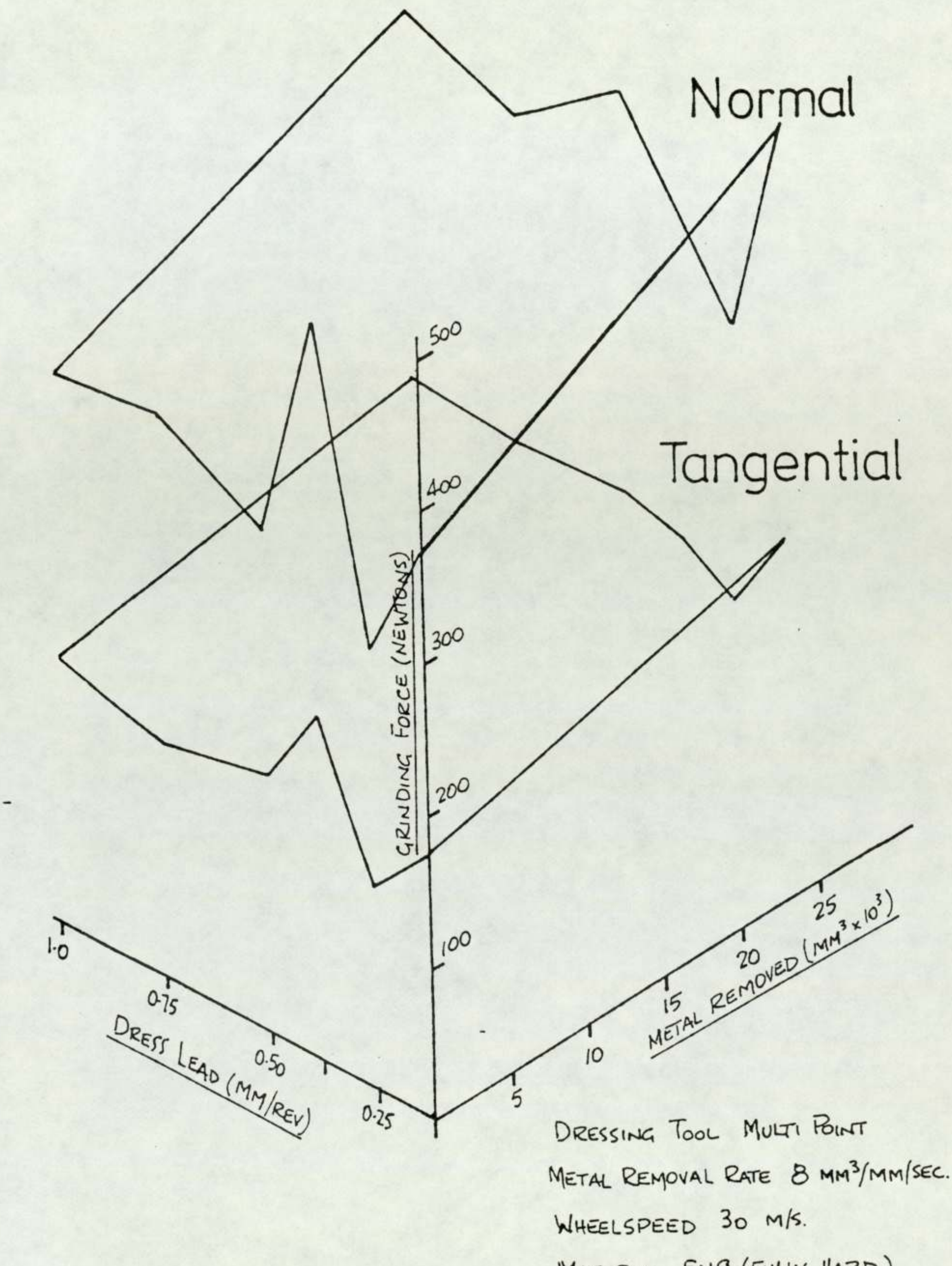


Fig 36 Grinding Forces

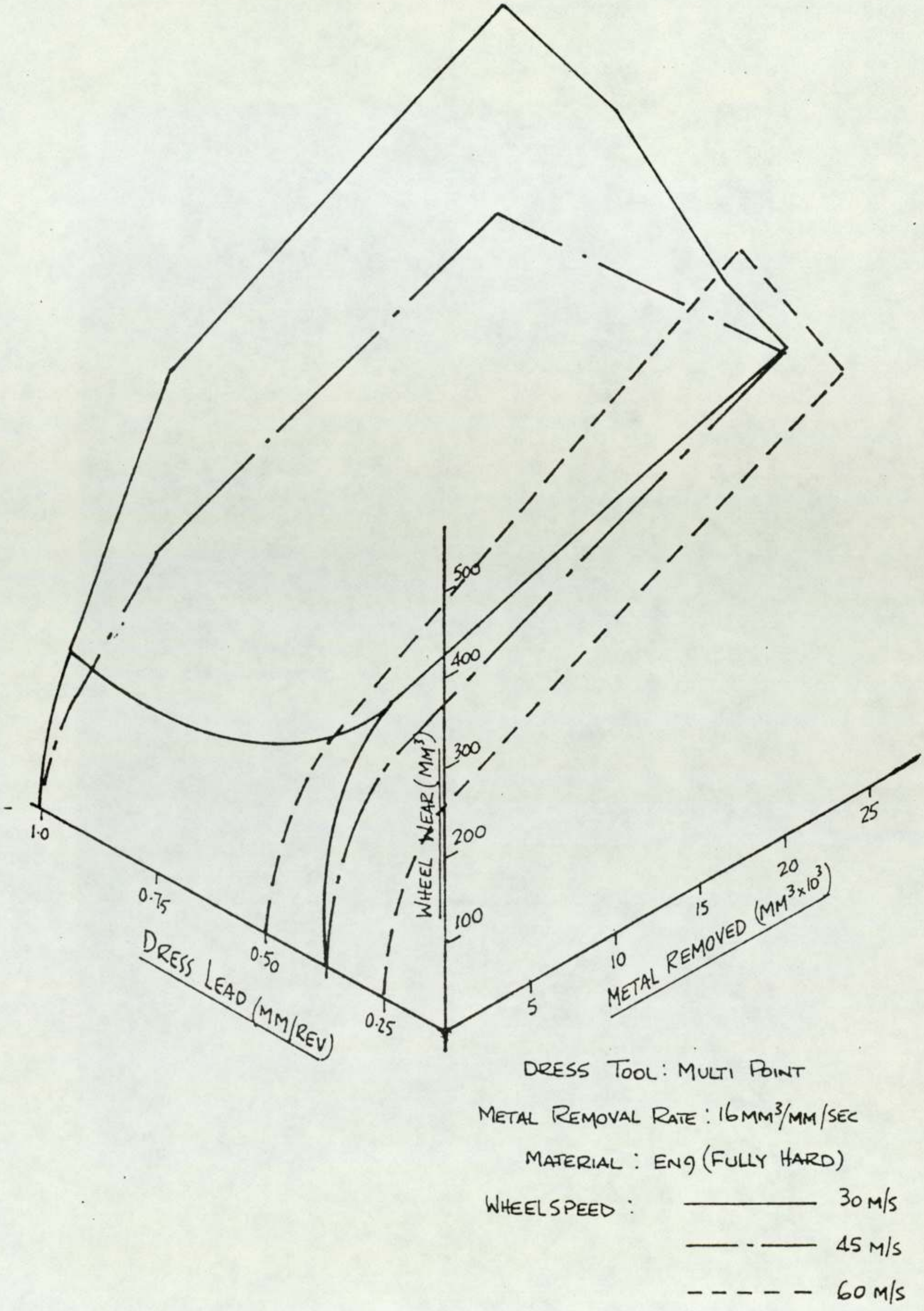


Fig 37 Wheel Wear

DRESSING TOOL MULTI POINT
METAL REMOVAL RATE 16MM³/MM/SEC
MATERIAL EN9 (FULLY HARD)

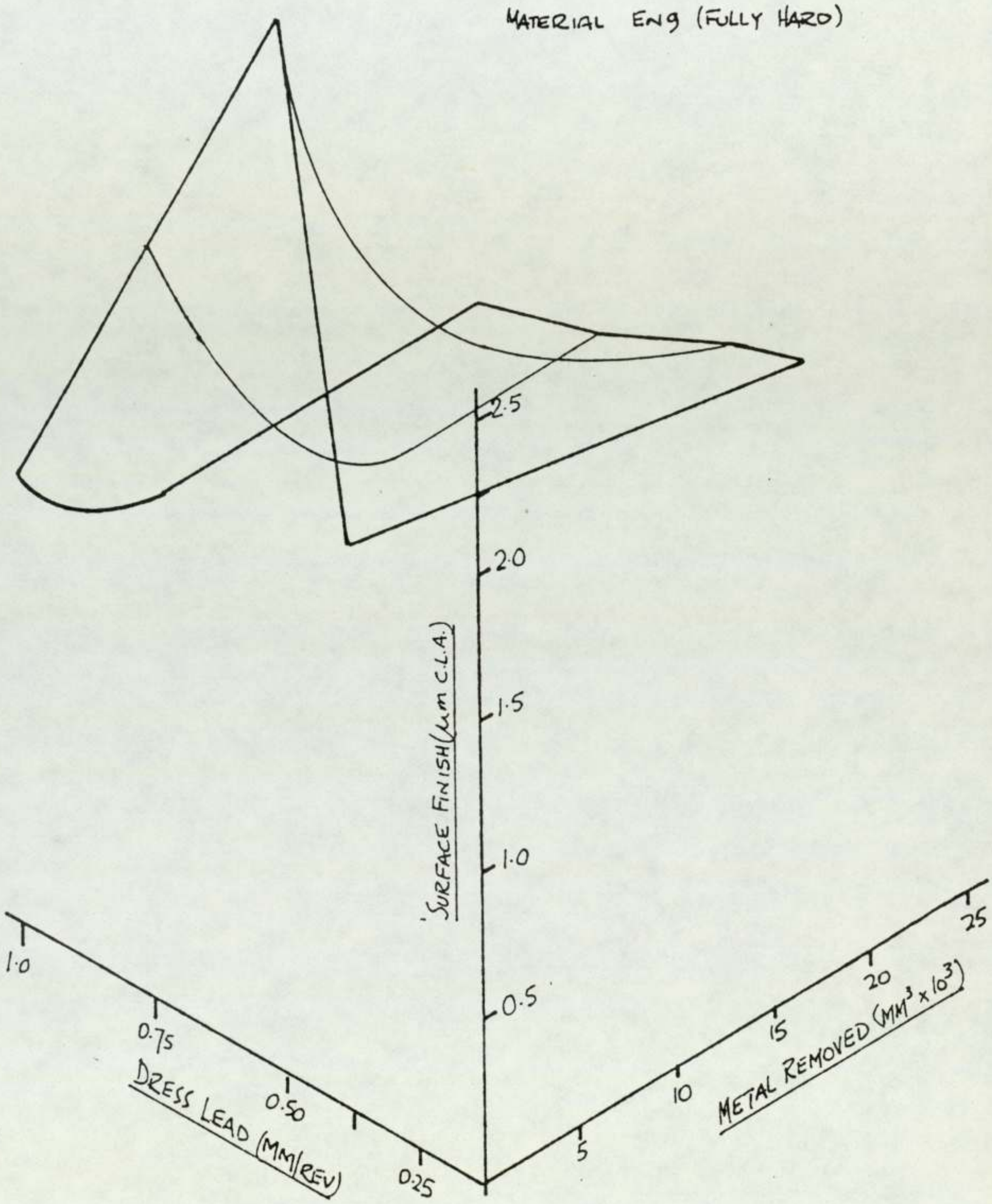


Fig 38 Surface Finish

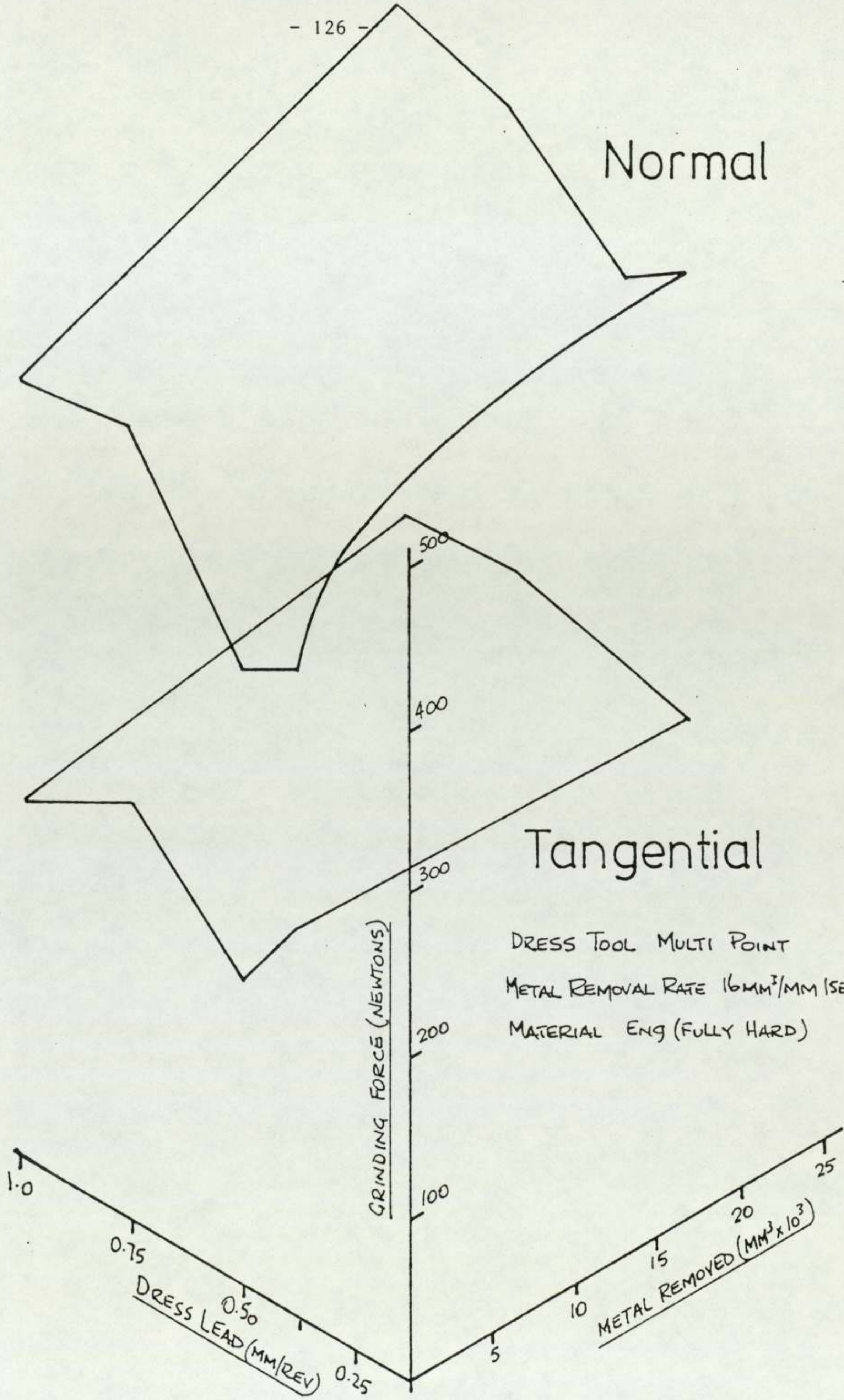


Fig 39 Grinding Force

DRESSING TOOL : BLADE DRESSER

METAL REMOVAL RATE 16 MM³/MM/SEC

MATERIAL EN 9 (FULLY HARD)

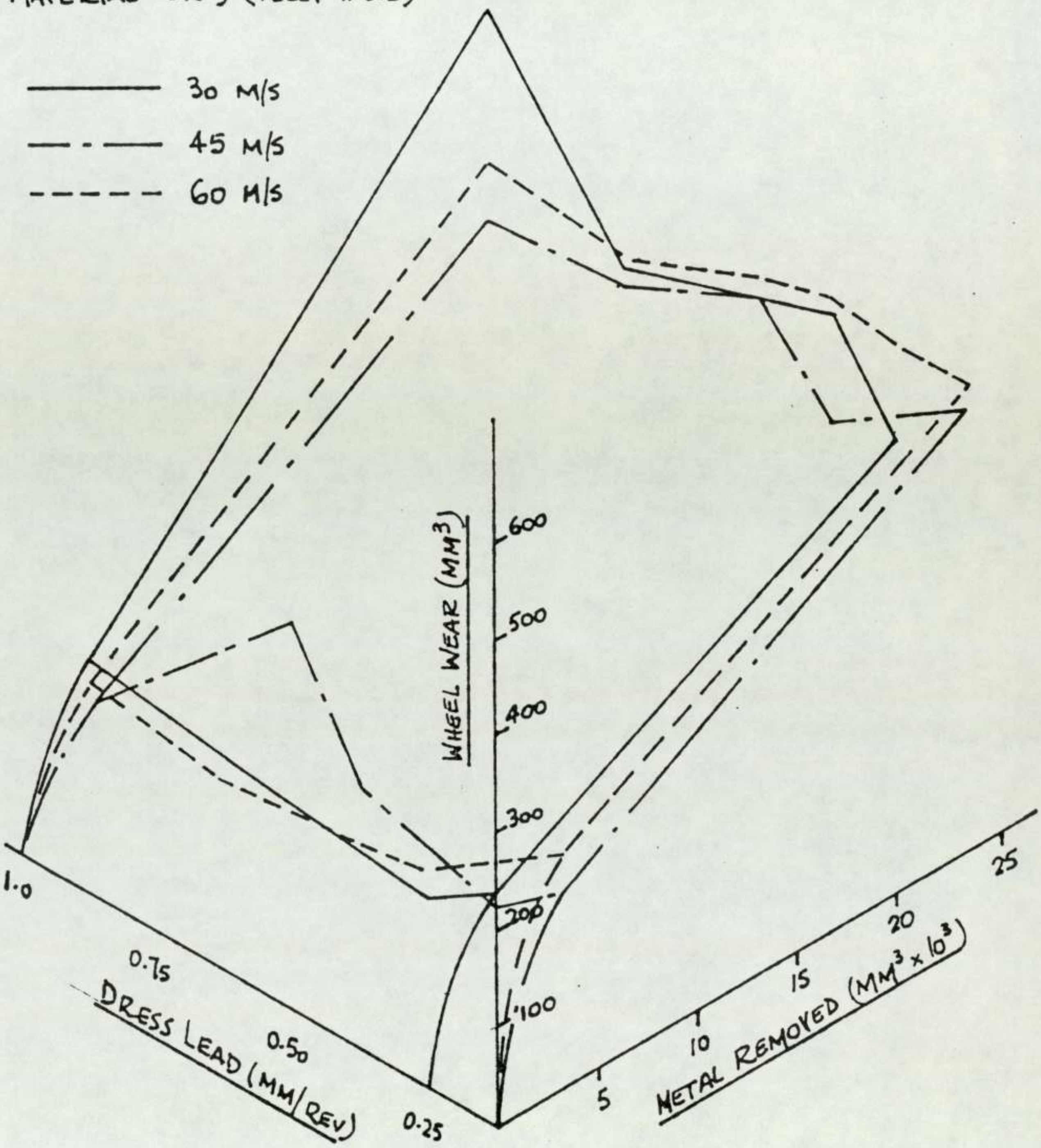


Fig 40 WHEEL WEAR

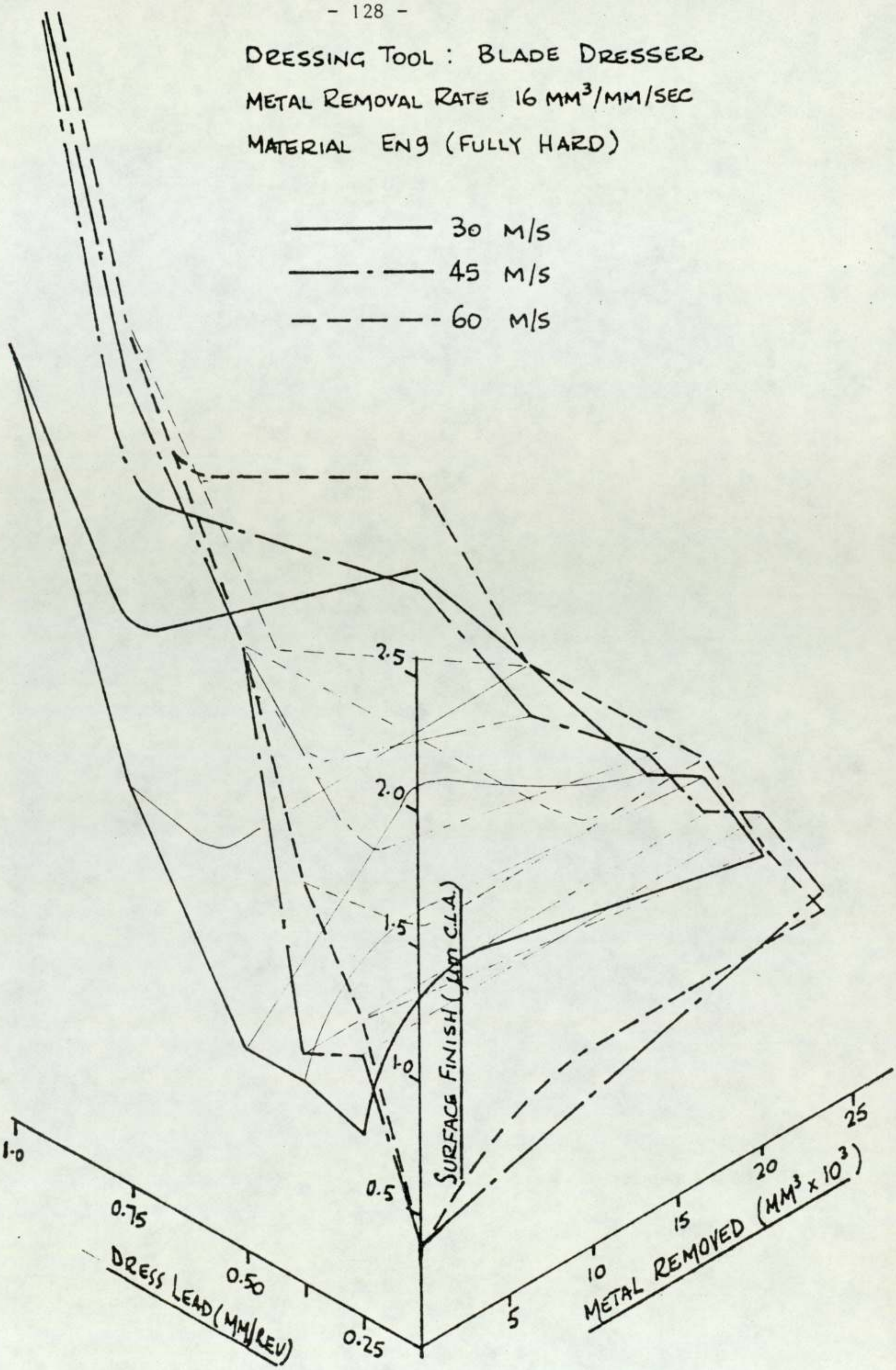


Fig. 41 SURFACE FINISH

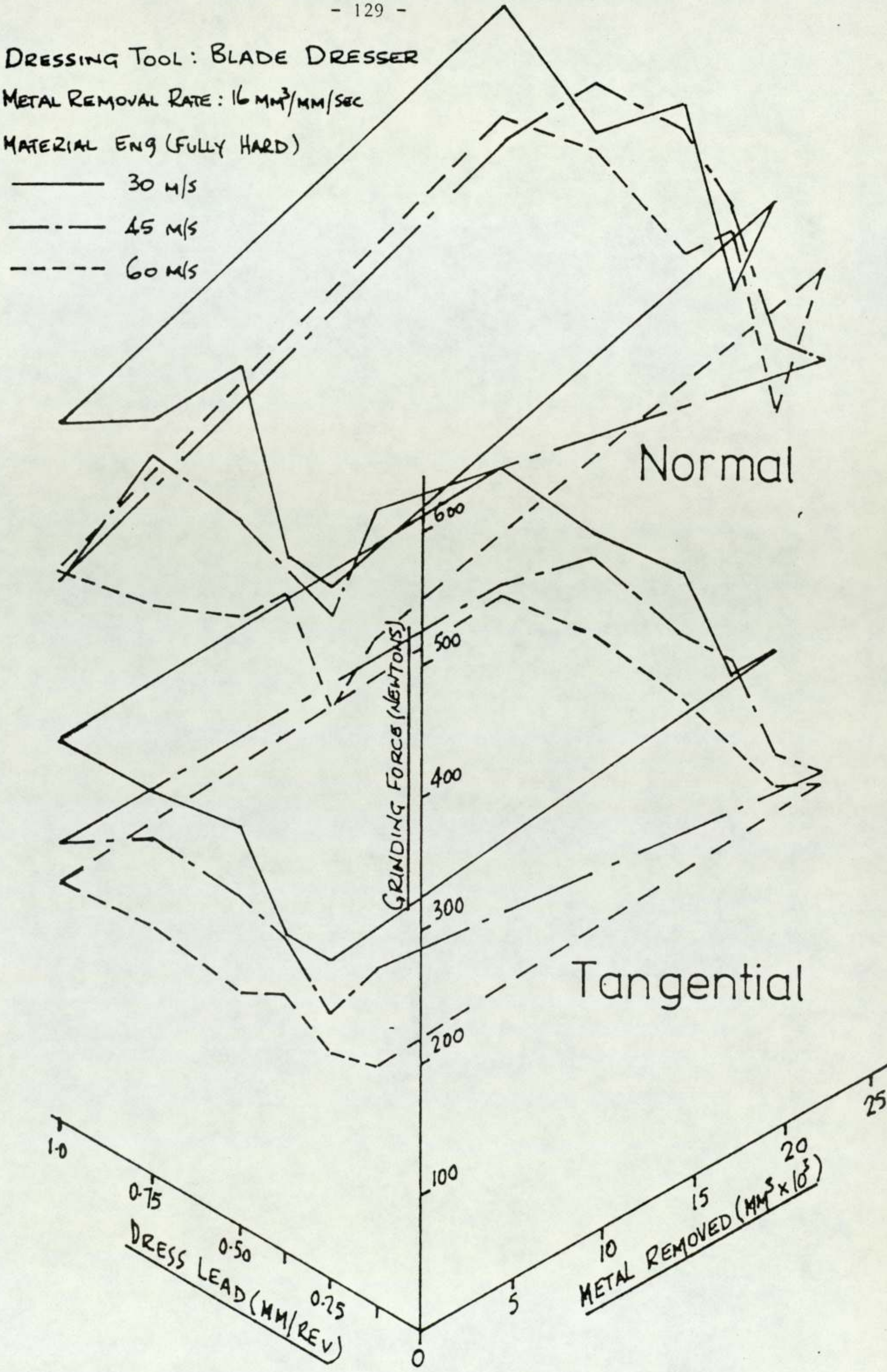


Fig 42 GRINDING FORCE

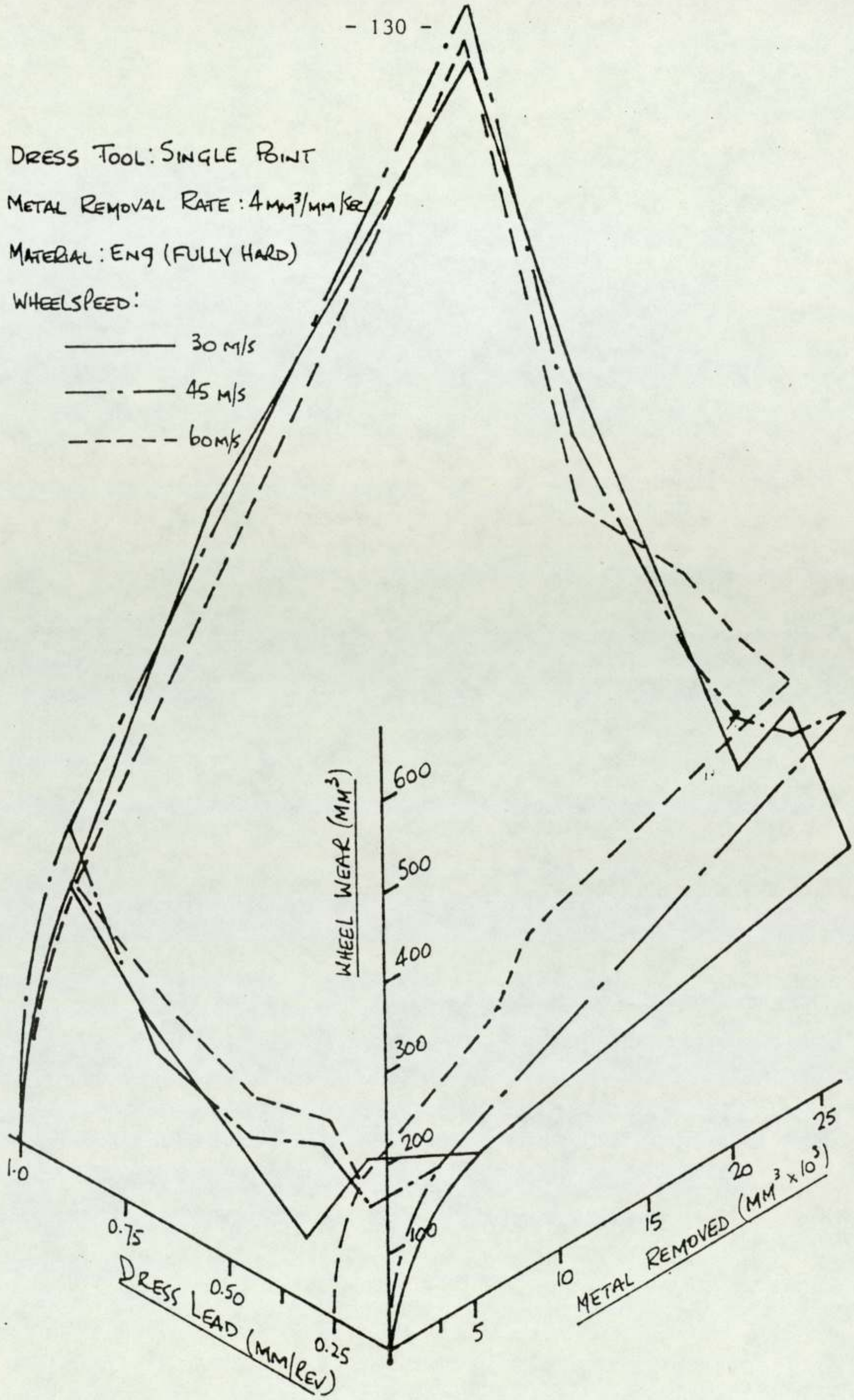


Fig 43 Wheel Wear

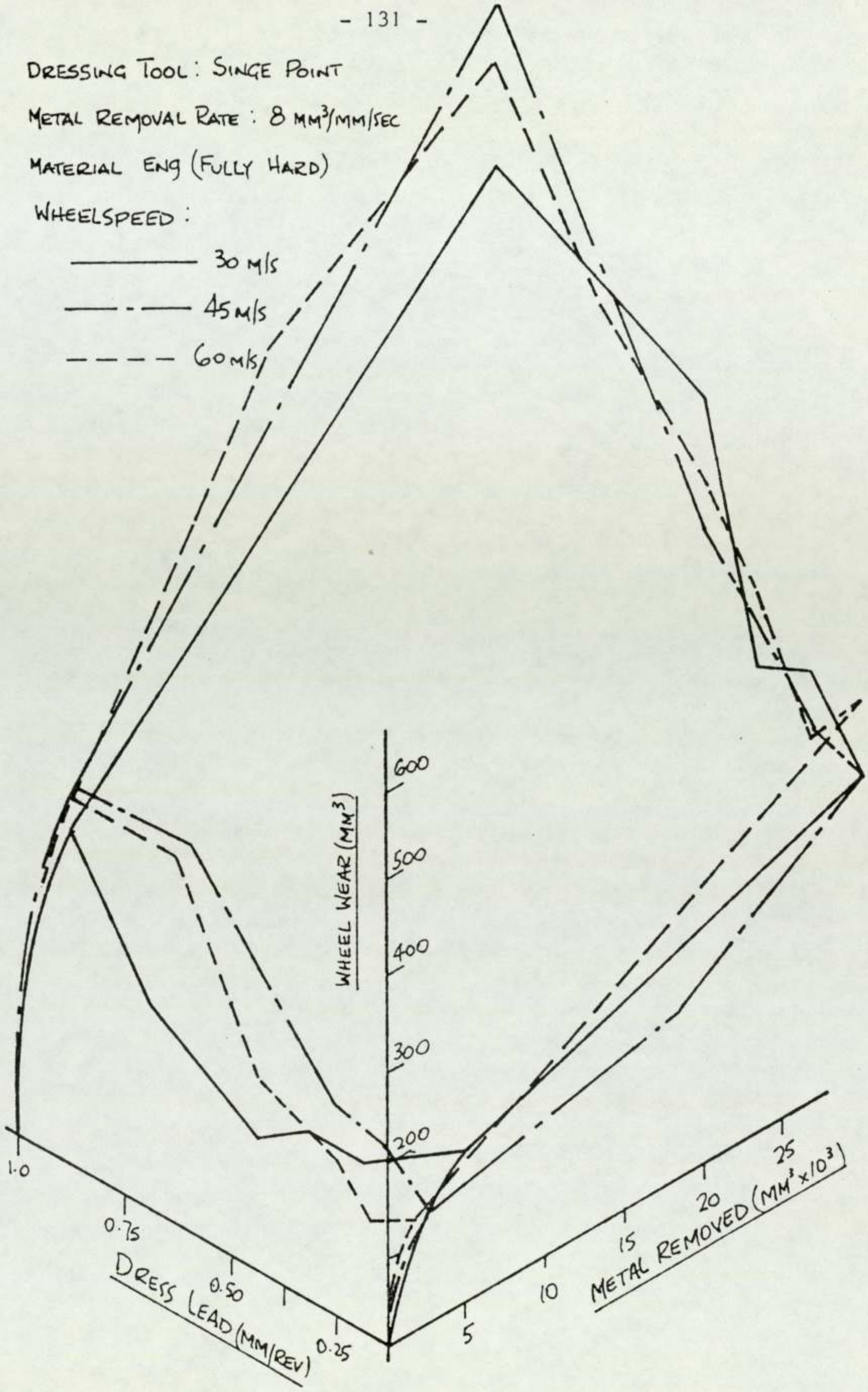


Fig 44 Wheel Wear

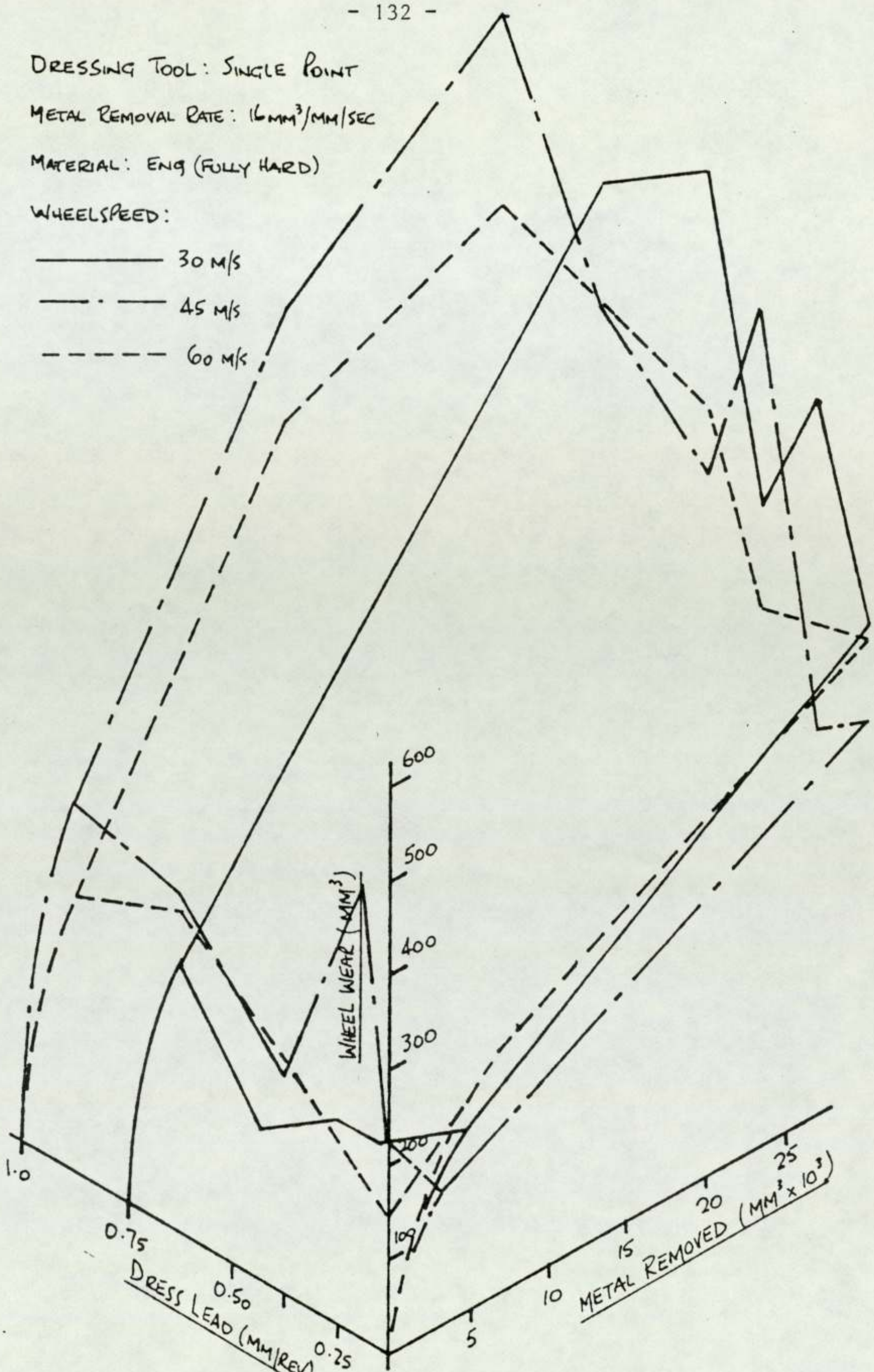


Fig 45 Wheel Wear

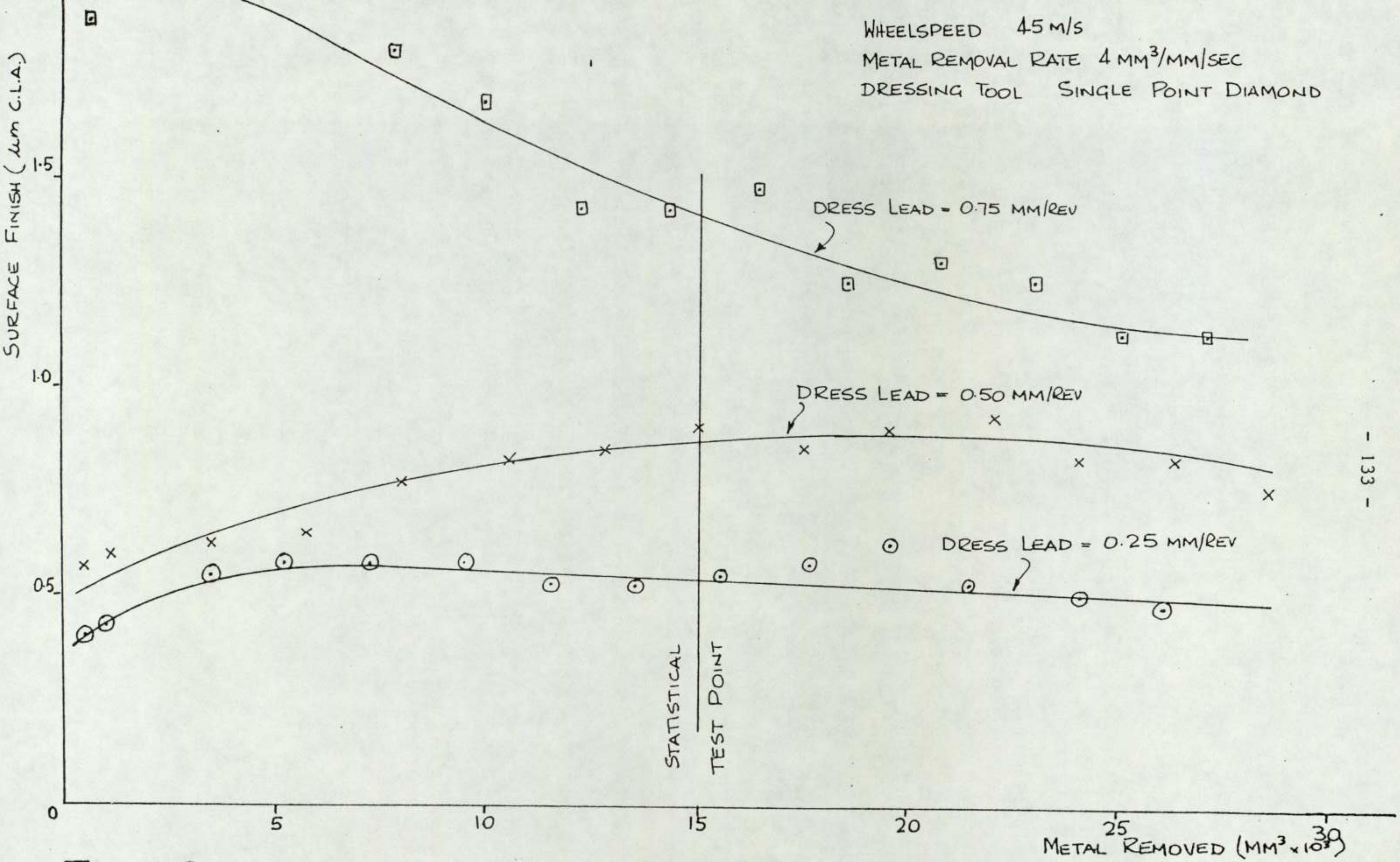


Fig 46 THE EFFECT OF DRESS LEAD ON SURFACE FINISH

DRESS TOOL: SINGLE POINT

METAL REMOVAL RATE: 4 MM³/MM/SEC.

MATERIAL EN9 (FULLY HARD)

WHEELSPEED:

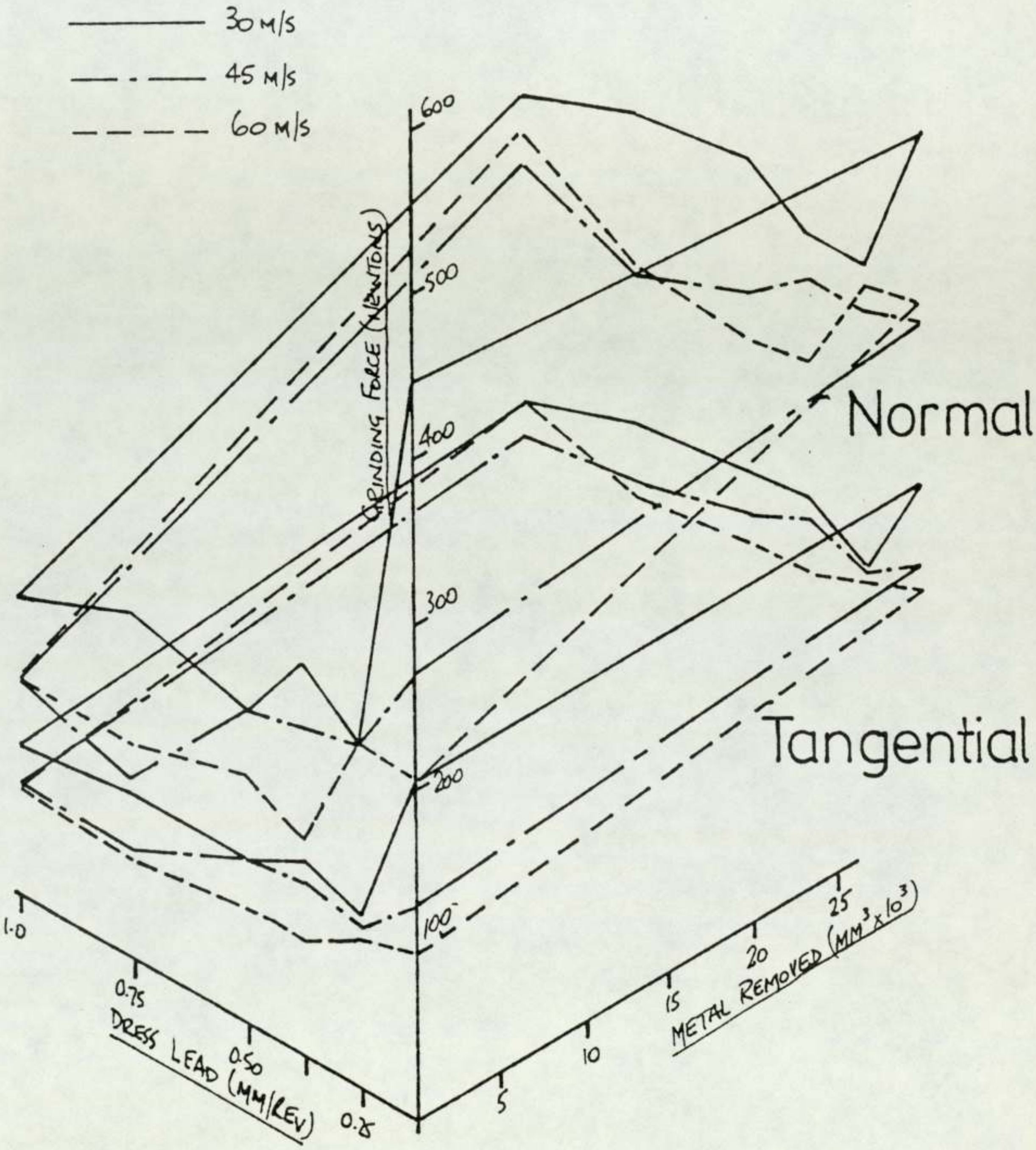


Fig 47 Grinding Forces

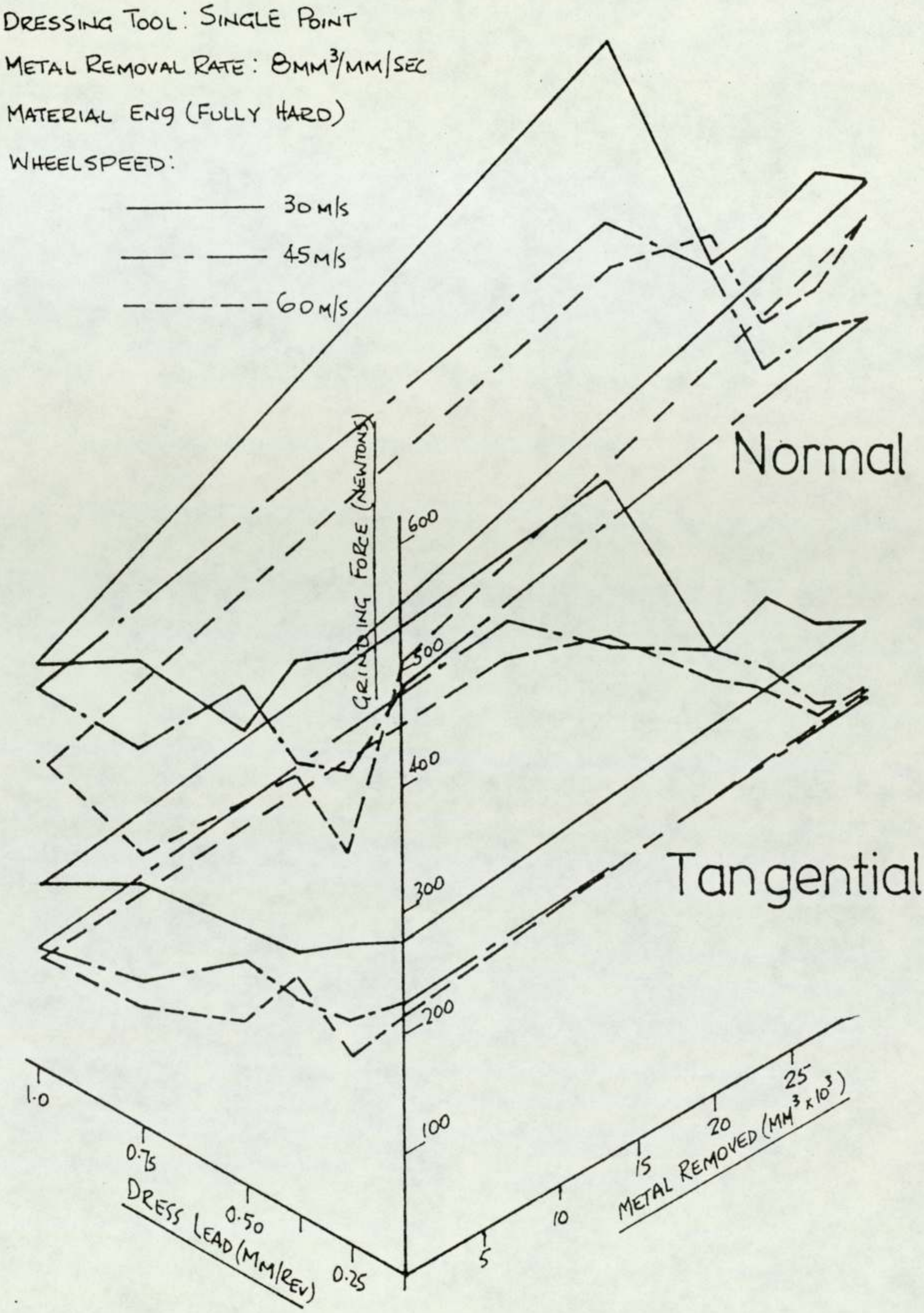


Fig 48 Grinding Forces

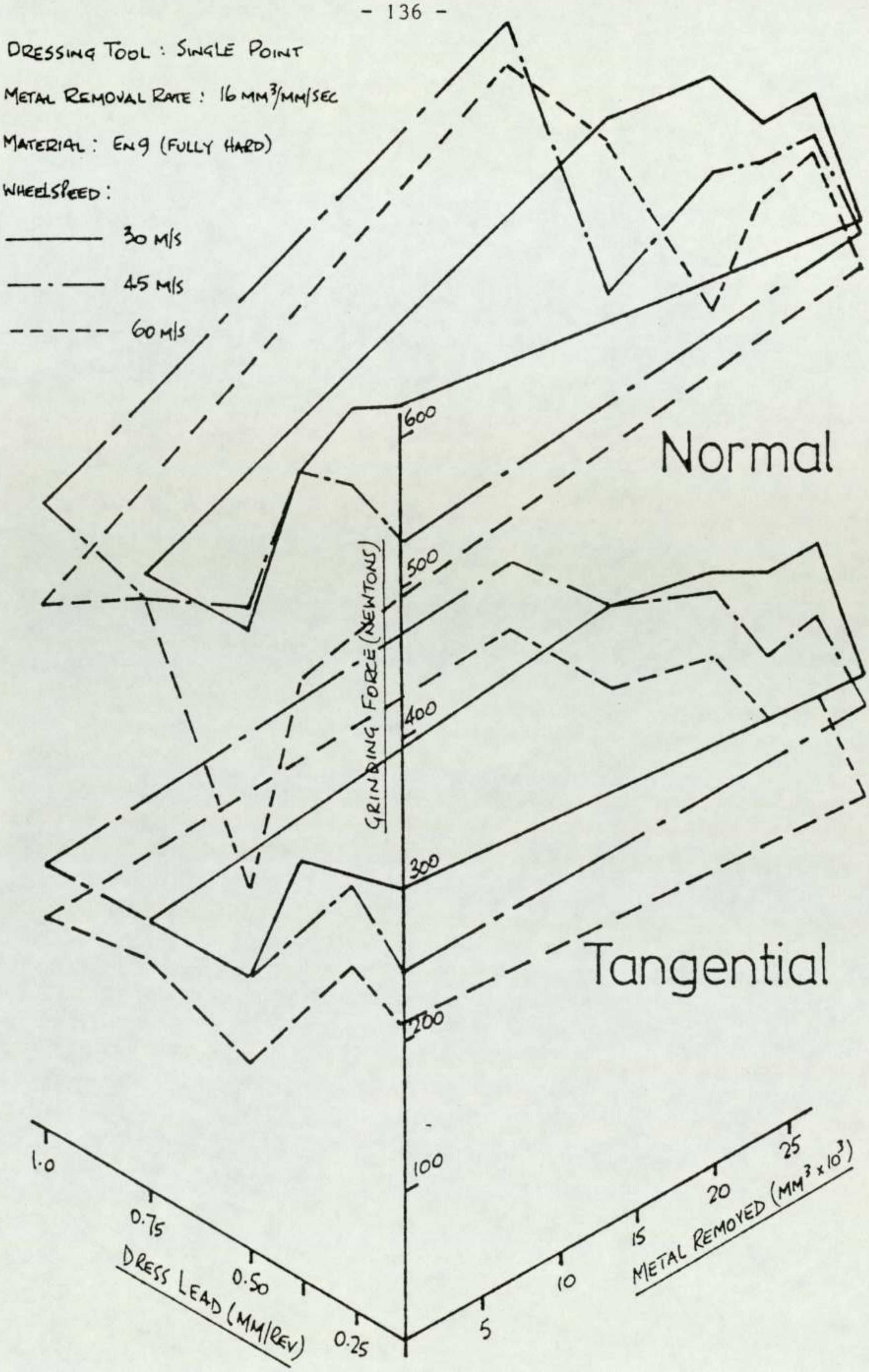


Fig 49 Grinding Forces

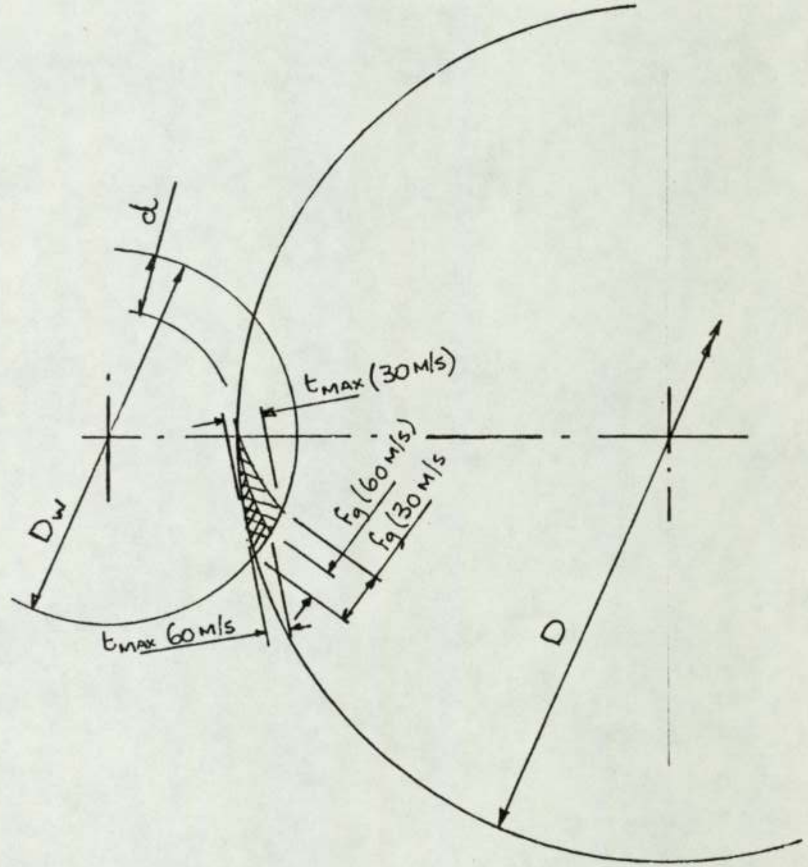


Fig 50 THE EFFECT OF WHEELSPEED ON CHIP THICKNESS

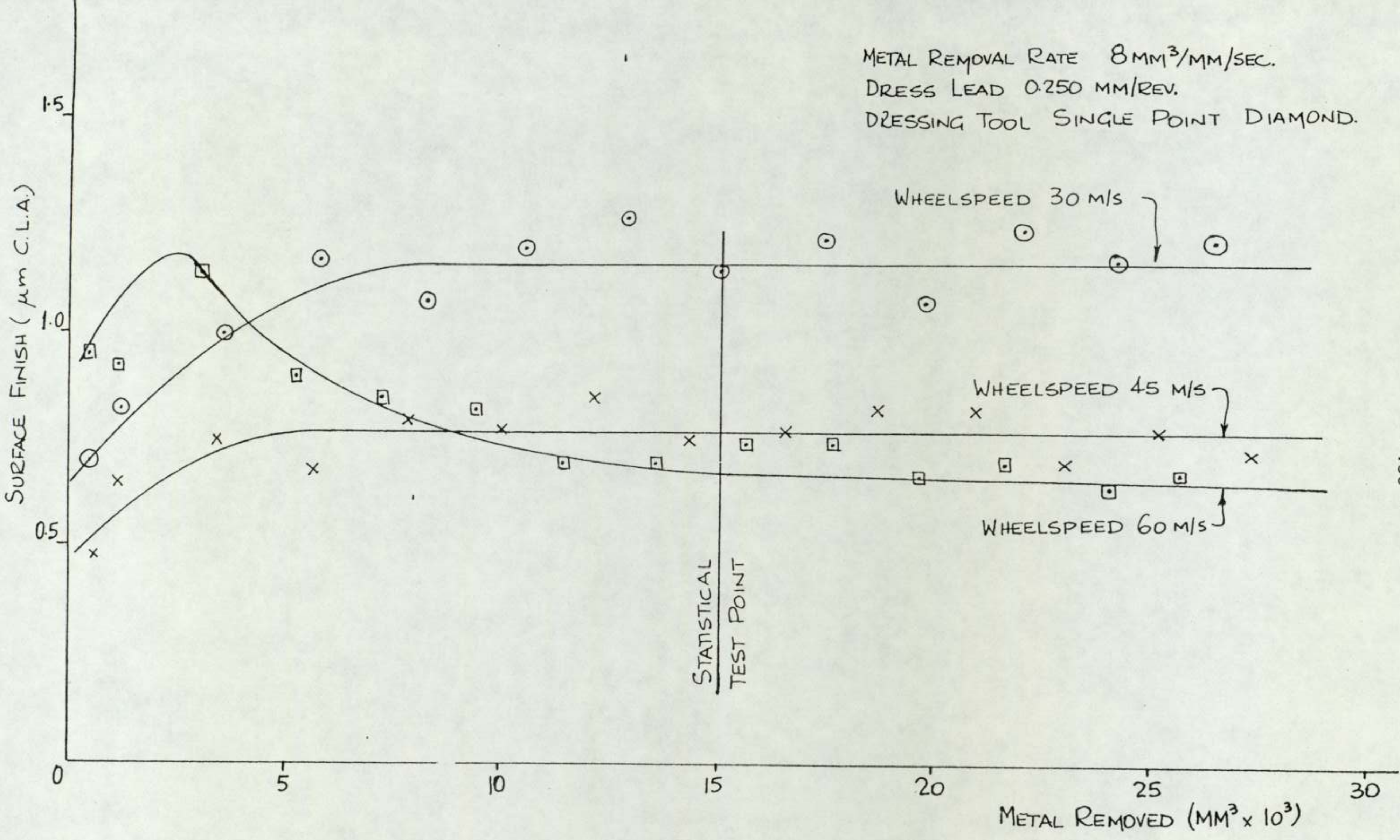


Fig 51 THE EFFECT OF WHEELSPEED ON SURFACE FINISH

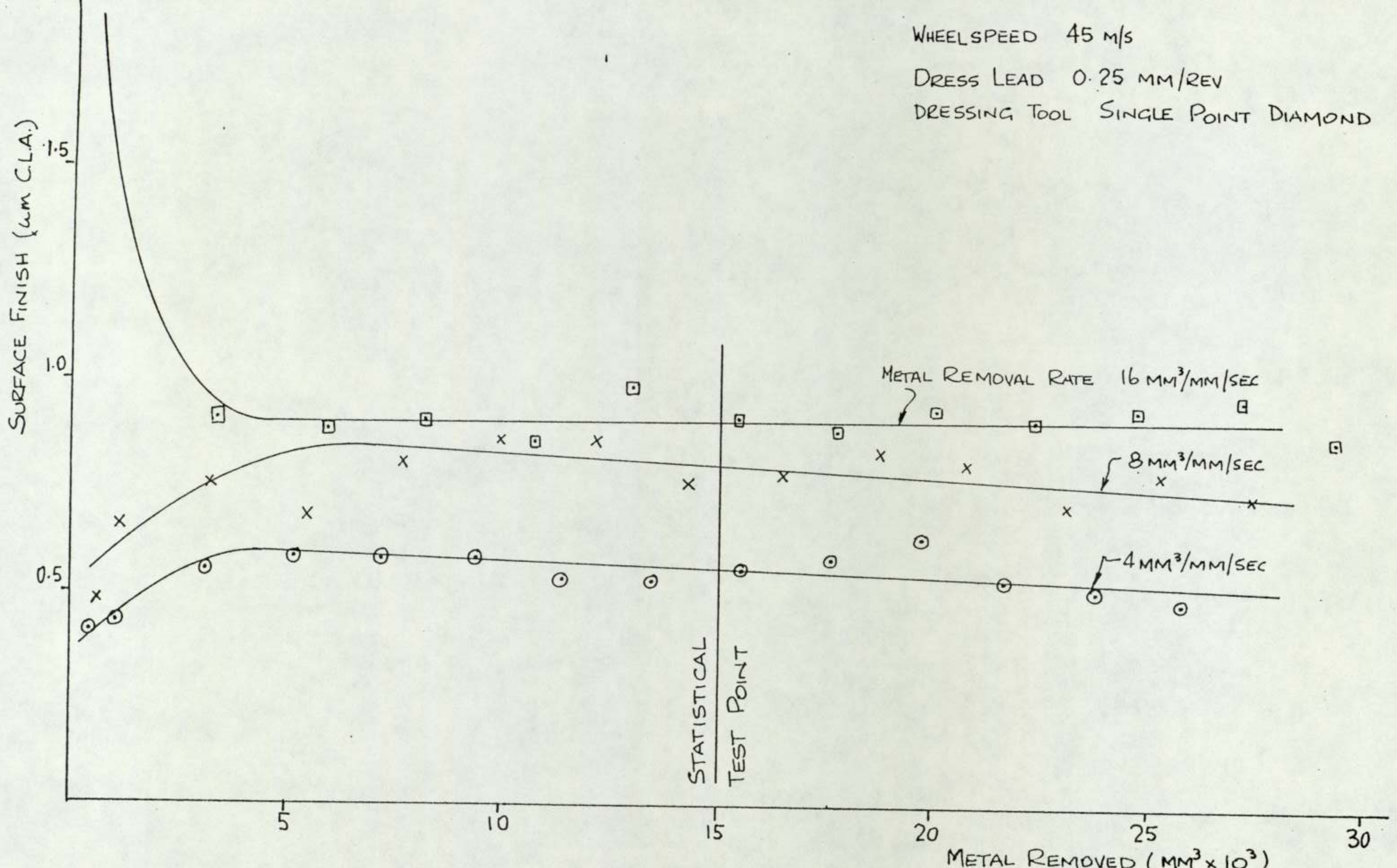


Fig 52 THE EFFECT OF METAL REMOVAL RATE ON SURFACE FINISH

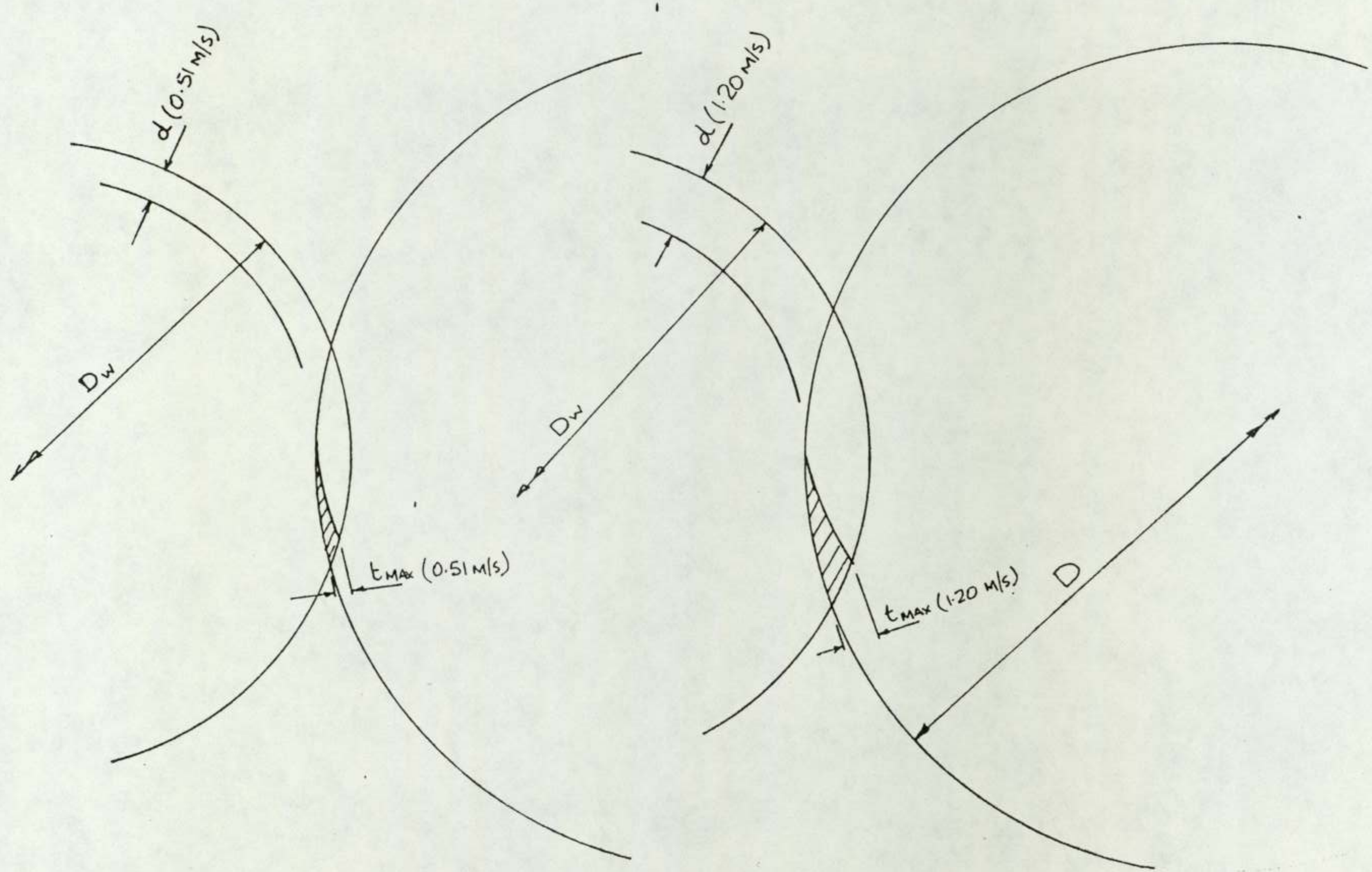


Fig 53 THE EFFECT OF WORKSPEED ON CHIP THICKNESS

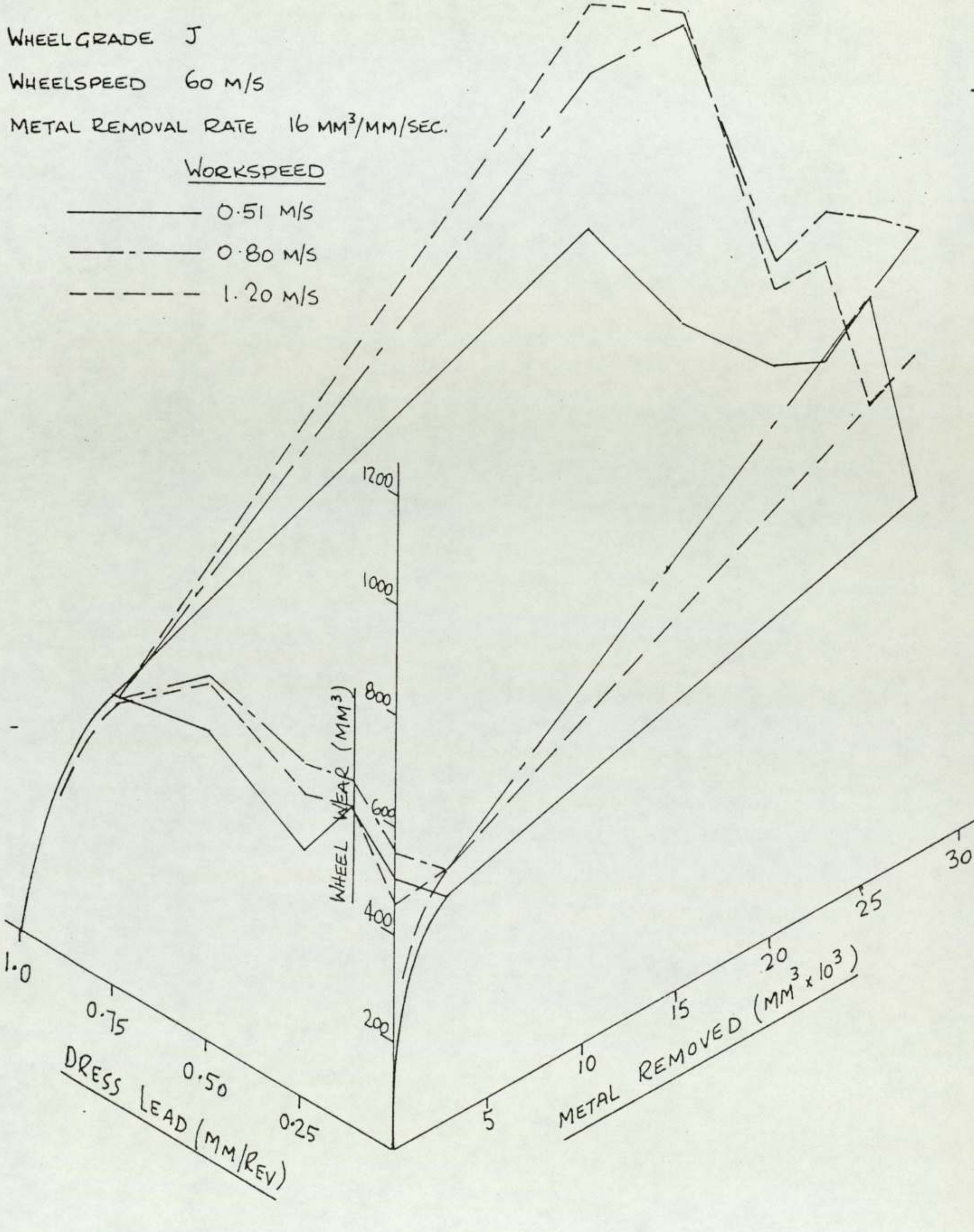


Fig 54 THE EFFECT OF WORKSPEED ON WHEEL WEAR

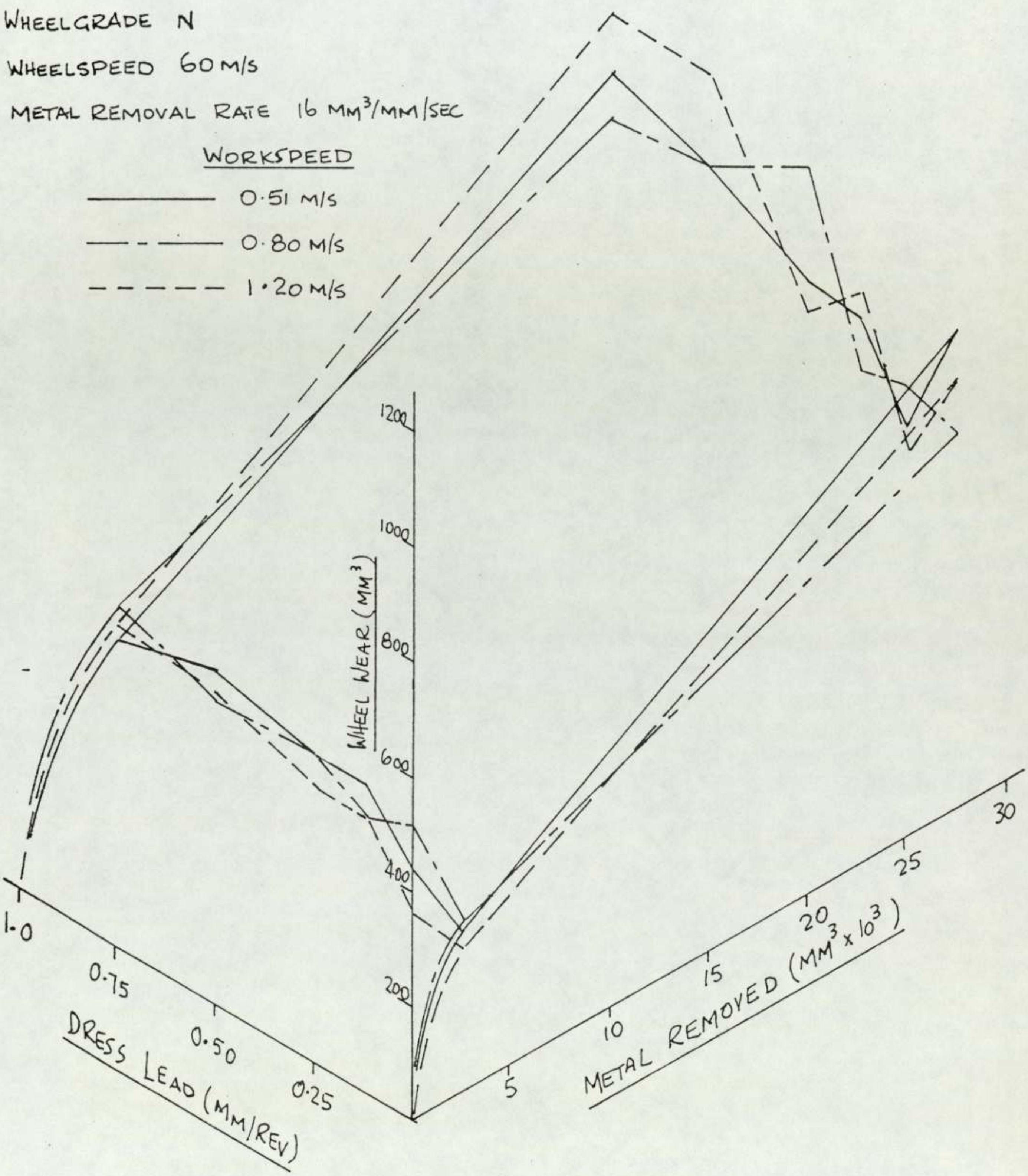


Fig 55 THE EFFECT OF WORKSPEED ON WHEEL WEAR

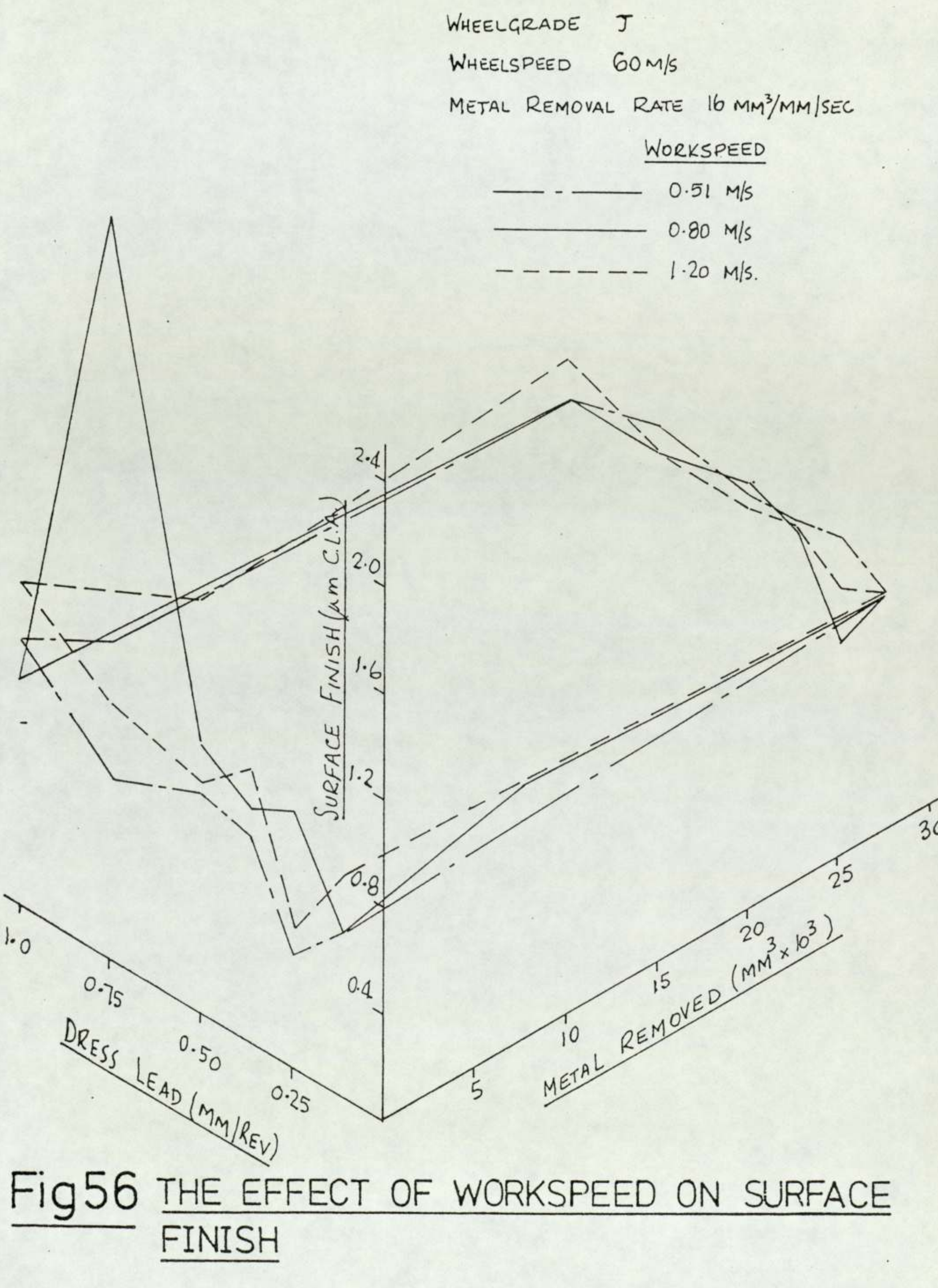


Fig 56 THE EFFECT OF WORKSPEED ON SURFACE FINISH

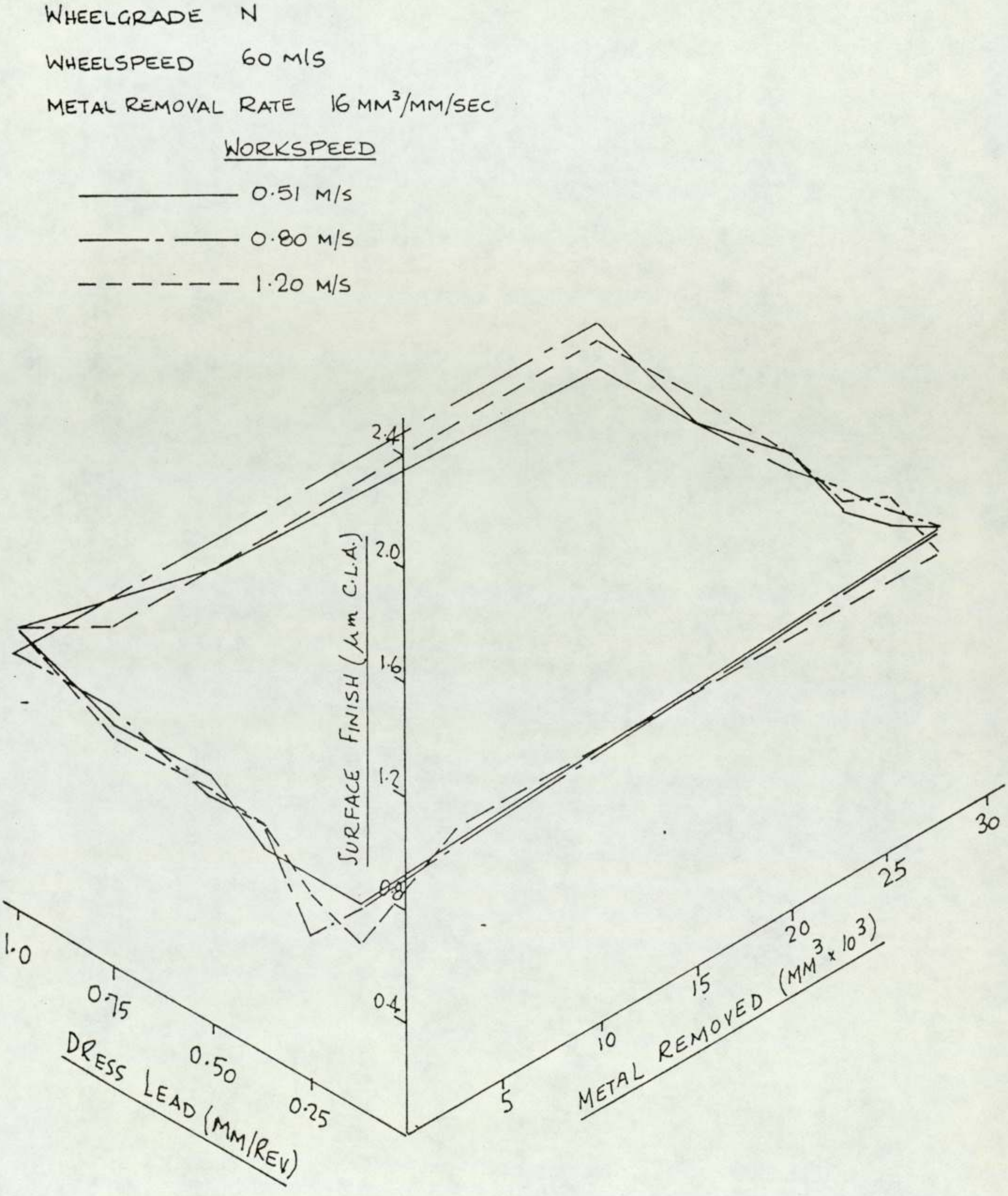


Fig 57 THE EFFECT OF WORKSPEED ON SURFACE FINISH

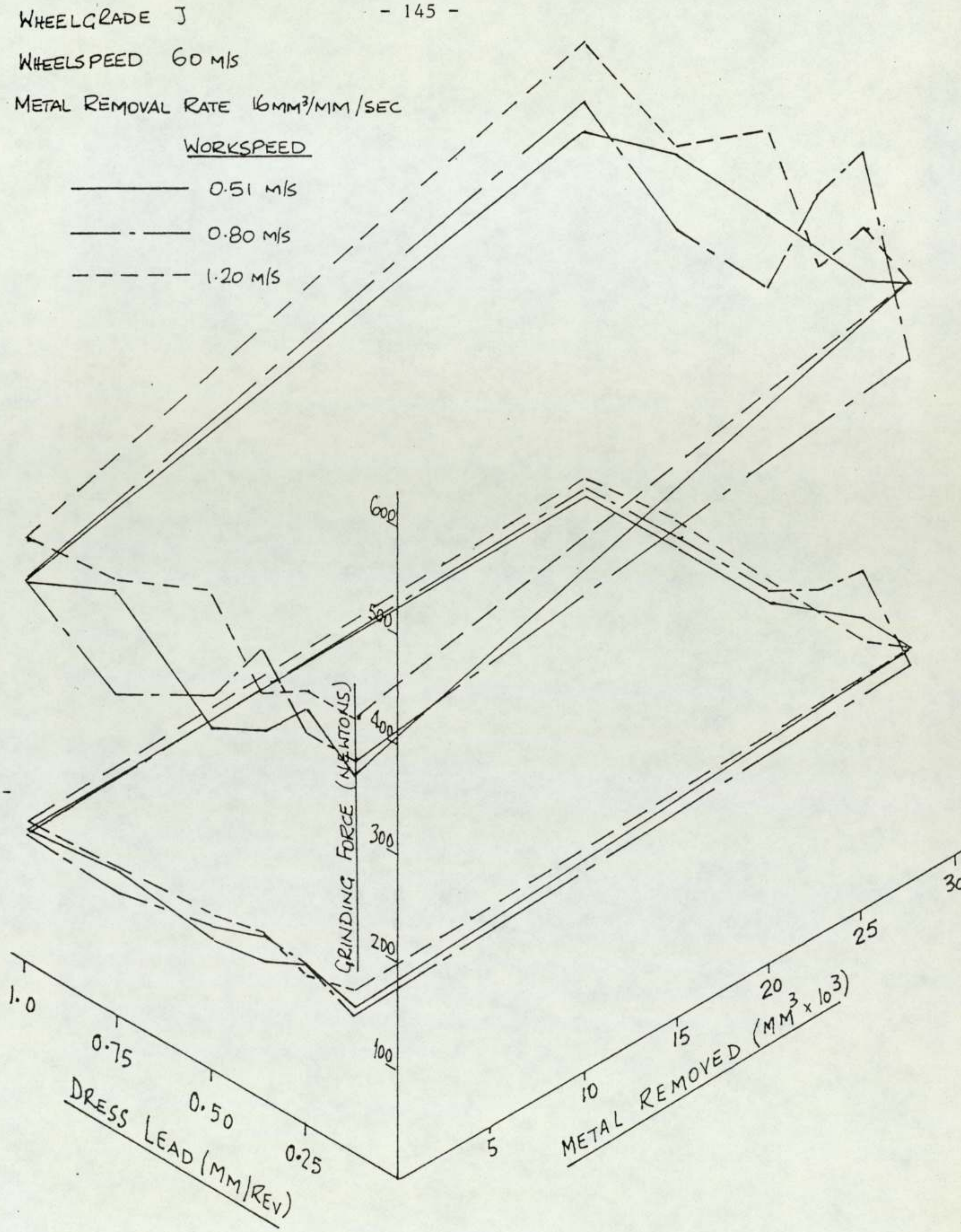


Fig 58 THE EFFECT OF WORKSPEED ON GRINDING FORCE

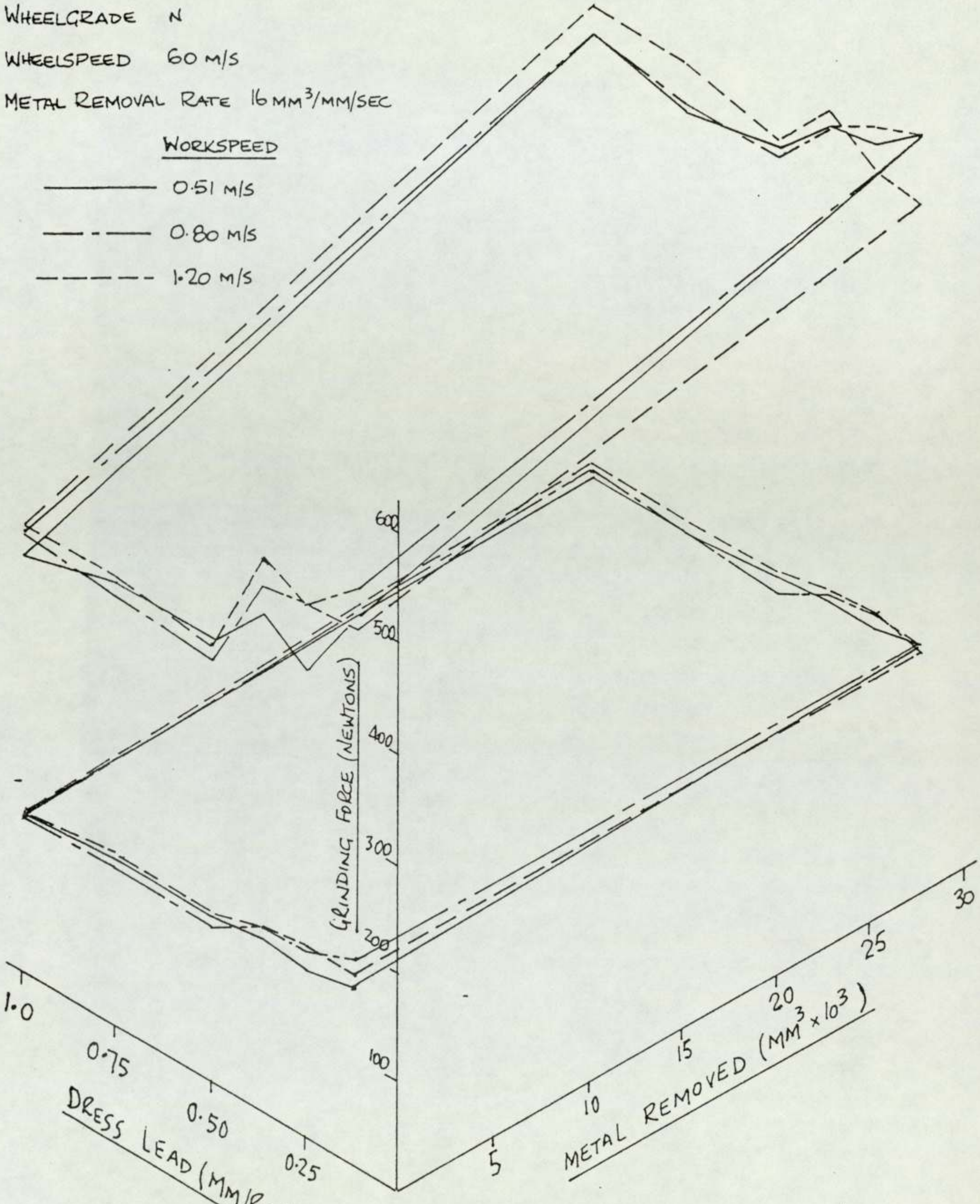


Fig 59 THE EFFECT OF WORKSPEED ON GRINDING FORCE

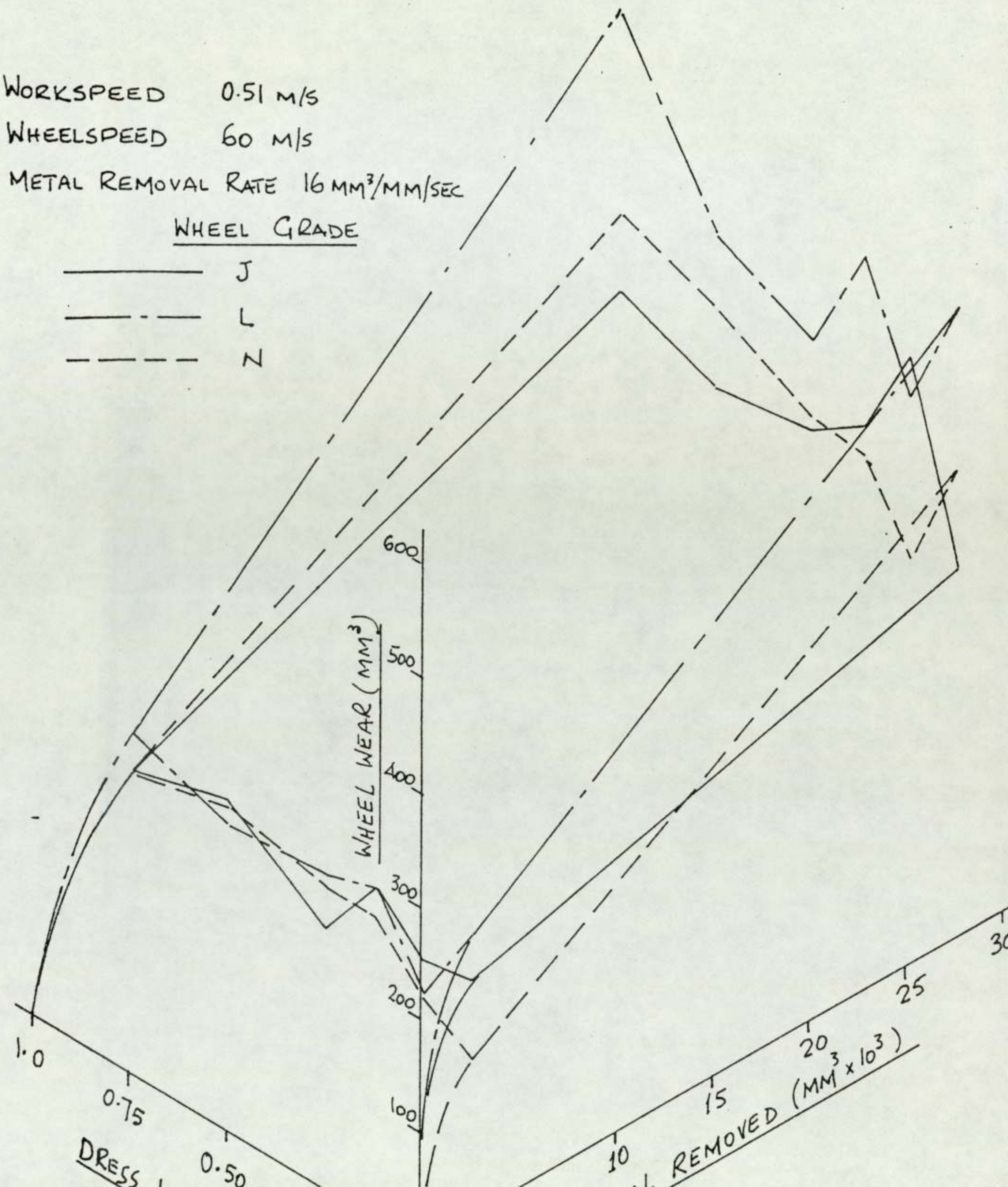


Fig 60 THE EFFECT OF GRADE ON WHEEL WEAR

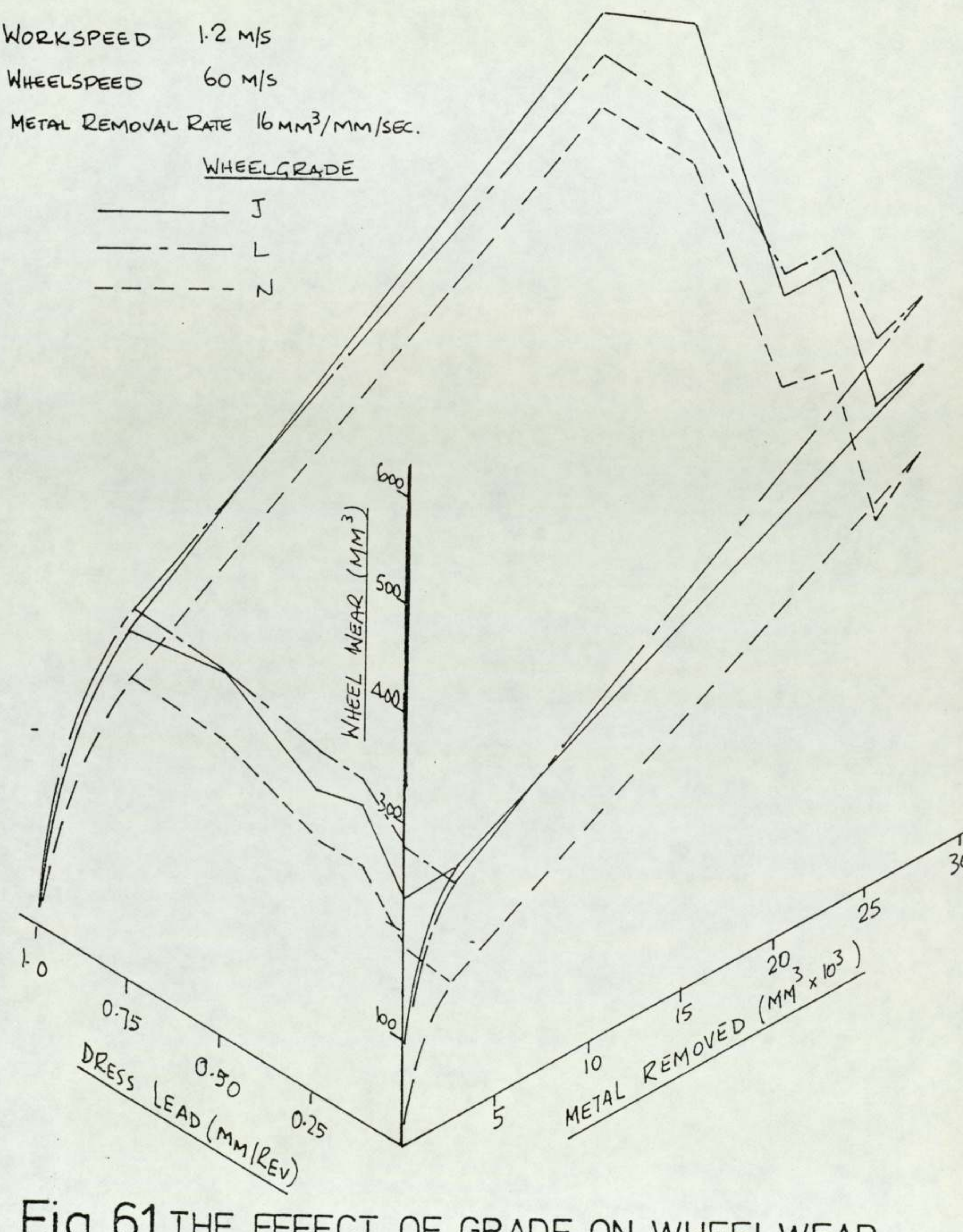


Fig 61 THE EFFECT OF GRADE ON WHEELWEAR

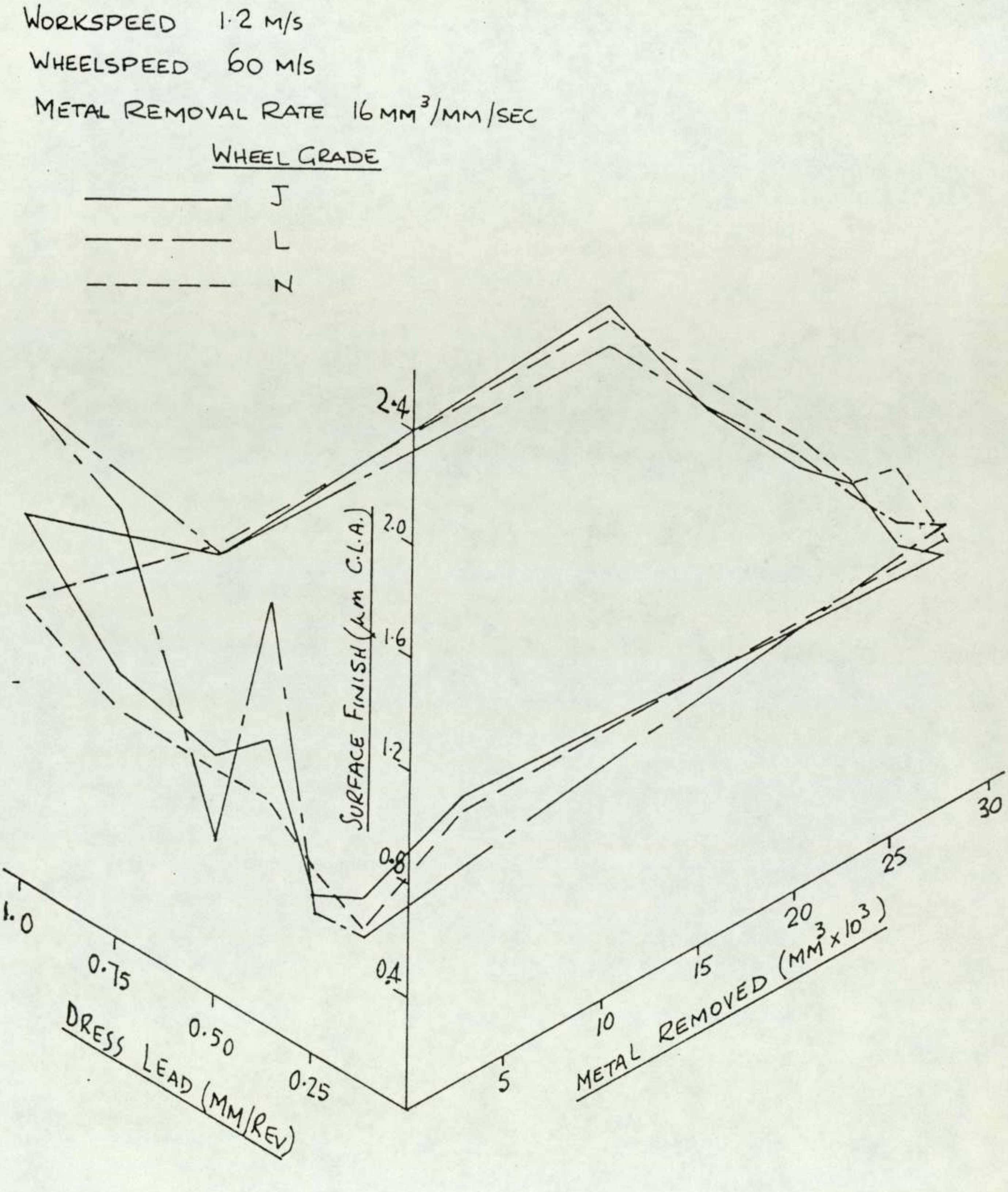


Fig 62 THE EFFECT OF GRADE ON SURFACE FINISH

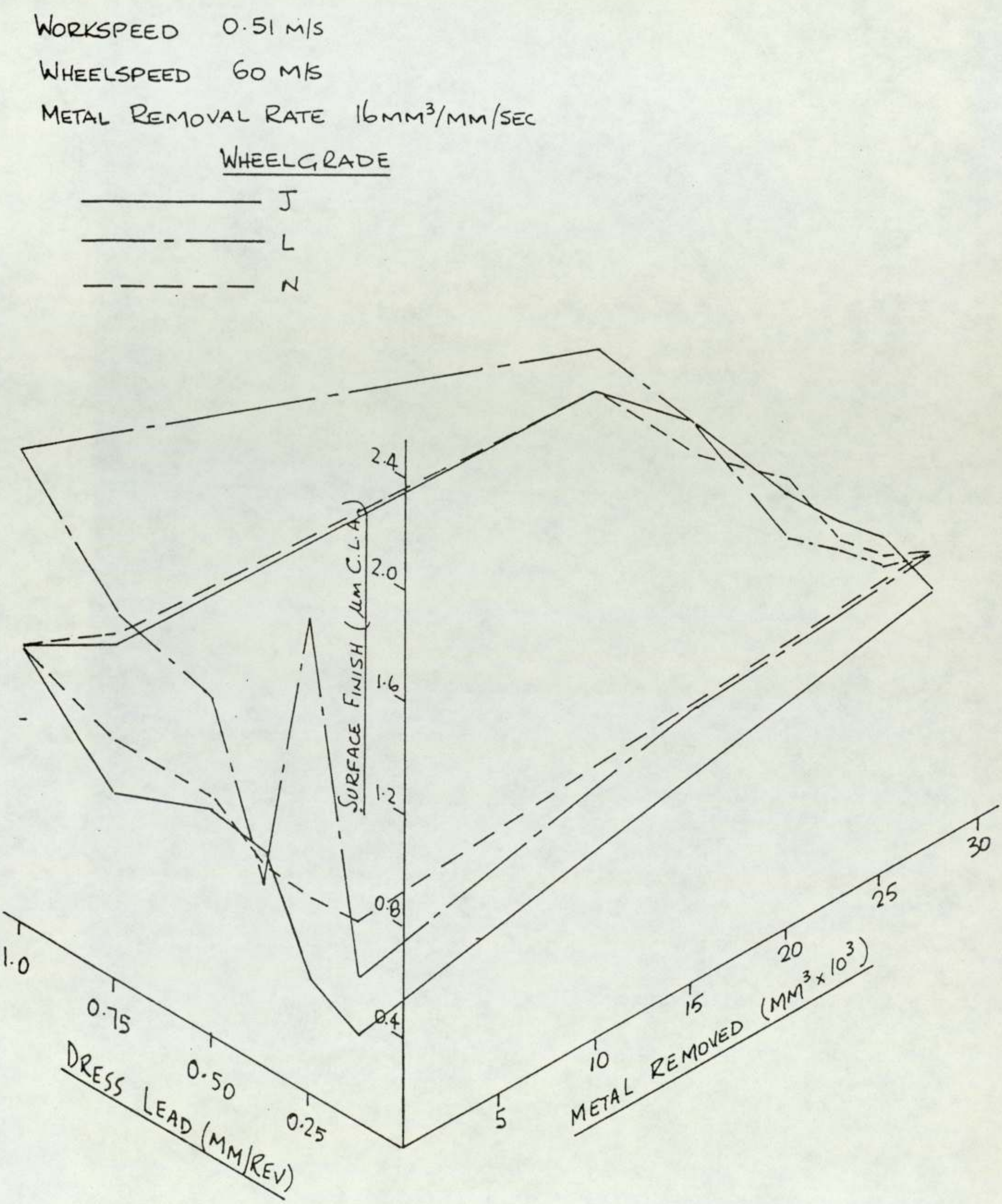


Fig 63 THE EFFECT OF GRADE ON SURFACE FINISH

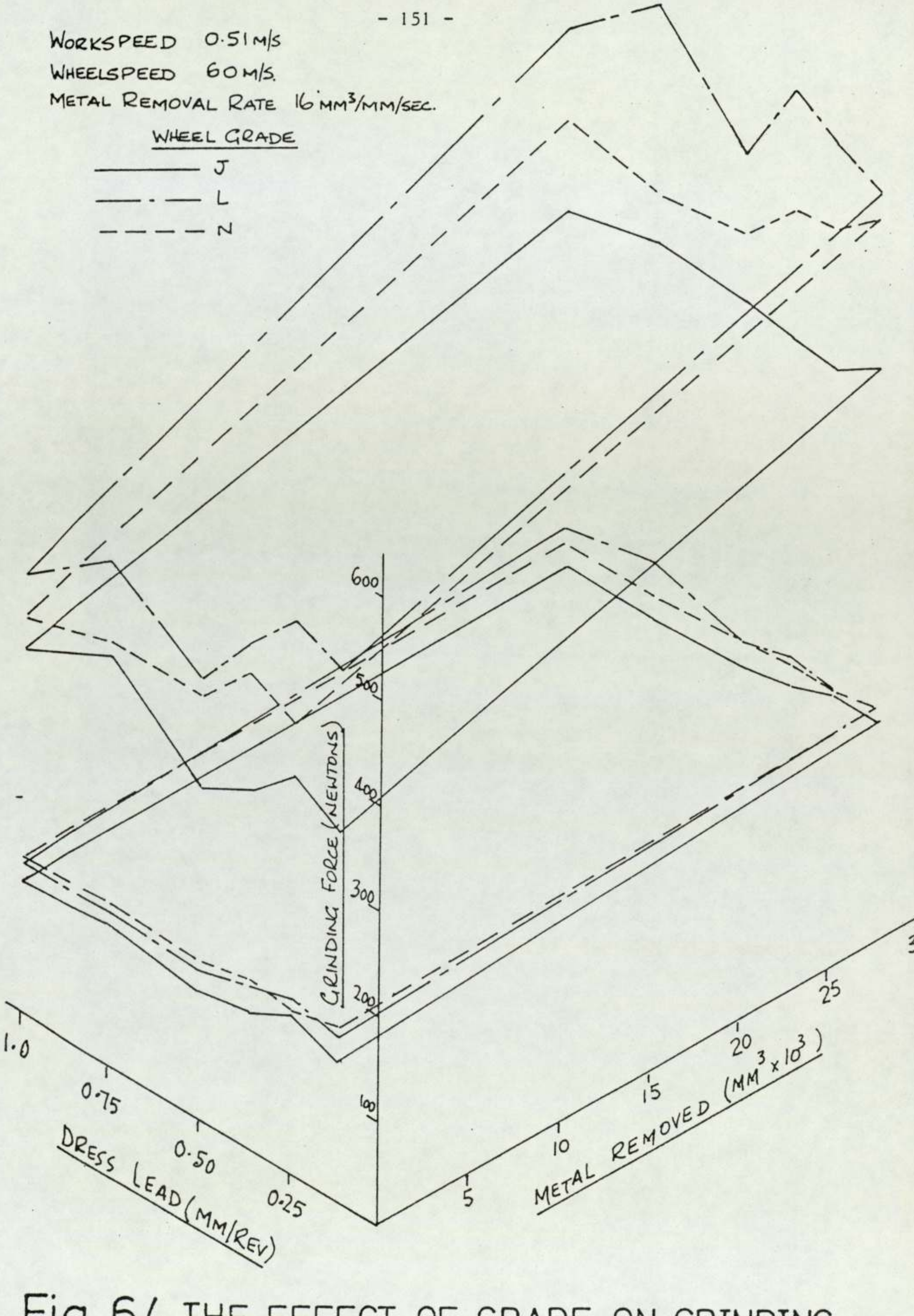


Fig 64 THE EFFECT OF GRADE ON GRINDING FORCE

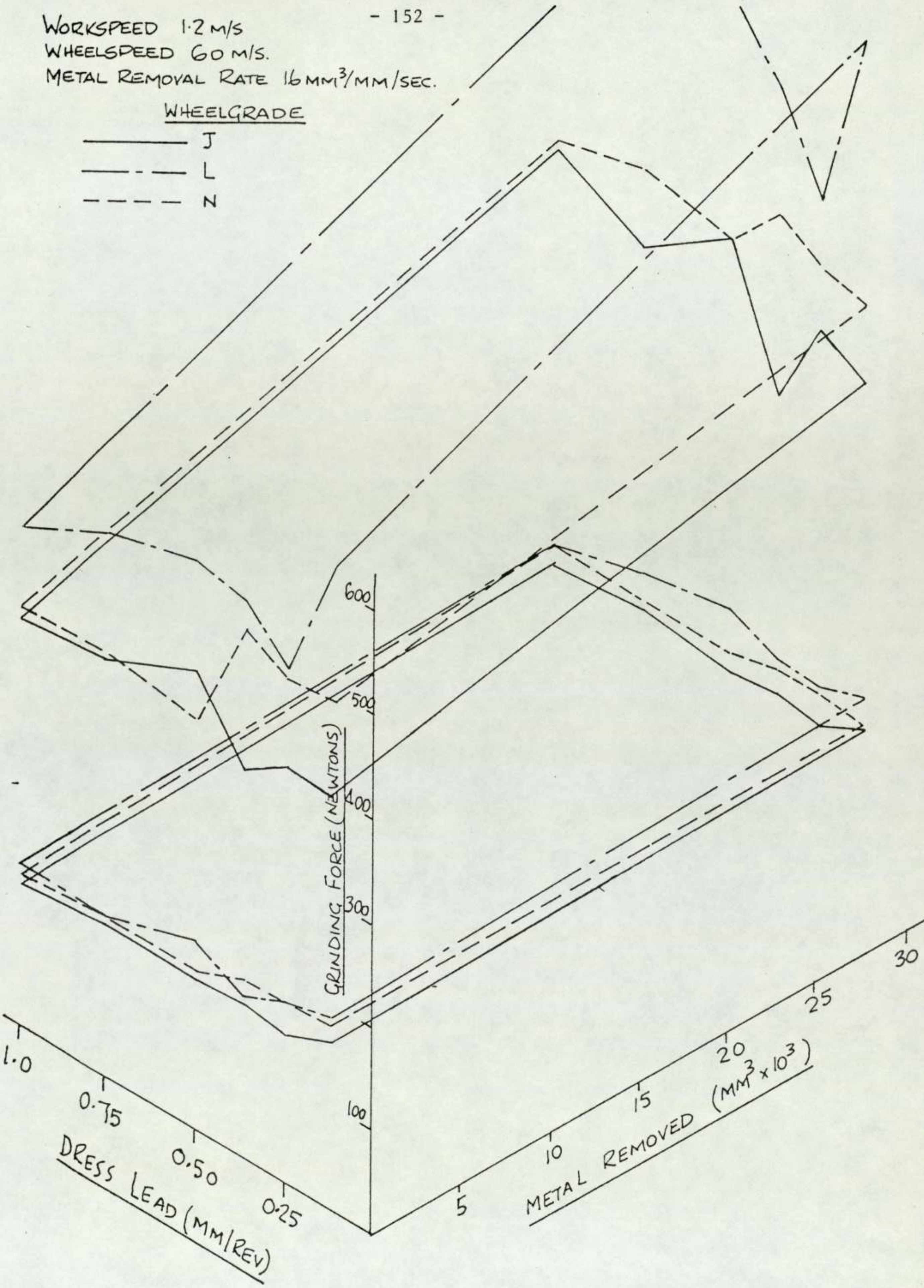
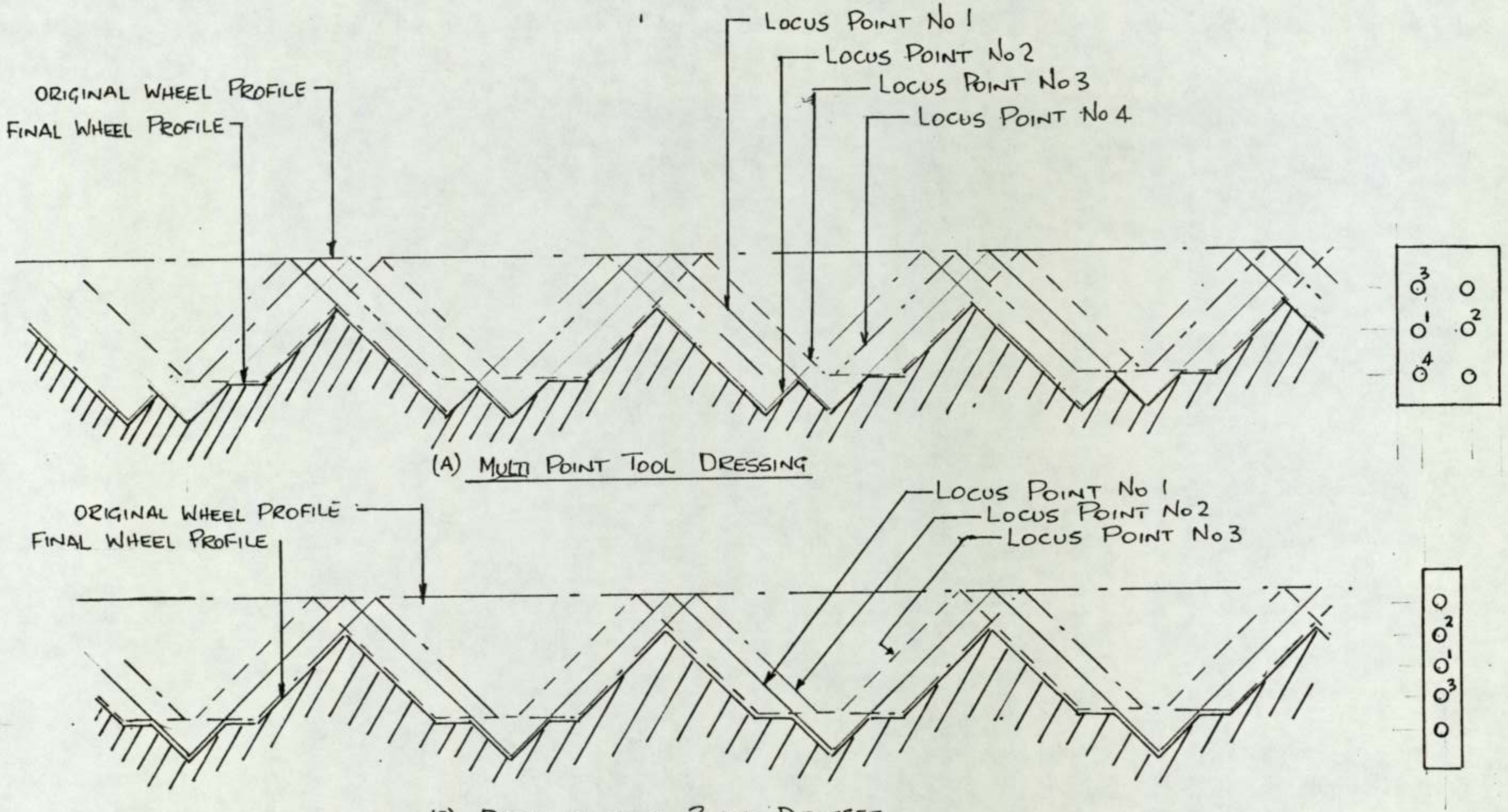


Fig 65 THE EFFECT OF GRADE ON GRINDING FORCE



(A) MULTI POINT TOOL DRESSING

(B) DRESSING USING BLADE DRESSER

Fig66 Wheel Profiles using Multi Point Tools

CHAPTER 6

Analysis and Prediction of Normal and Tangential forces during Cylindrical Plunge Grinding

6.1 Introduction

If the grinding process is to be fully understood instead of being regarded as an 'art', a full knowledge of how the forces in grinding are generated and how they are affected by the various grinding parameters is needed. Adaptive control of grinding relies in certain cases on monitoring the normal forces to control the infeed of the wheel. It would therefore be extremely useful to have a means of predicting the force patterns to be expected for a range of grinding conditions.

From a study of the results obtained for the series of tests reported here and analysed in Chapter 5, it is apparent that the main parameters that affect the level of both normal and tangential forces are the metal removal rate, grinding wheelspeed and the dress lead. The level of grinding force is also seen to depend upon the hardness or grade of the wheel and the workspeed selected. These latter effects will be discussed towards the end of the chapter.

There is one further factor to be considered. It is generally agreed (14, 24) that as grinding proceeds there is a build up of wear flats that lead to an increase in the level of normal force. This increase in wear flat area is dependent on the initial condition imparted to the wheel, the metal removal rate at which grinding takes place and the metal removed (21, 24, 25), ie a time dependency.

6.2 Prediction of Normal Force

6.2.1 Calculation of initial forces

To enable the analysis to be carried out each of the tests in Test Series I (tests using the single point dressing tool), were analysed to give expressions for normal force in the form $y = mx + c$ (linear regression)

where y = normal force (Newtons)

x = metal removed (mm^3)

m, c = constants

The values of the constants for the individual tests are given in Table 20 together with the values for the correlation coefficient. The constant, c, defines the initial force, the force at zero metal removed; the constant, m, defines the rate of increase in force. The values of correlation coefficient confirm that the normal force has a linear relationship with the amount of metal removed.

6.2.2 Calculation of initial forces at zero dress lead

The initial force values (c) were then segregated by metal removal rate and wheelspeed and the segregated data is presented in Table 21. The segregated data was analysed to give expressions in the form:-

(a) $y = mx + c$ (linear regression)

(b) $y = a_1 x^{b}$ (power curve fit)

(c) $y = a_2 e^{b_2 x}$ (exponential curve fit)

(d) $y = a_3 + b_3 x + c_3 x^2$ (polynomial regression) where

y = initial normal force (Newtons)

x = dress lead (mm/rev)

a_1,b,c,m etc = constants for each type of regression

The values obtained for the regression analyses are presented in Table 22.

The statistical analysis of the initial forces, shown in Table 23, suggests that the relationship between these forces and dress lead would be in the form of a polynomial. Examination of the correlation coefficients for each type of regression confirms this view as the coefficient for the polynomial is consistently higher than any other regression type, the nearest in order being the power curve fit. The power curve fit does not yield a realistic value at zero dress lead for normal force. It would be logical to assume that a value could be obtained if a perfectly smooth wheel could be achieved, though the wheel would not be able to sustain cutting for any appreciable time. Hence values obtained using polynomial curve fitting techniques were used for further analysis. A typical curve plotted on this basis is shown in Figure 67.

6.2.3 Calculation of base force

Where the curves of initial normal force cut the y axis, as shown in Figure 67, the value of force is the force that would be obtained using a wheel dressed with an infinitely low dress lead.

The initial forces at zero dress lead were segregated according to wheelspeed and then plotted against metal removal rate as shown in Figure 68. When the points are projected to the y axis at zero metal removal rate the force indicated by the intercept is the base force. This particular force has no physical significance but is a start point from which all other forces can be derived.

The 'best fit' for the values of initial force at zero dress lead was found to be by linear regression and the following values of slope and intercept were determined:-

Wheelspeed	Slope	Intercept (Newtons)	Correlation Coefficient (r)
30	23.45	406.59	0.876
45	22.93	275.98	0.995
60	22.80	196.76	0.996

The values of base force are related to wheelspeed in the following manner:-

$$F_{NF} = 607.86 - 6.99\ V_s \qquad (1)$$

where F_{NF} = base force (Newtons)

V_s = wheelspeed (m/s)

The correlation coefficient is 0.99

6.2.4 Prediction of initial forces at zero dress lead

Examination of Figure 68 reveals that the slopes of the three curves are similar and the values are given in Section 6.2.3. It is therefore appropriate to calculate an average slope for use in future calculations. This average slope is 23.06

It is now possible to deduce an expression for initial force at zero dress lead from a base force, in terms of wheelspeed and metal removal rate as follows:-

$$F_{NI} = 607.86 - 6.99\,V_s + 23.06\,(MRR)$$

or $$F_{NI} = K_1 - K_2\,V_s + K_3\,(MRR) \qquad (2)$$

where F_{NI} = initial force at zero dress lead (Newtons)

V_s = wheelspeed (m/s)

MRR = Metal Removal Rate (mm^3/mm/sec)

K_1 = 607.86

K_2 = 6.99

K_3 = 23.96

6.2.5 Prediction of initial forces

In a similar manner, it would be possible to analyse the values for the regression of dress lead and extend the expression for initial force to include in the expression values for dress lead in linear and quadratic terms. However, if reference is made to Table 23, it will be seen that in addition to the main effects of wheelspeed, metal removal rate and dress lead on initial normal force there are significant two factor interactions of metal removal rate and dress lead, and wheelspeed and dress lead to be taken into account. If each interaction were to be treated separately, the final expression that would be derived would be far too cumbersome. Therefore a multiple linear regression technique will be utilised to derive an expression to include all effects on the initial normal forces.

6.2.6 Multiple regression analysis

The Multiple Regression Analysis: Subprogram Regression from the Statistical Package for Social Sciences (48) was used to analyse the data on all the test series in this work. The computer print outs for both input and output for a typical example (multiple regression analysis of initial normal force) are given in Appendix 10.

The output of the Subprogram Regression is divided into two basic parts

i) step by step results

ii) a summary table

In the mode of analysis used each independent variable in the equation is input separately. The variable that explains the greatest amount of variance in the dependent variable is entered first. The next variable to be entered is that which explains the greatest amount of variance in conjunction with the first and so on through all the variables.

Each section of the analysis is headed with the step number and a list of the independent variables entered on the current step. On the left hand side of the output, a statistical summary of the prediction equation is presented. The statistics listed are (a) the multiple correlation coefficient (MULTIPLE R), (b) Coefficient of Determination(RSQUARE), (c) Adjusted Coefficient of Determination (ADJUSTED RSQUARE), and (d) the standard error of estimate (STANDARD ERROR).

where the coefficient of determination:-

$$R^2 = 1 - \left[\frac{\text{error variance in Y in the population}}{\text{total variance in Y in the population}} \right]$$

and adjusted

$$R^2 = R^2 - \left[\frac{k - 1}{N - k} \right] \left[1 - R^2 \right]$$

where k = number of independent variables in the equation

N = number of cases

The multiple correlation coefficient $r = \sqrt{R^2}$

On the right hand side is an analysis of variance table for the variable entered at that step.

Immediately below this section are two sections labelled 'Variables in the Equation' and 'Variables not in the Equation'. Under the heading 'Variables in the Equation' regression statistics are given for all variables entered into the equation up to the current step. The unstandardized regression coefficients are listed under the column headed 'B'. The last value in the list is the intercept on the y axis and is labelled 'CONSTANT'. Standardized partial regression coefficients are listed in the column headed 'BETA'. The column labelled 'STD ERROR B' contains the standard errors for each of the unstandardized regression coefficients, these values are used to establish confidence limits for each coefficient. The F Ratios are used in tests of significance for each variable.

Variables that have not been entered into the equation are listed in the 'VARIABLES NOT IN' segment. Under 'BETA IN' is listed a value for the partial regression coefficient a variable would have if it were entered alone on the next step. Under the heading 'PARTIAL' is the partial correlation coefficient for each variable after the variables in the equation have been partialled out. The values of 'TOLERANCE' and 'F' are required to enable the Regression program to be run. From these values the variable with the largest partial correlation coefficient is entered at the next step.

After all steps have been completed, a final summary table is printed. In this summary the value of the multiple regression coefficient, the coefficient of determination, the change of the coefficient of determination at each step, and the simple regression are output together with the final unstandardized regression coefficients.

6.2.7 Regression analysis output for initial normal force

Using the techniques outlined in the previous section, the expression for initial normal force is as follows:-

$$F_{NB} = 462.46 + 23.01(MRR) - 3.76(V_s) + 333.44(D^2 - 1.67D) + 3.01(MRR)(D - 2.14D^2) + 0.02(V_s^2)(D^2) \text{ Newtons} \quad (3)$$

where F_{NB} = initial normal force (Newtons)

MRR = metal removal rate ($mm^3/mm/sec$)

V_s = wheelspeed (m/s)

D = dress lead (mm/rev)

From the output for this programme listed in Appendix 10, it will be seen that the multiple regression coefficient is 0.956. The values for the variable coefficients account for 91.48% of the variation in initial normal force.

6.2.8 Calculation of normal force during grinding

Referring to Table 18 it will be seen that the normal force during grinding will be a less complex expression than that for the initial normal force. The main effects of metal removal rate, wheelspeed and dress lead only have significant linear effects on normal force and the only two factor interaction present is that between metal removal rate and dress lead.

Using the multiple regression analysis detailed in section 6.2.6, the normal force at a point when 15000 mm^3 of metal had been removed was computed as follows:-

$$F_{NR} = 361.91 + 24.49(MRR) - 2.60(V_s) - 92.31(D) - 3.23(MRR)(D) \text{ Newtons} \quad (4)$$

The correlation coefficient for this expression is 0.94 and the percentage of variation in normal force explained by the regression coefficients is 88.39%.

As the pattern of forces have been shown to be linear (see section 6.2.1) to obtain an expression for grinding force at any point of time until the conclusion of steady state grinding it is necessary to compute the increase in force per unit volume of metal removed and combine this with the expression for initial normal force in the following manner:-

$$F_N = F_{NB} + \frac{M}{K}\left[F_{NR} - F_{NB}\right] \text{ Newtons} \qquad (5)$$

where F_N = normal force (Newtons)

F_{NB} = initial normal force (Newtons)

F_{NR} = normal force at 15000 mm^3 of metal removed (Newtons)

M = metal removed (mm^3)

K = 15000

The overall expression is then:-

$$\begin{aligned} F_N = \; & 462.46 + 23.01(MRR) - 3.76(V_S) + 333.44(D^2 - 1.67D) \\ & + 3.01(MRR)(D - 2.14D^2) + 0.02\,(V_S{}^2)(D^2) + \frac{M}{15000}\Big[1.48(MRR) \\ & + 1.16(V_S) - 333.44\,(D^2 - 1.393D) - 6.24(MRR)(D - 1.034D^2) \\ & - 0.02(V_S{}^2)(D^2) - 100.55\Big] \text{ Newtons} \end{aligned} \qquad (6)$$

Using values predicted using this expression and comparing these in the ratio of $\frac{\text{normal force (predicted)}}{\text{normal force (test)}}$ the mean value of the ratios was found to be 1.017 with a standard deviation of 0.119. Thus for a predicted value of 300 newtons, the 95% confidence limits that the test value shall be within are in the range of 239 to 385 newtons.

The expression given in (6) is still extremely cumbersome when compared with those of other researchers. If log values of the dependent and independent variables are substituted in the multiple linear regression programme an expression would be derived in the form:-

$$F_N = KVs^{x} (MRR)^{y} D^{z}$$

where K = antilog (CONSTANT)

x = regression coefficient for Vs (wheelspeed)

y = regression coefficient for MRR (metal removal rate)

z = regression coefficient for D (dress lead)

Therefore using the regression subprogramme expression (3) is transformed as follows:-

$$F_{NB} = 315.33\, V_s^{-0.372}\, MRR^{0.597}\, D^{-0.219} \text{ Newtons} \quad (7a)$$

The correlation coefficient is 0.96

Expression (4) using the same technique becomes

$$F_{NR} = 343.09\, V_s^{-0.29}\, MRR^{0.524}\, D^{-0.148} \text{ Newtons} \quad (7b)$$

The correlation coefficient is 0.96

Combining (7a) and (7b) as before and simplifying

$$F_N = 315.33\, V_s^{-0.372}\, MRR^{0.597}\, D^{-0.219} \left[1 + \frac{M}{K} \left(\left(1.09 V_s^{0.082}\, MRR^{-0.073}\, D^{0.071} \right) - 1 \right) \right] \text{ Newtons} \quad (8)$$

Using values predicted using expression (8) and comparing these in the ratio of $\frac{\text{normal force (predicted)}}{\text{normal force (test)}}$ the mean value of the ratios was found to be 1.006 with a standard deviation of 0.09. For a predicted value of 300 Newtons, the 95% confidence limits for the test result are between 253 and 363 newtons.

The predicted and actual results are shown for a range of conditions in Figures 69, 70 and 71.

As this form of expression is slightly more accurate and presents an equation for a predicted force in a less cumbersome mode, this type of analysis will be used in computing the tangential forces.

6.3 Prediction of Tangential Force

The same techniques are used to obtain an expression for tangential force as was used in the preceding section to determine an expression for normal force.

6.3.1 Calculation of initial forces

All tests using a single point dressing tool in Test Series I were analysed to give expressions for tangential force in the form

$$y = mx + c$$

where y = tangential force (Newtons)

x = metal removed (mm^3)

m, c = constants

The values for the constants together with the correlation coefficients are given in Table 24.

6.3.2 Calculation of initial forces at zero dress lead

The initial force values (c) were then segregated by metal removal rate and wheelspeed, this segregated data is presented in Table 25. The data was analysed on the basis that the analysis of variance, which is summarised in Table 23, concluded that the effect of dress lead was significantly effective in both the linear and quadratic form on the initial tangential force. Therefore a polynomial regression analysis was carried out and expressions for initial tangential force obtained in the form:-

$$y = a + bx + cx^2$$

where y = initial tangential force

x = dress lead

a,b,c = constants

The regression analysis data is presented in Table 26. A typical plot of tangential force against dress lead is shown in Figure 72.

6.3.3 Calculation of base force

From the values of initial force at zero dress lead it is possible to obtain the base forces that act as a start point for future calculations.

The values for initial force at zero dress lead are segregated and plotted against metal removal rate as shown in Figure 72. When the points are joined and projected to the y axis, the intercept is the base force.

Using linear regression the values of base force and slope for each wheelspeed were as follows:-

Wheelspeed m/s	Slope	Intercept (Threshold force) Newtons	Correlation Coefficient
30	12.52	202.86	0.959
45	10.55	133.74	0.982
60	9.76	87.87	0.988

The values of base force are related to wheelspeed in the following manner:-

$$F_{TF} = 313.98 - 3.83V_s \text{ Newtons} \qquad (9)$$

where F_{TF} = base tangential force (Newtons)

V_s = wheelspeed (m/s)

The correlation is 0.99

6.3.4 Prediction of initial force at zero dress lead

Examination of Figure 72 reveals that the slopes of the three plots are similar and the values are given in Section 6.3.2. It was decided therefore to calculate an average for use in further calculations. The average slope is 10.94.

It is now possible to deduce an expression for the initial tangential force based on the base tangential force, in terms of wheelspeed and metal removal rate as follows:-

$$F_{TI} = 313.98 - 3.83(V_s) + 10.94(MRR)$$

or $$F_{TI} = K_3 - K_4(V_s) + K_5(MRR) \text{ Newtons} \qquad (10)$$

where F_{TI} = initial tangential force (Newtons)

V_s = wheelspeed (m/s)

MRR = metal removal rate ($mm^3/mm/sec$)

K_3 = 313.98

K_4 = 3.83 constants

K_5 = 10.94

6.3.5 Prediction of initial tangential forces

In a somewhat similar manner it would be possible to analyse the values for dress lead and extend expression (10) to include in that expression values for dress lead in linear and quadratic terms.

As has been shown however in the treatment of the normal forces using logarithmic values in the regression subprogram, an expression for forces in an accurate and less cumbersome form will be derived. Therefore the technique described in the latter part of section 6.2.8 was again used to derive expressions for the tangential forces.

6.3.6 Regression Analysis for initial tangential force

Using the multiple linear regression technique in conjunction with log values for the dependent and independent variables the expression for initial tangential force was determined to be:-

$$F_{TB} = 290.83 V_s^{-0.503} \, MRR^{0.516} \, D^{-0.244} \text{ Newtons} \tag{11}$$

where F_{TB} = initial tangential force (Newtons)

MRR = metal removal rate ($mm^3/mm/sec$)

V_s = wheelspeed (m/s)

D = dress lead (mm/rev)

The correlation coefficient was found to be 0.96.

6.3.7 Calculation of tangential force during grinding

Using identical techniques the tangential force at a point when 15000 mm^3 of metal had been removed was computed as:-

$$F_{TR} = 355.27 V_s^{-0.486} \, MRR^{0.454} \, D^{-0.205} \text{ Newtons} \tag{12}$$

The correlation coefficient for this expression is 0.96. The pattern of forces have been shown to be linear (see Section 6.3.1) and as expression (12) represents the forces at a time when 15000 mm^3 of metal have been removed, the expression for tangential force at any point of time during steady state grinding will be:-

$$F_T = F_{TB} + \frac{M}{K}\left[F_{TR} - F_{TB}\right] \text{ Newtons} \tag{13}$$

where F_T = tangential force (Newtons)

F_{TB} = initial tangential force (Newtons)

F_{TR} = tangential force at 15000 mm^3 of metal removed (Newtons)

M = metal removed (mm^3)

K = 15000 mm^3

Combining (11) and (12) and simplifying:-

$$F_T = 290.83V_s^{-0.503}\,MRR^{0.516}\,D^{-0.244}\left[1 + \frac{M}{K}\left((1.22V_s^{0.017}\,MRR^{-0.062}\,D^{0.039}) - 1\right)\right] \text{ Newtons} \tag{14}$$

Using values predicted using this expression and comparing these in the ratio of $\frac{\text{tangential force (predicted)}}{\text{tangential force (test)}}$ the mean value of the ratios was found to be 1.004 with a standard deviation of 0.093. For a predicted tangential force of 200 Newtons the 95% confidence limits that test results will be within are 168 to 244 Newtons.

The predicted and actual results are compared graphically for a range of conditions in Figures 69, 70 and 71.

6.4 The Relationship between Normal and Tangential Force

Several researchers (12, 22, 24, 28) in analysing grinding forces found a relationship between normal and tangential forces based on a frictional coefficient μ.

Malkin (24) established threshold forces related to a zero value of wear flat area and developed an expression for normal force based on a contact pressure and the wear flat area:-

$$F_N = F_{NF} + \overline{P}\, a_r$$

the expression for tangential force was quoted as:-

$$F_T = F_{TF} + \mu \overline{P}\, a_r$$

where F_N = normal force

F_{NF} = normal threshold force

$\overline{P}$ = contact pressure

a_r = wear flat area

F_T = tangential force

F_{TF} = tangential threshold force

μ = coefficient of friction

The frictional coefficient was found to be 0.61 when grinding at 30 m/s with a workspeed of 2.44 m/min and a metal removal rate of 1.09 $mm^3/mm/sec$.

Tsuwa (28) developed formulae which are similar in basic concept:-

$$F_N = K_N V_s^{-0.78} V_W^{0.78} t^{0.78} B^{1.0} + K_{NF} \, lsB\varepsilon$$

$$F_T = K_T V_s^{-0.75} V_W^{0.75} t^{0.83} B^{1.0} + \mu K_{NF} \, lsB\varepsilon$$

where F_N = normal force

F_T = tangential force

V_s = wheelspeed

V_W = workspeed

t = depth of cut

B = grinding width

ls = length of arc

ε = wear flat area

K_N, K_T, K_{NF} = constants

The coefficient of friction for the series of tests carried out by Tsuwa (28) was found to be in the range 0.3 - 0.5. For the particular test cited, carried out at 31.5 m/s wheelspeed, 10 m/min workspeed and with a metal removal rate of 0.83 $mm^3/mm/sec$, the value quoted for μ was 0.4.

Pacitti and Rubenstein (12) and Rubenstein (22) suggested that the relationship was of the form $F_N = (\frac{1}{\mu}) F_T + C$ where C was a complex function of wheelspeed, wheel geometry, workpiece and material properties, the coefficients of friction between grit and workpiece (μ), bond and workpiece (μ_B) and the proportion of grit and bond in contact with the workpiece (α).

In an earlier work Greenhow and Rubenstein (49) had shown that the coefficient of friction, μ, for H.S.S. tooling was temperature dependent and that during the steady state of wear this value was constant. However, when 'burn out' conditions were reached due to rapid increase of the wear land, temperatures at the tool tip were shown to rise rapidly. In conjunction with this temperature increase, a reduction in the coefficient of friction was noted. Pacitti and Rubenstein (12) applied these results to their work and anticipated that the slope ($\frac{1}{\mu}$) would be lower in the steady state than in the later stages of grinding where temperatures will be higher. Their results showed that the coefficient of friction did in fact drop from 0.4 to 0.22.

In this work it has been shown that the force levels will increase with grinding time and that the rate of increase can be predicted by a consideration of the conditions of wheel preparation and in particular the dress lead used. If it is accepted that an increase in wear flat area is a cause of a force increase then it follows from the above that the rate of wear flat development is a consequence of the wheel preparation technique.

For this statement to be true, there must be a broad measure of agreement obtained for the value of the coefficient of friction, μ, in this work and the work of other researchers.

Rubenstein (22) in developing the expression $F_N = (\frac{1}{\mu}) F_T + C$ postulated that for fixed geometry, wheelspeed, table speed and constant values for μ and $\propto$ (the proportion of bond/workpiece and grit/workpiece contact) the value of C would be constant. However, in this work some of these parameters have been varied and it cannot be expected that this value will be constant.

Rubenstein (22) using as a model the expressions for cutting with worn tools developed earlier (49) showed that the normal cutting force component in grinding could be represented as:-

$$f_n^1 + pa + p_1 K_1 r t_1^2$$

and the tangential cutting force component as:-

$$\mu(f_n^1 + pa) + S(2 + K_1) r t_1^2$$

where f_n^1 was the force component due to the radius of curvature of cutting edge

μ, the coefficient of friction between grit and workpiece

p, the pressure between flank wear land and workpiece

a, the plateau area

K_1 a constant for a given workpiece material at a given rake angle

r, the grit chip width to depth ratio

t_1 the mean grit depth of cut

p_1, S stresses acting on the idealised lower boundary of the shear zone

In the theory as presented (22), it is assumed that each grit whether ploughing or cutting will make an equal contribution to either the total ploughing force or the total cutting force.

If n_p = ploughing grits per unit area of wheel surface, and

n_c = cutting grits per unit area of wheel surface

then when the wheel is in a stable condition:-

$$\frac{n_p}{n_c} = K \text{ (a constant)}$$

An indentor was used to simulate a grinding grit and it was shown that the projected area of contact for ploughing grits is $\beta_1 r t_1{}^2$ and the normal force on a ploughing grit indented to a depth t_1 was $H\beta_1 r t_1{}^2$ the tangential force for the same grit was:-

$$P\beta_2 r t_1{}^2$$

where H = hardness of the workpiece material

$\beta_1\beta_2$ = geometrical factors for the grit

The pressure between bond and workpiece was designated as P_B and μ_B as the coefficient of friction between bond and workpiece. The contributory force components due to bond contact were given as $\propto A\ P_B$ normally and $\mu_B \propto A\ P_B$ tangentially where:-

A = the total area of contact

$\propto$ = proportion of bond/workpiece contact area

The total normal cutting force was then found to be:-

$$n_c\ A\ (f_n^1 + pa + P_1 K_1 r t_1{}^2)$$

and the total tangential cutting force defined as:-

$$n_c A \left[\mu(f_n^1 + pa) + S(2 + K_1)\, rt_1{}^2 \right]$$

when the wheel is in a stable condition:-

$$n_p = Kn_c$$

and the total normal force is then given by:-

$$F_N = W \sqrt{dD} \;\; n_c \left[(K\, \beta_1 H + P_1 K_1) rt_1{}^2 + f_n^1 + pa \right] + \propto W \sqrt{dD} \;\; P_B$$

where A has been replaced by $W \sqrt{dD}$

Putting $B_1KH + P_1K_1 = L$

and $$rt_1{}^2 = \frac{v \sqrt{d/D}}{Vn_c}$$

$$F_N = \frac{Wvd}{V}(L) + W \sqrt{dD} \left[n_c (f_n^1 + pa) + \propto P_B \right] \qquad (a)$$

and

$$F_T = \frac{Wvd}{V}(M) + W \sqrt{dD} \left[\mu n_c (f_n + pa) + \propto \mu_B P_B \right] \qquad (b)$$

where $M = \beta_2 KP + S(2 + K_1)$

If expression (b) is divided by μ and subtracted from (a):-

$$F_N = \left(\frac{1}{\mu} \right) F_T + \frac{Wvd}{V} B - \propto P_B W \sqrt{dD} \left(\frac{\mu_B}{\mu} \right) \qquad (c)$$

where $B = L - \left(\frac{M}{\mu} \right)$

The term (Wvd) is in fact the metal removal rate. Thus it can be seen that the factor C is directly related to the metal removal rate, wheelspeed and the length of the chip.

The factor α, the ratio of contact of bond and workpiece, will be modified by the dress lead applied to the wheel.

An analysis of variance carried out on the results obtained for C from the values obtained for normal and tangential force confirm this analysis. There are highly significant linear relationships between the value of C and metal removal rate and wheelspeed. In addition to these effects, there is a highly significant quadratic effect due to the metal removal rate. Highly significant two way reactions of metal removal rate and wheelspeed and wheelspeed and dress lead are also apparent on the value of C. These values of significance are detailed in Table 29.

The expression $F_N = \left(\frac{1}{\mu} \right) F_T + C$ may be rewritten

$$\mu = \frac{F_T}{(F_N - C)}$$

The values of normal and tangential force have already been shown to be positively related to wheelspeed, metal removal rate and dress lead and as C is also related to those same factors, the value of μ must be determined by wheelspeed, metal removal rate and dress lead.

An analysis of variance carried out on the values of coefficient of friction determined for the series of tests shows that the following are highly significant in relation to the coefficient of friction:-

i) Metal removal rate (linear)

ii) Wheelspeed (linear and quadratic)

iii) Dress lead (linear and quadratic)

iv) Linear interaction of wheelspeed and dress lead

v) Linear dress lead, quadratic wheelspeed interaction

In addition, there are further significant effects caused by linear interactions of metal removal rate and wheelspeed, metal removal rate and dress lead and the quadratic effect of dress lead.

Using the multiple regression techniques described earlier in Section 6.2.6, in association with log values for the variables, the following relationships were determined:-

$$\mu = 3.07\, V_s^{-0.548}\, MRR^{-0.147}\, D^{-0.17} \tag{17}$$

correlation coefficient = 0.87

$$C = -2.84\, V_s^{0.608}\, MRR^{0.848}\, D^{0.077} \text{ Newtons} \tag{18}$$

correlation coefficient = 0.95

Values predicted by these equations for the coefficient of friction vary from 0.6 at low metal removal rates and low wheelspeed to 0.23 at high metal removal rates and high wheelspeeds. Pacitti and Rubenstein (12) showed that the coefficient of friction μ was dependant on temperature and these results show that at high metal removal rates and high wheelspeeds the coefficient of friction is lower and this is due to the higher heat input associated (a) with the increased chip thickness at high metal removal rates, and (b) the increase in sliding velocity of the grit at higher wheelspeeds.

If the formula for coefficient of friction is applied to the data of other researchers, it is found that there is good agreement with Malkin's results (0.57 predicted, 0.61 quoted) but the correlation between Tsuwa's and Pacitti and Rubensteins figures are not of the same order (0.53 predicted, 0.4 quoted). During the tests carried out by Tsuwa, a very fine feed was used in dressing while Pacitti and Rubenstein used a dressing diamond with a pronounced wear flat. Both these conditions could have led to the production of a glazed wheel which in turn, would have led to an additional amount of heat and correspondingly lower values for the coefficient of friction.

6.5 The Influence of Wheel Grade and Workspeed

Test Series II was designed to evaluate the effects of varying the grade and workspeed on both the normal and tangential force. All tests were carried out using a grinding wheelspeed of 60 m/s and a metal removal rate of 16 mm^3/mm/sec. This combination of parameters was chosen as this work is primarily concerned with the investigation of grinding at high metal removal rates and this is most efficiently carried out at high wheelspeeds.

The results of the tests in the second series are summarised in Tables 12 - 16 inclusive and Tables 27 and 28.

6.5.1 The effect of grade and workspeed on normal force

Using multiple linear regression techniques the following relationships were determined between normal force, grade, work speed and dress lead:-

$$F_{NR} = 490.34 + 39.81G - 31.0G^2 + 20.53V_w + 143.14V_w{}^2 + 23.19V_w{}^2D$$

$$- 115.63G^2V_w{}^2 - 14.80V_w{}^2D^2 - 34.8D + 15.29D^2 \text{ Newtons} \qquad (19)$$

where F_{NR} = normal force after 15000 mm^3 of metal had been removed

G = wheel grade

V_w = work speed

D = dress lead

For the regression analysis all values were coded as follows:-

G (wheel grade)	:	-1,J	: 0, L	: 1,N
V_w (work speed)	:	-1,0.51	: 0,0.8	: 1,1.2 m/sec
D (dress lead)	:	-1,0.25	: 0,0.5	: 1,0.75 mm/rev

If expression (19) is analysed with all dress lead and dress lead related factors set at zero, ie for 0.5 mm/rev the effects of grade and workspeed may be quantified and their effects on normal force assessed in the following manner:-

(a) J wheel; 0.51 m/s : -12.86%

(b) J wheel; 1.2 m/s : -4.49%

(c) L wheel; 0.8 m/s : 0

(d) N wheel; 0.51 m/s : +3.06%

(e) N wheel; 1.2 m/s : +11.43%

Thus it is seen that for all J wheels there is a reduction in normal force in comparison with the L wheel and for the N wheels, there is an increase in force.

The correlation coefficient for expression (19) is 0.89. The average value for the ratio of $\frac{\text{predicted normal force}}{\text{test normal force}}$ is equal to 1.004 with a standard deviation of 0.072. The 95% confidence limits for a predicted force of 500 Newtons will be 436 to 581 Newtons.

If these values of force obtained in this test series are combined with those from test series I and log values taken for the dependent and independent variables, an expression combining all parameters can be obtained in the form:-

$$F_{NR} = Vs^a \, MRR^b \, D^c \, V_w{}^d \, G^e$$

where F_{NR} = normal force when 15000 mm^3 of metal were removed

Vs = wheelspeed

MRR = metal removal rate

D = dress lead

V_w = work speed

G = wheel grade

Values for wheel grade are coded as follows:-

1 = J ; 3 = L ; 5 = N

all other values were entered as raw data.

The computed results for the normal force after 15000 mm^3 of metal had been removed was:-

$$F_{NR} = 320.81 V_s^{-0.281} MRR^{0.530} D^{-0.1} V_w^{0.082} G^{0.119} \text{ Newtons} \qquad (20)$$

which may be compared with expression (8):-

$$F_{NR} = 343.09 V_s^{-0.29} MRR^{0.524} D^{-0.148} \text{ Newtons} \qquad (8)$$

and shows the effect of the addition of the parameters of grade and workspeed. The correlation coefficient for expression (20) is 0.92.

A comparison between the two expressions show that the addition of the factors of grade and workspeed does not alter the basic form of the original equation and the exponents for metal removal rate and wheelspeed are only altered slightly. The exponent for dress lead is altered because of the significant interaction of dress lead and workspeed on normal force. This indicates that the latter expression will be valid for a wide range of conditions.

6.5.2 The effect of grade and workspeed on tangential force

In the previous section, it was seen that if the values of normal force obtained in the second test series were combined with those from the first series, there were some changes of a minor nature to the original exponents.

Therefore using multiple regression techniques in association with the logarithmic values of the variables the following expression for tangential force is derived:-

$$F_{TR} = 378.14V_s^{-0.504}\ MRR^{0.445}\ D^{-0.139}\ V_w^{0.072}\ G^{0.087}\ \text{Newtons} \qquad (22)$$

The correlation coefficient for this expression is 0.93.

This may be compared to the expression obtained when only wheelspeed, metal removal rate and dress lead were considered:-

$$F_{TR} = 355.27V_s^{-0.486}\ MRR^{0.454}\ D^{-0.205}\ \text{Newtons} \qquad (12)$$

The change in the exponent for dress lead is again due to the significant interaction between workspeed and dress lead.

If expression (22) is analysed the affects of grade and workspeed may be quantified as follows:-

(a) J wheel; 0.51 m/s workspeed : -12.8%

(b) J wheel; 1.2 m/s workspeed : -6.6%

(c) L wheel; 0.8 m/s workspeed : 0.0%

(d) N wheel; 0.51 m/s workspeed : +1.02%

(e) N wheel; 1.2 m/s workspeed : +7.61%

Thus it is seen that the variation of face due to the alterations of grade and workspeed follow the same pattern as those for normal force in section 6.5.1.

In the foregoing sections it has been shown that the selection of a softer wheel is instrumental in lowering the force levels and that the selection of lower workspeeds will also contribute to lower forces due to the modification of the chip cross section. This leads to the further benefit that the overall wear of the wheel is reduced. Thus the commonly quoted ratio of $\frac{V_s}{V_w} = 60$ should be treated with caution when specifying grinding parameters. In particular when grinding at high wheelspeeds this work has shown that this ratio should be increased.

6.6 Comments on the Form of the Empirical Equations Derived

If the equations derived for normal and tangential force are compared with those derived by other researchers basic points of similarity can be observed.

Both Tsuwa (28) and Malkin (24) concluded that there was a threshold force. Malkin determined this value and used it as a constant. Tsuwa derived an expression for threshold force as follows:-

$$F_N = K_N V^{-0.78} v^{0.78} t^{0.78} B^{1.0}$$

and $$F_T = K_T V^{-0.75} v^{0.75} t^{0.83} B^{1.0}$$

this compared with the expressions derived for initial forces as follows:-

$$F_{NB} = 315.33\, V_s^{-0.372}\, MRR^{0.597}\, D^{-0.219}$$

$$F_{TB} = 290.83\, V_s^{-0.503}\, MRR^{0.516}\, D^{-0.244}$$

The factors relating to metal removal rate are presented in a slightly different manner. Tsuwa separates the infeed which is raised to a power (0.78 for normal force and 0.83 for tangential force) and the width of the cut. In the empirical equations derived here, the metal removal rate per unit width of wheel is used to calculate the forces. Tsuwa's work was carried out using only one dress lead. From the work carried out here, it has been shown that incorporation of the factor of dress lead is essential. Although the factor of workspeed was not included in the expression derived for base forces, it would appear that the exponent derived by Tsuwa is too high even allowing for the fact that values in m/min were used.

Subsequent treatment of the problem of prediction of force differs from that of other researchers, but it is thought that the method derived here will be more acceptable to users as it utilises values of dress lead, metal removal rate and metal removed, as opposed to values of wear flat area, contact pressure and length of arc. The values used here are those that can be readily specified whereas those used in other derivations need to be determined by experiment.

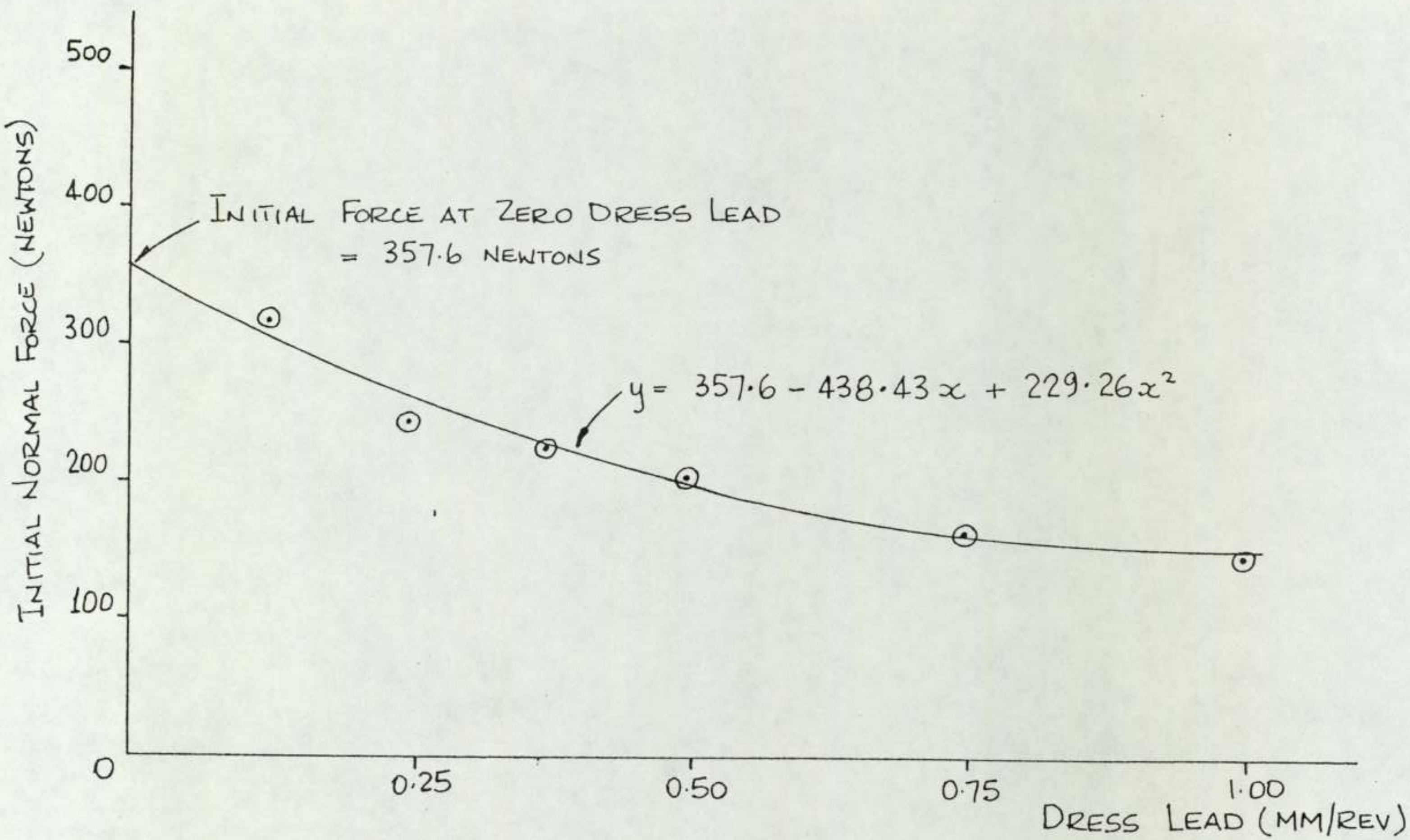


Fig67 INITIAL NORMAL FORCE vs. DRESS LEAD

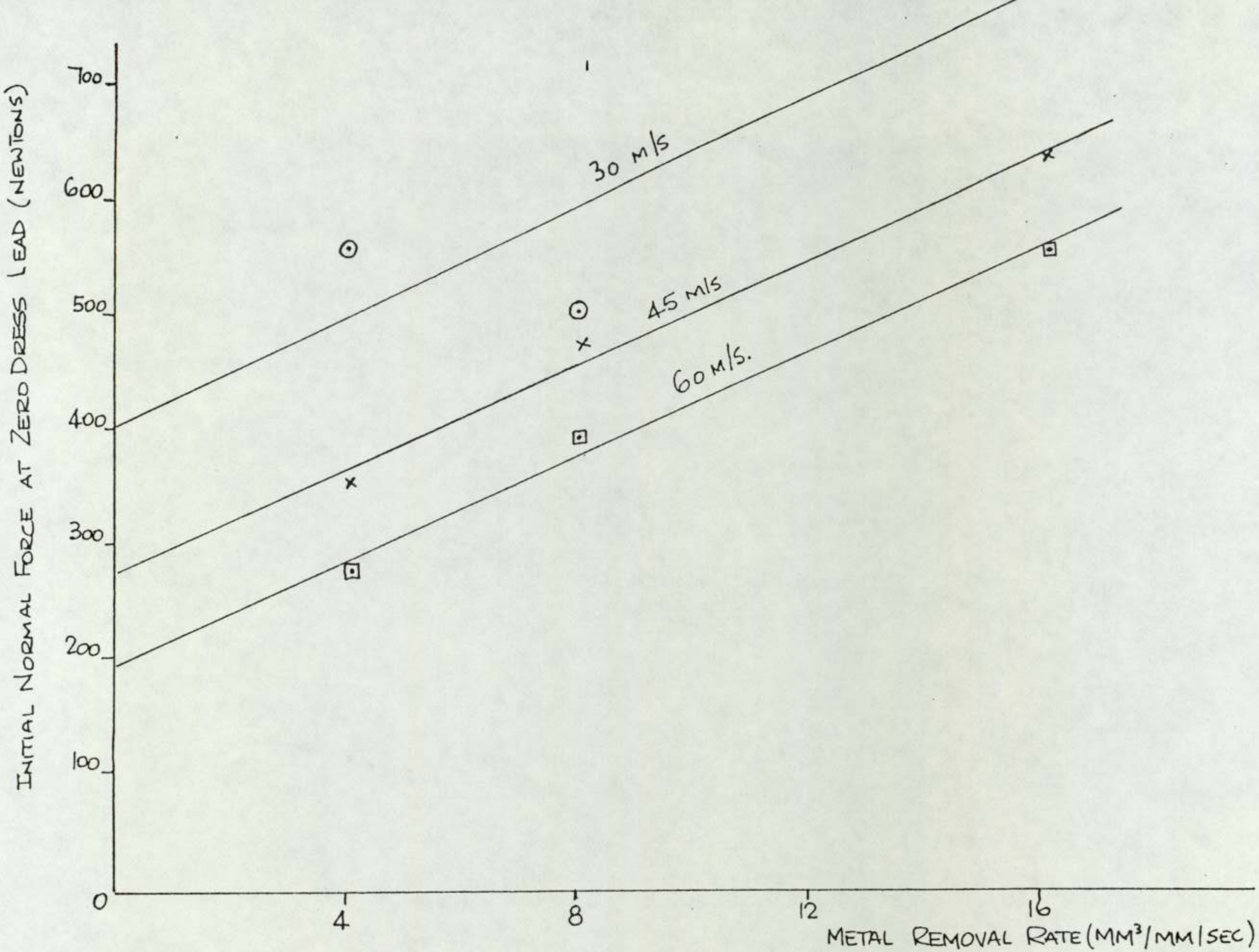


Fig68 BASE NORMAL FORCES

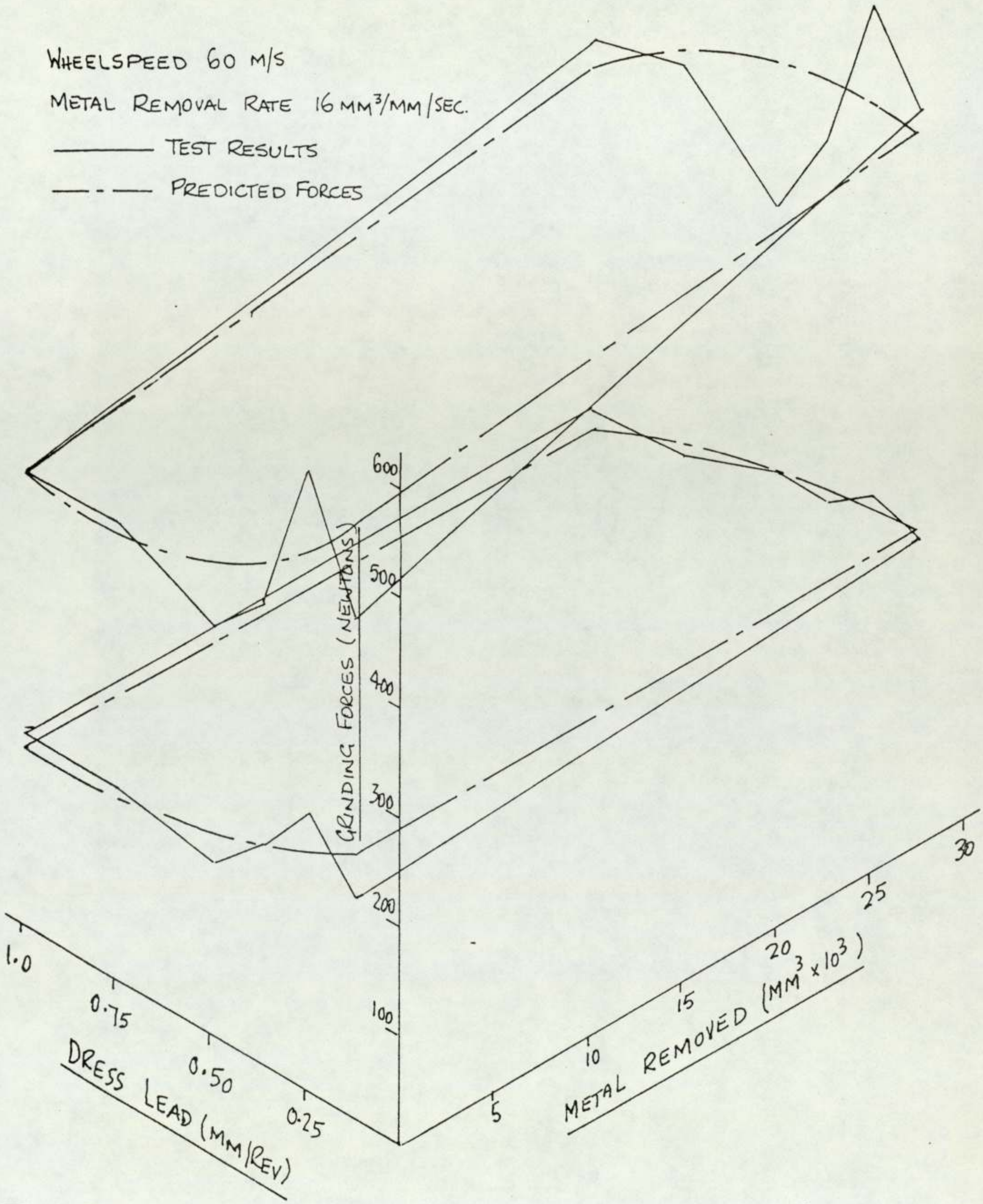


Fig 69 PREDICTED AND ACTUAL FORCES

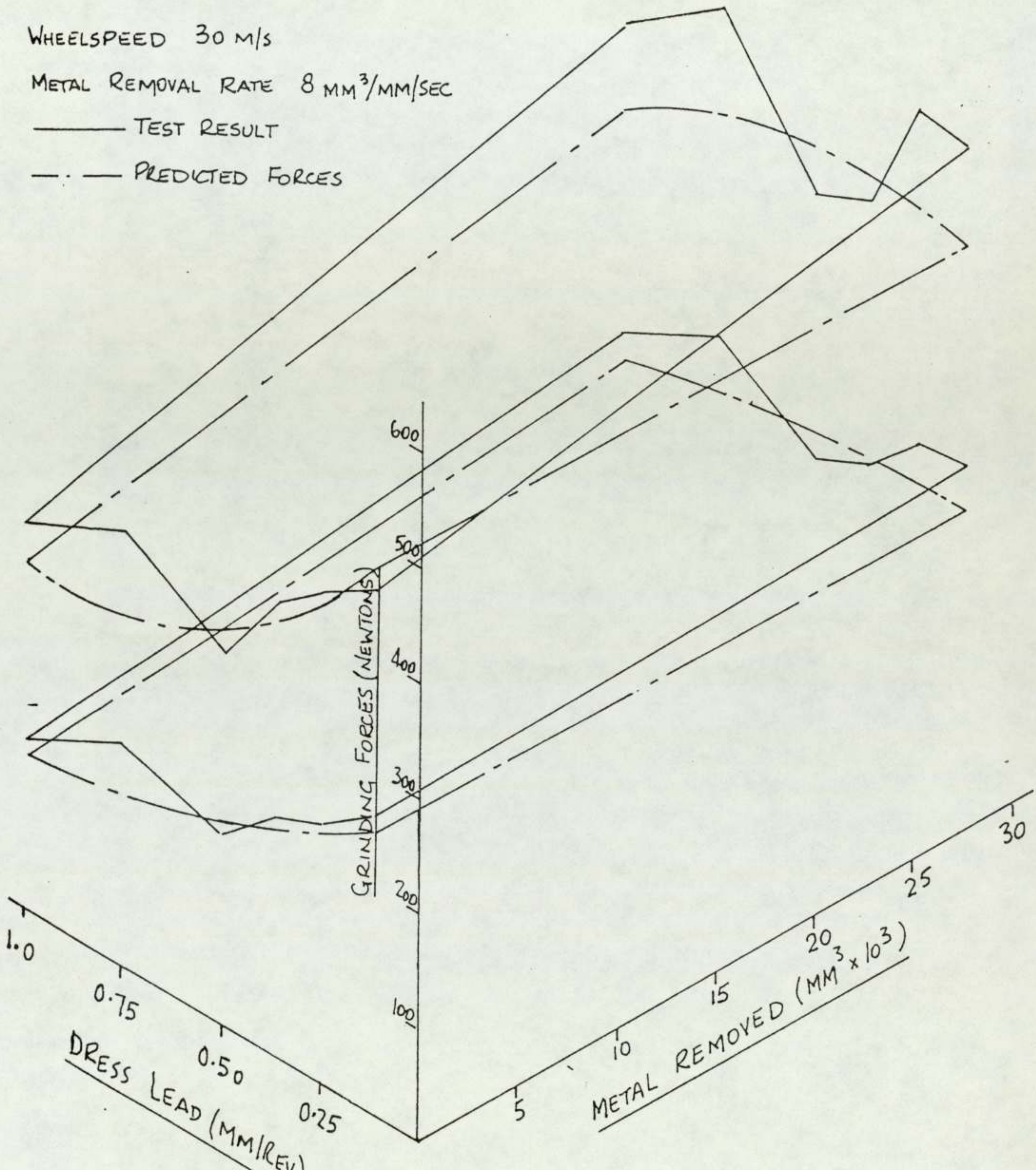


Fig 70 PREDICTED AND ACTUAL FORCES

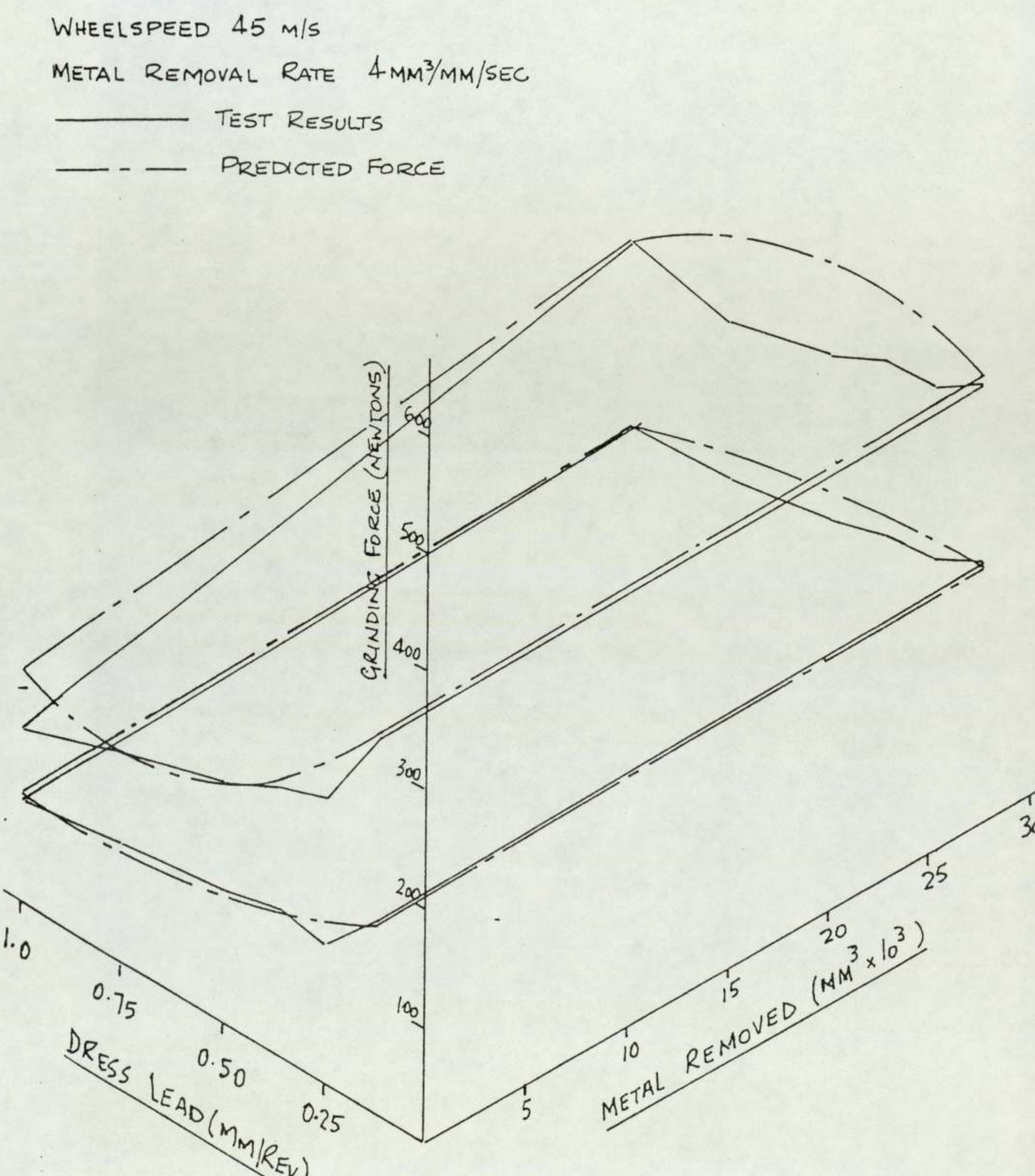


Fig 71 PREDICTED AND ACTUAL FORCES

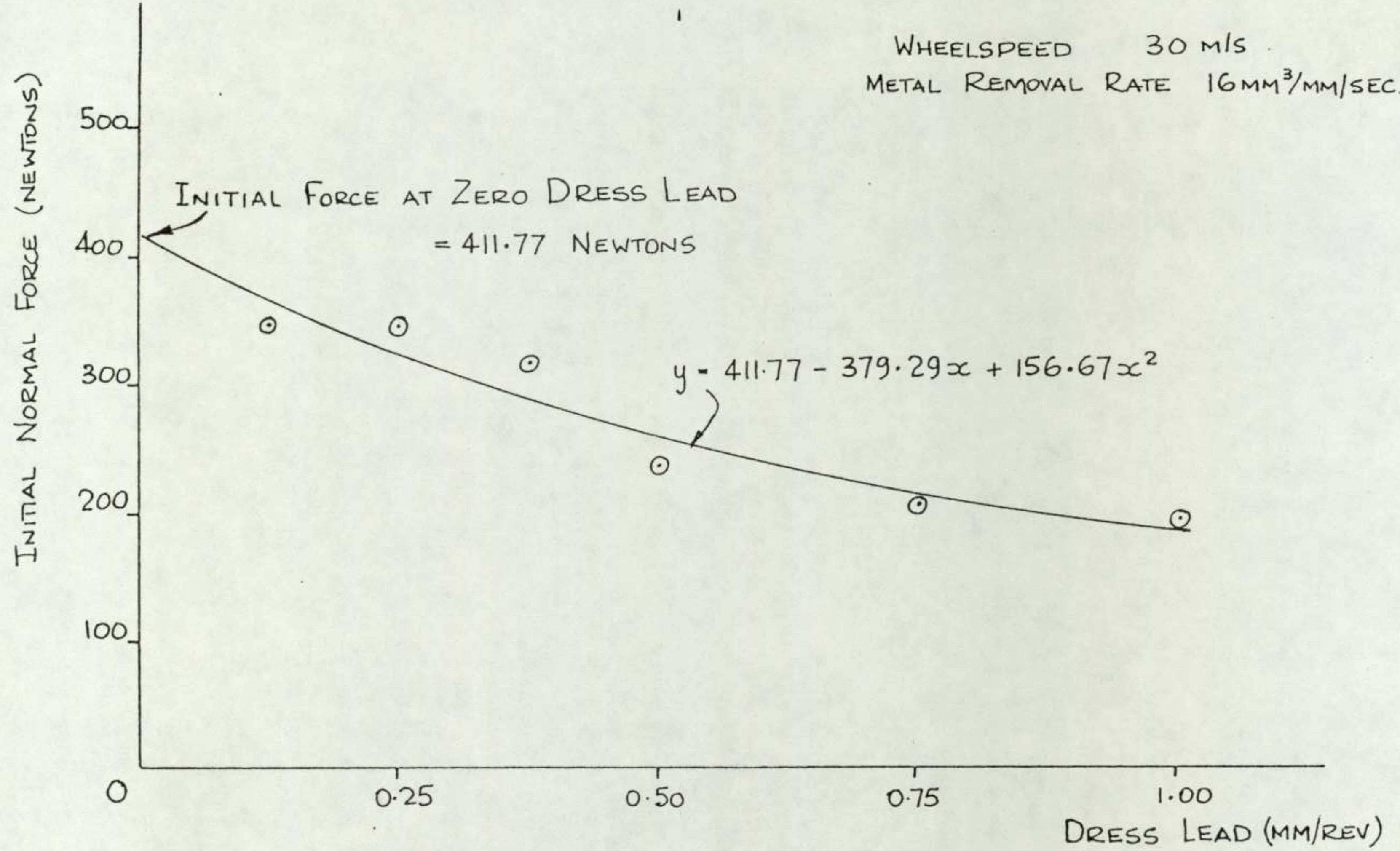


Fig 72 INITIAL TANGENTIAL FORCE vs. DRESS LEAD

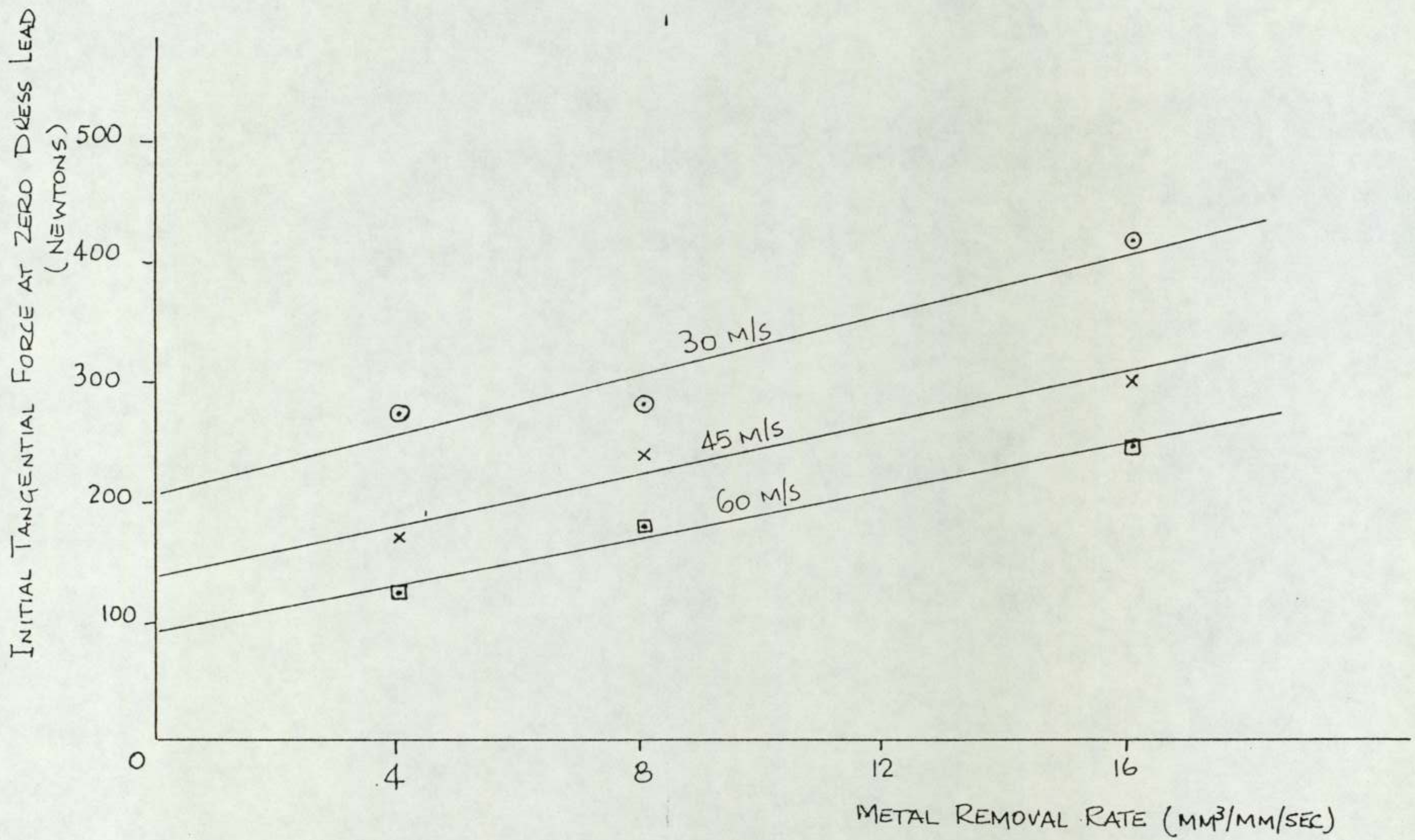


Fig 73 BASE TANGENTIAL FORCES

CHAPTER 7

CONCLUSIONS

(i) Dressing Tools

The use of multi point tooling will give higher grinding ratios in comparison with a single point dressing tool under the same dressing conditions. There is no significant difference between the levels of surface finish or grinding forces under equivalent conditions.

The multi point tool however presents problems when increased metal removal rates are required. The tendency to produce a smoother wheel surface reduces the metal removal capability of the wheel due to the decreased chip clearance. Therefore the amount of useful life in the steady state wear phase is reduced. This effect can be overcome to a certain extent by applying higher dress leads.

(ii) Wheelspeed

In the work carried out here the tests have all been made with a view to improving the characteristics of the workpiece. Increased wheelspeed has been shown to give an improvement in grinding ratio, a reduction in surface roughness and a reduction in both normal and tangential forces.

(iii) Dress Lead

As dress lead is increased, a more open freer cutting wheel results, grinding ratios are lower and a poorer surface finish results. If consistent levels of surface finish are required, it is recommended that dress leads in excess of 0.50 mm/rev are not applied.

Both normal and tangential forces are found to be lower as the dress lead is increased. The relationship between dress lead and grinding force undergoes a change when the steady state wear phase is attained, but the characteristics of the initial preparation are retained throughout the useful life of the wheel. Due to this change of relationship, it is essential to consider both phases of wheel wear when predicting grinding forces.

(iv) Metal Removal Rate

As metal removal rate is increased, there will be a reduction in grinding ratio and an increase in the grinding forces generated.

Variations in metal removal rate do not have a direct effect on surface finish but due to interactions with wheelspeed and dress lead, increases in metal removal rate tend to lead towards poorer surface finish.

(v) Wheel Grade

At high wheelspeeds and metal removal rates the hardness of the wheel will affect grinding performance. The selection of a softer grade of wheel will lead to lower grinding forces but the overall wear of wheel will be increased. However, the grinding ratio will not be directly affected by an alteration of wheel grade. In addition, there is a tendency towards poorer surface finish as the hardness of the wheel is reduced.

(vi) Workspeeds

As workspeed is reduced when grinding at high wheelspeeds, it was found that both the normal and tangential forces were reduced. Ratios of 60:1 between wheelspeed and workspeed are found to be inappropriate and ratios in excess of 100 should be considered.

Workspeed cannot be conclusively shown to have an affect on wheel wear. As the second series of tests were limited in range, it would be advisable to extend this range before making definite conclusions.

(vii) The relationship between normal and tangential force

Normal and tangential forces have been shown to be related to a frictional coefficient, μ. This coefficient will depend upon the values of metal removal rate, wheelspeed and dress lead.

It has been found that the values for the coefficient of friction will be lowest when the heat input to the process is highest. Thus the minimum values for the coefficient of friction are attained when the values for metal removal rate and wheelspeed are at their highest.

(viii)

As a result of this work, empirical formulae have been advanced to enable the prediction of grinding forces to be made using parameters commonly associated with the grinding process. Application of these formulae could be useful both in designing and operating grinding machines, whereas previously measurements had to be made practically or calculations made on the basis of experimental readings.

CHAPTER 8

FUTURE WORK

The results of this work are entirely based on the use of single and multi point diamond dressing tools. Although the majority of wheel dressing operations are carried out using these tools, there are two alternative methods of dressing that have not been considered here. These alternative methods are the use of crush dressing and diamond roller dressing techniques. Both these methods have been the subject of some study by other researchers and it is known that they will produce wheel surfaces with different cutting characteristics to those obtained using single and multi point diamonds. It is therefore recommended that studies be undertaken to determine the degree of interrelation between the dressing processes.

During testing the wheel specification and the workpiece speed were varied only on tests at high metal removal rates and high workspeeds. It would be advantageous if further metal removal rate and wheelspeed combinations were investigated to confirm the conclusions drawn here. In addition, the workpiece specification was held constant and obviously an index based on workpiece characteristics is required in order to fully predict grinding forces.

When grinding is to be carried out at high wheelspeeds, it would be advantageous if dressing operations were carried out at the operating wheelspeed. Dressing at higher wheelspeeds will obviously incur an increased penalty in terms of diamond wear. At higher wheelspeeds the traverse rate of the diamond can be adjusted to maintain a constant dress lead but the nature of the wheel surface may well be altered due to the effects of the increased wheelspeed. A certain amount of work has been carried out to determine the effects of dressing at higher wheelspeeds but not enough to draw firm conclusions.

CHAPTER 9

REFERENCES

1. D W ANDERSON
"Right Dress"
Grinding and Finishing, December 1967

2. D M BUSCH
"The Dressing of Grinding Wheels"
De Beers Industrial Diamond Division, London

3. MERLIJN and DRUKKER
"Getting the best out of Diamond Dressers and Truers"
Cutting Tool Engineering, June 1967

4. ANON
"Dressing of Wheels for Cylindrical Grinding"
Published by Production Engineering Research Association

5. J E SELBY
"Dressing Abrasive Grinding Wheels with Diamond Tools"
De Beers Industrial Diamond Division, London

6. G PAHLITZSCH
"Scientific Data on the use of Diamonds in Finishing Techniques"
Industrial Diamond Review, V 27, 1967

7. ANON

"Understanding Wheel Dress"

Metalworking Production, June 1969

8. T J VICKERSTAFF

"Diamond Dressing - its effect on work surface roughness"

Industrial Diamond Review, July 1970

9. G PAHLITZSCH and J APPUN

"Effect of Trueing Conditions on Circular Grinding"

Industrial Diamond Review, V 14, September/October 1954

10. G PAHLITZSCH and W THOEING

"New Research into the Trueing Process in Grinding"

Industrial Diamond Review, V 19, May/June/July 1959

11. H KALISZER and G TRMAL

"Effect of Dressing upon Grinding Performance"

Annals of CIRP, V 25 n 2 1976

12. V PACITTI and C RUBENSTEIN

"The Influence of dressing depth of cut on the performance of a single point diamond dressing alumina grinding wheel"

Int J Mach Tool Des Res, V 12, 1972

13. E J PATTINSON and A J W CHISHOLM

"The effect of Dressing Techniques on Grinding Wheel Wear"

Int Conf on Manufacturing Technology, Ann Arbor, Michigan 1967

14. H TSUWA

"An investigation of Grinding Wheel Cutting Edges"

Transactions of ASME, Journal of Engineering for Industry, 1964

15. R P LINDSAY

"Dressing and its effect on Grinding Performance"

ASTME, Creative Manufacturing Seminars, Paper MR69-568, 1969

16. S J PANDE and G K LAL

"Effect of Dressing on Grinding Wheel Performance"

Int J Machine Tool Des Res, V 19, 1979

17. A R THORN

"The effect of Grinding Wheel Speed on the life of Single Point Tools"

MTIRA Report to Advisory Panel on Grinding Machines

18. R FURUICHI, M NAKAYAMA and T DOI

"Influence of Dressing Conditions of Grinding Wheel"

Bulletin of JSME, V10, n 38, 1967

19. J M BRECKER

"Wheel Dressing Variations influencing Grinding"

SME Tech Paper, MR75-104, 1975

20. R C FISHER

"The Twelve Diamond Dressing Variables"

Cutting Tool Engineering, April 1973

21. H GRISBROOK, R H HOLLIER and P G VARLEY
"Related Patterns of Grinding Forces, Wheel Wear and Surface Finish"
Int J Prod Res, V 1, 1962

22. C RUBENSTEIN
"The Mechanics of Grinding"
Int J Mach Tool Des Res, Vol 12, 1972

23. J KOLOC
"On the Wear of Grinding Wheels"
Microtecnic, V XIII, n 1, 1959

24. S MALKIN
"The Wear Mechanisms of Grinding Wheels"
Abrasive Engineering, October 1969

25. C P BHATEJA, E J PATTINSON and A W J CHISHOLM
"The Influence of Dressing on the Performance of Grinding Wheels"
Annals of CIRP, V21/1, 1972

26. E R MARSHALL and M C SHAW
"Forces in Dry Surface Grinding"
Transactions of ASME, January 1952

27. H YOSHIKAWA
"Criterion of Grinding Wheel Tool Life"
Japan Soc Precision Eng - Bul V 1, n 1, October 1963

28. H TSUWA, H YAMADA and S KAWAMURA
"The Change of the Grinding Froce during Surface Grinding Process"
Bull Japan Soc of Prec Eng, Vol 10, No 1, March 1976

29. R S HAHN and R P LINDSAY
"Principles of Grinding" Part IV
Machinery (NY) October 1971

30. R P LINDSAY
"On the metal removal and wheel removal parameters, surface finish and geometry and thermal damage in precision grinding"
PhD Thesis, Worcester Poly Inst, 1971

31. T J VICKERSTAFF
"A study of some factors which influence surface finish in the grinding process"
PhD Thesis, University of Aston in Birmingham, 1974

32. S HERBERT
"Dressing Costs Down - Productivity Up"
Industrial Diamond Review, October 1972

33. E L BROWN, F L SCHIERLOH and A R McMILLAN
"High Speed OD Plunge Grinding"
SME Tech Paper, MR79-952

34. ANON
"High Speed Plunge Grinding"
Manuf Eng, V 82, no 6

35. V I MUTSYANGO
"Effect of High Speed Grinding on Surface Quality"
Machines and Tooling, V 49, no 11

36. B GOLDING et al
"Recent Research and Development in Grinding"
Annals of CIRP Vol 21/2, 1972

37. J PETERS, K V LEUVEN and R AERENS
"Evaluation of some factors influencing Tool Life in Plunge Grinding"
Annals of CIRP, Vol 26, n 1/2, 1977

38. R W MAYNE and S MALKIN
"Parameter Optimisation of Steel Grinding Process"
J Eng Ind, V 98 (1), 1976

39. H OPITZ and K GUHRING
"High Speed Grinding"
Annals of CIRP, V 16, n 1, 1968

40. N N Z GINDY and T J VICKERSTAFF
"Crush Dressing of Grinding Wheels for Plunge Cut Cylindrical Grinding"
Machine Tool Design & Research Conf Proc, 1981

41. D BROUGH, W F BELL and W B ROWE
"Achieving and monitoring High Rate Centreless Grinding"
Machine Tool Design & Research Conf Proc, 1981

42. E J KRABACHER
"Factors Influencing the performance of Grinding Wheels"
Journal of Engineering for Industry, August 1959

43. J PEKLENIK
"Grinding Fundamentals II"
ASME Int Conf on Prod Eng Res, September 1963

44. G PAHLITZSCH and H HELMERDIG
"Bestimmung und Bedentung der Spandicke beim Schleifen"
Der Betrieb, Nos 11, 12, 1943

45. G S REICHENBACH, J E MAYER, S KALPAKCIOGLU and M C SHAW
"The Role of Chip Thickness in Grinding"
Trans ASME (pp847-859), 1956

46. J E MIDDLE
"Grinding Equivalent and Grinding Ratio as Parameters for Grinding Wheel Wear"
Proc Inst of Production Engineers, pp637-654, 1965

47. M C SHAW
"The Grinding of Metals"
Conf on Technology of Engineering Manufacture, 25-27th March 1958

48. N H NIE, C H HULL, J G JENKINS, K STEINBRENNER and D H BENT
"Statistical Package for the Social Sciences" - 2nd Edition
McGraw Hill Book Co

49. J N GREENHOW and C RUBENSTEIN
"The Dependence of Cutting Force on Feed and Speed in Orthogonal Cutting with Worn Tools"
Int J Mach Tool Des Res, V 9, 1969

Appendix 1

DETAILS OF GRINDING MACHINE

Type	Jones and Shipman Hydraulic Precision Grinder	
	Model 1051 Type E	
	Plain Cylindrical Model (modified by makers)	
Capacities	Max Diameter swing	10"
	Max grinding length	27"
	Traverse speed range	3" to 240" in/min (hydraulic)
	Traverse speed range	0 - 30 in/min (motorised)
	Workhead speeds	40, 60, 90, 140, 210, 320 RPM
	Workhead HP	$\frac{3}{4}$
	Wheel Size	18 x 2 x 8
	Wheelhead HP	10
	Grinding Wheel Speeds	inf variable to 2700 RPM
	Coolant Tank Capacity	450 litres
	Coolant Flow Rate (max)	135 litres/min

Appendix 2

Kistler Type 9251 d e Quartz Force Transducer

Measuring ranges with an external preload of		2500 kp
Compression (+) traction (-) z axis		±500 kp
Shear (x, y - axis)		±250 kp
Resolution		0.001 kp
Overload		20%
Sensitivity	Compression (z axis)	41 pC/kp
	Shear (x, y axis)	75 pC/kp
Rigidity	Z direction	85 kp/μm
	x, y direction	30 kp/μm
Resonant frequency in Z direction loaded with 400 g		8 KHz
Linearity	(max error)	±1%
Cross influence of components		< 5%
Insulation resistance		$5 \times 10^3 \Omega$
Capacity		30 pF
Temperature coefficient		$0.02\%/^0C$
Working temperature range		-60 to 150^0C

APPENDIX 3

Kistler Type 5001 Charge Amplifier

Measuring Ranges, 12 steps, 1: 2 : 5 : ...,	
Continuous 1 : 10	pC ±10 - 500,000
Range capacitors 1 : 2 : 5 : ...,	pF 10 - 50,000
Calibration factor setting	pC/MU 0.1 - 110,000
(MU = Mechanical Unit)	
Output Voltage	V ±10
Voltage saturation, no load	V < ±15
with load of 50 mA	V > ±10
Output current	mA eff 50
Output impedance A1	Ω 100
Output impedance A2 (inc 50 mA slow blow fuse)	Ω 0.5 (35)
Max input voltage w/o damage	V ±125 short peak
Insulation at input	Ω 10^{14}
Frequency range with standard filter	kHz 0-180
Time constant 'Long'	S 1,000 - 100,000
'Medium'	S 1 - 5,000
'Short'	S 0.01 - 50
Bleeder resistance (long, medium, short)	Ω 10^{14}, 10^{11}, 10^{9}
Linearity (max error)	% <0.05
Accuracy of ranges	% ±1
(of the two most sensitive)	% ±3
Max capacity at input	pF 100,000

Appendix 4

CHEMICAL ANALYSIS OF EN9

Carbon	0.50 - 0.60
Silicon	0.05 - 0.35
Manganese	0.50 - 0.60
Sulphur	0.060 Max
Phosphorus	0.060 Max

-

Appendix 5

Details of chart ranges and Cut-off for Talysurf 3

(a) Ranges of magnifications and scales

Setting	Magnification	Chart Full Scale		CLA Index Full Scale	
		Imperial µ in	Metric Microns	Imperial µ in	Metric Microns
1	1000	2000	50	200	5.0
2	2000	1000	25	100	2.5
3	5000	400	10	40	1.0
4	10000	200	5	20	0.5
5	20000	100	2.5	10	0.25
6	50000	40	1	4	0.1

(b) Meter Cut Offs and Stroke Lengths

Meter Cut-off	Operative Traverse Length	Effective No of samples
0.01"	0.07"	7
0.03"	0.15"	5
0.1"	0.30"	3

APPENDIX 6

SELECTION OF SINGLE POINT DIAMOND

Points Allowance	Grinding Wheel Dimensions		Abrasive	Grit Size	Grade	Bond
	Diameter (in)	Width (in)				
1	up to 6	1	Aluminium Oxide	46-80	Soft	Vitrified
2	6 - 12	2		-	Medium	Shellac
3	12 - 16	-		90 & finer		
4	16 - 20	3				Resinoid
5	20 - 24	-				
6	24 - 30	4	Silicon Carbide	12-36	Hard	Rubber
7	30 - 36	-				
8	36 - 40	5				
10		6				
12		7			Very Hard	
14		8				
16		9				
18		10				

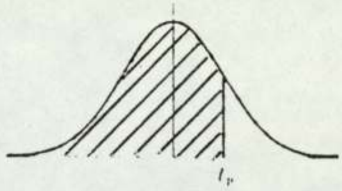
Factor	Points
Wheel dia (18") -	4
Wheel width (2")	2
Grit Type (Aluminium Oxide)	1
Grit Size (60)	1
Grade (K)	1
Bond (Vitrified)	1
Total	11

DIAMOND SIZE (MINIMUM) 1.83 carats

To obtain diamond size the total is divided by 6.

Appendix 7

PERCENTILE VALUES (t_p)
for
STUDENT'S t DISTRIBUTION
with ν degrees of freedom
(shaded area = p)



t_p

ν	$t_{0.995}$	$t_{0.99}$	$t_{0.975}$	$t_{0.95}$	$t_{0.90}$	$t_{0.80}$	$t_{0.75}$	$t_{0.70}$	$t_{0.60}$	$t_{0.55}$
1	63·66	31·82	12·71	6·31	3·08	1·376	1·000	0·727	0·325	0·158
2	9·92	6·96	4·30	2·92	1·89	1·061	0·816	0·617	0·289	0·142
3	5·84	4·54	3·18	2·35	1·64	0·978	0·765	0·584	0·277	0·137
4	4·60	3·75	2·78	2·13	1·53	0·941	0·741	0·569	0·271	0·134
5	4·03	3·36	2·57	2·02	1·48	0·920	0·727	0·559	0·267	0·132
6	3·71	3·14	2·45	1·94	1·44	0·906	0·718	0·553	0·265	0·131
7	3·50	3·00	2·36	1·90	1·42	0·896	0·711	0·549	0·263	0·130
8	3·36	2·90	2·31	1·86	1·40	0·889	0·706	0·546	0·262	0·130
9	3·25	2·82	2·26	1·83	1·38	0·883	0·703	0·543	0·261	0·129
10	3·17	2·76	2·23	1·81	1·37	0·879	0·700	0·542	0·260	0·129
11	3·11	2·72	2·20	1·80	1·36	0·876	0·697	0·540	0·260	0·129
12	3·06	2·68	2·18	1·78	1·36	0·873	0·695	0·539	0·259	0·128
13	3·01	2·65	2·16	1·77	1·35	0·870	0·694	0·538	0·259	0·128
14	2·98	2·62	2·14	1·76	1·34	0·868	0·692	0·537	0·258	0·128
15	2·95	2·60	2·13	1·75	1·34	0·866	0·691	0·536	0·258	0·128
16	2·92	2·58	2·12	1·75	1·34	0·865	0·690	0·535	0·258	0·128
17	2·90	2·57	2·11	1·74	1·33	0·863	0·689	0·534	0·257	0·128
18	2·88	2·55	2·10	1·73	1·33	0·862	0·688	0·534	0·257	0·127
19	2·86	2·54	2·09	1·73	1·33	0·861	0·688	0·533	0·257	0·127
20	2·84	2·53	2·09	1·72	1·32	0·860	0·687	0·533	0·257	0·127
21	2·83	2·52	2·08	1·72	1·32	0·859	0·686	0·532	0·257	0·127
22	2·82	2·51	2·07	1·72	1·32	0·858	0·686	0·532	0·256	0·127
23	2·81	2·50	2·07	1·71	1·32	0·858	0·865	0·532	0·256	0·127
24	2·80	2·49	2·06	1·71	1·32	0·857	0·685	0·531	0·256	0·127
25	2·79	2·48	2·06	1·71	1·32	0·856	0·684	0·531	0·256	0·127
26	2·78	2·48	2·06	1·71	1·32	0·856	0·684	0·531	0·256	0·127
27	2·77	2·47	2·05	1·70	1·31	0·855	0·684	0·531	0·256	0·127
28	2·76	2·47	2·05	1·70	1·31	0·855	0·683	0·530	0·256	0·127
29	2·76	2·46	2·04	1·70	1·31	0·854	0·683	0·530	0·256	0·127
30	2·75	2·46	2·04	1·70	1·31	0·854	0·683	0·530	0·256	0·127
40	2·70	2·42	2·02	1·68	1·30	0·851	0·681	0·529	0·255	0·126
60	2·66	2·39	2·00	1·67	1·30	0·848	0·679	0·527	0·254	0·126
120	2·62	2·36	1·98	1·66	1·29	0·845	0·677	0·526	0·254	0·126
∞	2·58	2·33	1·96	1·645	1·28	0·842	0·674	0·524	0·253	0·126

Source**:** R. A. Fisher and F. Yates, *Statistical Tables for Biological, Agricultural and Medical Research* (5th edition), Table III, Oliver and Boyd Ltd., Edinburgh, by permission of the authors and publishers.

Appendix 8

Analysis of Variance

```
*****************************************************************************
*****************************************************************************
***********
** Pdn    6   3199-ERF                 TERMINAL: 47                 6 JAN 82 16:
***********
*****************************************************************************
*****************************************************************************

NUMBERED           YES
RUN NAME           THREE WAY ANOVA
FILE NAME          ANOV5
VARIABLE LIST      F,M,D,V
INPUT MEDIUM       CARD
INPUT FORMAT        FREEFIELD(4F0.0)
N OF CASES         27
VAR LABELS         F   ACTUAL NORMAL FORCE AT 500MM3/
                   M      METAL REMOVAL RATE/
                    D     DRESS LEAD/
                   V      WHEELSPEED/
VALUE LABELS          M  (-1) 4  (0)  8  (1)  16/
                    D  (-1) 0.25 (0)  0.5  (1)  0.75/
                    V  (-1) 30  (0) 45  (1)  60/
ANOVA                F BY M,D,V (-1,1)/
OPTIONS             4
STATISTICS          2
READ INPUT DATA
203  -1  -1  -1
406  0  -1  -1
572  1  -1  -1
257  -1  -1  0
347  0  -1  0
518  1  -1  0
230  -1  -1  1
283  0  -1  1
612  1  -1  1
158  -1  0  -1
296  0  0  -1
372  1  0  -1
168  -1  0  0
332  0  0  0
423  1  0  0
158  -1  0  1
459  0  0  1
281  1  0  1
245  -1  1  -1
352  0  1  -1
457  1  1  -1
163  -1  1  0
292  0  1  0
411  1  1  0
143  -1  1  1
210  0  1  1
438  1  1  1
SAVE FILE
FINISH
STOP SPSS
EOF..
```

```
****************************************************************************************************************
****************************************************************************************************************
***********                                                                                      ***************
** Pdn    6   3199-ERF              TERMINAL: 47              6 JAN 82 16:43:03                  ****** V002 ***
***********                                                                                      ***************
****************************************************************************************************************
****************************************************************************************************************

1STATISTICAL PACKAGE FOR THE SOCIAL SCIENCES  ---  BATCH SYSTEM                6 JAN 82 16:31:20        PAGE    1
 --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
 SPSS FOR HARRIS/VULCAN 09A. VERSION H. RELEASE 8.1, AUGUST 15, 1980
-DEFAULT SPACE ALLOCATION..       ALLOWS FOR..    67 TRANSFORMATIONS
 WORKSPACE      11844 DBLWORDS                   270 RECODE VALUES + LAG VARIABLES
 TRANSPACE       1691 DBLWORDS                  1085 IF/COMPUTE OPERATIONS

                    1 NUMBERED         YES
                    2 RUN NAME         THREE WAY ANOVA
                     3 FILE NAME        ANOV5
                     4 VARIABLE LIST    F,M,D,V
                     5 INPUT MEDIUM     CARD
                     6 INPUT FORMAT      FREEFIELD(4F0.0)
                     7 N OF CASES       27
                     8 VAR LABELS       F   ACTUAL NORMAL FORCE AT 500MM3/
                     9                  M      METAL REMOVAL RATE/
                    10                  D     DRESS LEAD/
                    11                  V     WHEELSPEED/
                    12 VALUE LABELS       M  (-1) 4  (0)  8  (1)  16/
                    13      ,           D  (-1) 0.25 (0)  0.5  (1)  0.75/
                    14                  V  (-1) 30  (0) 45  (1)  60/
                    15 ANOVA             F BY M,D,V (-1,1)/
                    16 OPTIONS          4
                    17 STATISTICS       2
O'ANOVA' PROBLEM REQUIRES       559 DBLEWORDS OF SPACE.

                    18 READ INPUT DATA
1THREE WAY ANOVA                                                               6 JAN 82 16:31:20        PAGE    2
 --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
 FILE     ANOV5  (CREATED   6 JAN 82 16:31:20)
0* * * * * * * * * A N A L Y S I S   O F   V A R I A N C E * * * * * * * * * * *
                   F        ACTUAL NORMAL FORCE AT 500MM3
             BY    M        METAL REMOVAL RATE
                   D        DRESS LEAD
                   V        WHEELSPEED
 * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
-                                          SUM OF                 MEAN          SIGNIF
 SOURCE OF VARIATION                      SQUARES      DF        SQUARE      F    OF F
0MAIN EFFECTS                           354774.000      6     59129.000  11.661  0.001
      M                                 309549.407      2    154774.704  30.524  0.000
      D                                  41783.185      2     20891.593   4.120  0.059
      V                                   3441.407      2      1720.704   0.339  0.722
02-WAY INTERACTIONS                      54048.222     12      4504.019   0.888  0.588
      M         D                        42422.593      4     10605.648   2.092  0.174
      M         V                          402.370      4       100.593   0.020  0.999
      D         V                        11223.259      4      2805.815   0.553  0.703
0EXPLAINED                              408822.222     18     22712.346   4.479  0.018
0RESIDUAL                                40564.296      8      5070.537
0TOTAL                                  449386.519     26     17284.097
-       27 CASES WERE PROCESSED
         0 CASES (  0.0 PCT) WERE MISSING
```

```
1THREE WAY ANOVA                                                                  6 JAN 82 16:31:20      PAGE    3
  --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
OCPU TIME REQUIRED..      1.67 SECONDS
 ELAPSED WALL TIME..         4 SECONDS



                19 SAVE FILE
OFILE   ANOV5  HAS BEEN SAVED WITH    7 VARIABLES..

   SEGNUM    SUBFIL    CASWGT    F          M          D          V
0
                                 THE SUBFILES ARE..
0                                            NO OF
                                 NAME        CASES

                                 ANOV5          27
0
                20 FINISH
OCPU TIME REQUIRED..      0.22 SECONDS
 ELAPSED WALL TIME..         1 SECONDS
1          NORMAL END OF SPSS RUN.
             20 COMMAND RECORDS READ
              0 ERRORS DETECTED

************************************************************************************************************************
************************************************************************************************************************
***********                                                                                             ***************
** Pdn    6   3199-ERF          TERMINAL: 47          6 JAN 82 16:43:47       No of Pages     2          ****** V002 ***
***********                                                                                             ***************
************************************************************************************************************************
************************************************************************************************************************
```

```
*************************************************************************
*************************************************************************
***********
** Pdn    6   3199-ERF              TERMINAL: 47              6 JAN 82 16:
***********
*************************************************************************
*************************************************************************

1 RUN NAME          ONEWAY DRESS LEAD
2 GET FILE         ANOV5
3 ONEWAY           F BY D(-1,1)
4                  POLYNOMIAL = 2/
5 STATISTICS        1
6 FINISH
7 STOP SPSS
EOF..

*************************************************************************
*************************************************************************
***********
** Pdn    6   3199-ERF              TERMINAL: 47              6 JAN 82 16:
***********
*************************************************************************
*************************************************************************
```

```
**************************************************************************************************************************************
**************************************************************************************************************************************
***********                                                                                                           ***************
** Pdn   6   3199-ERF              TERMINAL: 47              6 JAN 82 16:43:58                                        ****** V002 ***
***********                                                                                                           ***************
**************************************************************************************************************************************
**************************************************************************************************************************************

1STATISTICAL PACKAGE FOR THE SOCIAL SCIENCES  ---  BATCH SYSTEM              6 JAN 82 16:34:39         PAGE    1
  --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
 SPSS FOR HARRIS/VULCAN 09A, VERSION H, RELEASE 8.1, AUGUST 15, 1980
-DEFAULT SPACE ALLOCATION..        ALLOWS FOR..    67 TRANSFORMATIONS
 WORKSPACE      11844 DBLWORDS                     270 RECODE VALUES + LAG VARIABLES
 TRANSPACE       1691 DBLWORDS                    1085 IF/COMPUTE OPERATIONS

                       1 RUN NAME         ONEWAY DRESS LEAD
                       2 GET FILE        ANOV5
0
0                                    FILE   ANOV5  HAS   7 VARIABLES

                                     THE SUBFILES ARE..
0                                                NO OF
                                     NAME        CASES

                                     ANOV5         27
0
OCPU TIME REQUIRED..      0.11 SECONDS
 ELAPSED WALL TIME.        0 SECONDS



                       3 ONEWAY           F BY D(-1,1)
                       4                  POLYNOMIAL = 2/
                       5 STATISTICS        1


  ***** ONEWAY PROBLEM REQUIRES        48 DBLEWORDS WORKSPACE *****


1ONEWAY DRESS LEAD                                                            6 JAN 82 16:34:39         PAGE    2
  --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
 FILE      ANOV5  (CREATED   6 JAN 82 16:31:20)

 - - - - - - - - - - - - - - - - - - - - - - - - - - - O N E W A Y - - - - - - - - - - - - - - - - - - - - - - - - -



       VARIABLE    F        ACTUAL NORMAL FORCE AT 500MM3

                                                ANALYSIS OF VARIANCE


                SOURCE                D.F.    SUM OF SQUARES     MEAN SQUARES          F RATIO    F PROB.

           BETWEEN GROUPS               2       41783.1852        20891.5926          1.230     0.3100

                       LINEAR TERM         1        28560.5000        28560.5000          1.682     0.2070
              DEVIATION FROM  LINEAR       1        13222.6852        13222.6852          0.779     0.3863

           WITHIN GROUPS               24      407603.3333        16983.4722
```

```
        TOTAL                          26        449386.5185




                                  STANDARD      STANDARD
 GROUP        COUNT        MEAN   DEVIATION       ERROR      MINIMUM      MAXIMUM       95 PCT CONF INT FOR MEAN

 GRPO            9     380.8889   154.0523      51.3508     203.0000     612.0000      262.4739  TO     499.3038
 GRPOO           9     294.1111   114.2557      38.0852     158.0000     459.0000      206.2865  TO     381.9357
 GRPO1           9     301.2222   119.0124      39.6708     143.0000     457.0000      209.7413  TO     392.7031
OTOTAL          27     325.4074   131.4690      25.3012     143.0000     612.0000      273.4000  TO     377.4148
1ONEWAY DRESS LEAD                                                    6 JAN 82 16:34:39          PAGE    3
  --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
OCPU TIME REQUIRED..     0.46 SECONDS
 ELAPSED WALL TIME..        2 SECONDS



                 6 FINISH
1          NORMAL END OF SPSS RUN.
             6 COMMAND RECORDS READ
             0 ERRORS DETECTED

************************************************************************************************************************
************************************************************************************************************************
***********                                                                                             **************
** Pdn    6    3199-ERF            TERMINAL: 47              6 JAN 82 16:44:35        No of Pages      2      ****** V002 ***
***********                                                                                             **************
************************************************************************************************************************
************************************************************************************************************************
```

Appendix 9

F - Distribution

F-DISTRIBUTION

n_1 (Degrees of freedom of the greater mean square estimate of variance)
n_2 (Degrees of freedom of the lesser mean square estimate of variance)

n_1 / n_2	1	2	3	4	5	6	7	8	9	10	15	oo
1	39.9	49.5	53.6	55.8	57.2	58.2	58.9	59.4	59.9	60.2	61.2	63.3
	161	199	216	225	230	234	257	239	241	242	246	254
	4052	4999	5403	5625	5764	5859	5928	5982	6022	6050	6157	6366
2	8.53	9.00	9.16	9.24	9.29	9.33	9.35	9.37	9.38	9.39	9.42	9.49
	18.5	19.0	19.2	19.2	19.3	19.3	19.4	19.4	19.4	19.4	19.4	19.5
	98.5	99.0	99.2	99.2	99.3	99.3	99.4	99.4	99.4	99.4	99.4	99.5
3	5.54	5.46	5.39	5.34	5.31	5.28	5.27	5.25	5.24	5.23	5.20	5.13
	10.1	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79	8.70	8.53
	34.1	30.8	29.5	28.7	28.2	27.9	27.7	27.5	27.3	27.2	26.9	26.1
4	4.54	4.32	4.19	4.11	4.05	4.01	3.98	3.95	3.94	3.92	3.87	3.76
	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96	5.86	5.63
	21.2	18.0	16.7	16.0	15.5	15.2	15.0	14.8	14.7	14.5	14.2	13.5
5	4.06	3.78	3.62	3.52	3.45	3.40	3.37	3.34	3.32	3.30	3.24	3.10
	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74	4.62	4.36
	16.3	13.3	12.1	11.4	11.0	10.7	10.5	10.3	10.2	10.1	9.72	9.02
6	3.78	3.46	3.29	3.18	3.11	3.05	3.01	2.98	2.96	2.94	2.87	2.72
	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06	3.94	3.67
	13.7	10.9	9.78	9.15	8.75	8.47	8.26	8.10	7.98	7.87	7.56	6.88
7	3.59	3.26	3.07	2.96	2.88	2.83	2.78	2.75	2.72	2.70	2.63	2.47
	5.59	4.74	4.35	4.12	3.97	3.87	3.70	3.73	3.68	3.64	3.51	3.23
	12.2	9.55	8.45	7.85	7.46	7.19	6.99	6.84	6.72	6.62	6.31	5.65
8	3.46	3.11	2.92	2.81	2.73	2.67	2.62	2.59	2.56	2.54	2.46	2.29
	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35	3.22	2.93
	11.3	8.65	7.59	7.01	6.63	6.37	6.18	6.03	5.91	5.81	5.52	4.86
9	3.36	3.01	2.81	2.69	2.61	2.55	2.51	2.47	2.44	2.42	2.34	2.16
	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14	3.01	2.71
	10.6	8.02	6.99	6.42	6.06	5.80	5.61	5.47	5.35	5.26	4.96	4.31
10	3.28	2.92	2.73	2.61	2.52	2.46	2.41	2.38	2.35	2.32	2.24	2.06
	4.96	4.01	3.71	3.48	3.33	3.22	3.14	3.06	3.02	2.98	2.84	2.54
	10.0	7.56	6.55	5.99	5.64	5.39	5.20	5.06	4.94	4.85	4.56	3.91
12	3.18	2.81	2.61	2.48	2.39	2.33	2.28	2.24	2.21	2.19	2.10	1.90
	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80	2.75	2.62	2.30
	9.33	6.93	5.95	5.41	5.06	4.82	4.64	4.50	4.39	4.30	4.01	3.36
15	3.07	2.70	2.49	2.36	2.27	2.21	2.16	2.12	2.09	2.02	1.97	1.76
	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59	2.54	2.40	2.07
	8.68	6.36	5.42	4.89	4.56	4.39	4.14	4.00	3.89	3.80	3.52	2.87

cont.....

Appendix 10

Multiple Linear Regression

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*************************************************************************************
*************************************************************************************
***********
** Pdn    6   3199-ERF                  TERMINAL: 72                  17 DEC 81 16:
***********
*************************************************************************************
*************************************************************************************

RUN NAME          MULTIPLE REGRESSION RUN USING CARD INPUT AND RAW DATA
FILE NAME         FILE 4
VARIABLE LIST     FNB, MRR, VS, DL, DL2, MRRXDL, MRRDL2, VS2DL2
VAR LABELS        FNB      BASE NORMAL FORCE/
                  MRR      METAL REMOVAL RATE/
                  VS       WHEELSPEED/
                  DL       DRESS LEAD/
                  DL2      DL QUAD/
                  MRRXDL   MRR AND DL INTERACT/
                   MRRDL2  MRR AND DL2 INTERACT/
                   VS2DL2  VS2 AND DL2 INTERACT
INPUT FORMAT      FREEFIELD(8F0.0)
PRINT FORMATS     FNB(1) MRR TO VS2DL2(0)
N OF CASES        54
REGRESSION        VARIABLES=FNB, MRR, VS, DL, DL2, MRRXDL, MRRDL2, VS2DL2/
                  REGRESSION=FNB WITH MRR TO VS2DL2(1)
READ INPUT DATA
498  4  30  0.125  0.0156  0.5  0.0625  14.06
458  8  30  0.125  0.0156  1  0.125  14.06
686  16  30  0.125  0.0156  2  0.25  14.06
318  4  45  0.125  0.0156  0.5  0.0625  31.64
417  8  45  0.125  0.0156  1  0.125  31.64
578  16  45  0.125  0.0156  2  0.25  31.64
230  4  60  0.125  0.0156  0.5  0.0625  56.25
357  8  60  0.125  0.0156  1  0.125  56.25
466  16  60  0.125  0.0156  2  0.25  56.25
249  4  30  0.375  0.141  1.5  0.5625  126.56
396  8  30  0.375  0.141  3  1.125  126.56
580  16  30  0.375  0.141  6  2.25  126.56
228  4  45  0.375  0.141  1.5  0.5625  284.77
317  8  45  0.375  0.141  3  1.125  284.77
561  16  45  0.375  0.141  6  2.25  284.77
172  4  60  0.375  0.141  1.5  0.5625  506.25
332  8  60  0.375  0.141  3  1.125  506.25
423  16  60  0.375  0.141  6  2.25  506.25
211  4  30  1  1  4  4  900
337  8  30  1  1  8  8  900
448  16  30  1  1  16  16  900
146  4  45  1  1  4  4  2025
338  8  45  1  1  8  8  2025
425  16  45  1  1  16  16  2025
156  4  60  1  1  4  4  3600
261  8  60  1  1  8  8  3600
411  16  60  1  1  16  16  3600
231  4  30  0.25  0.0625  1  0.25  56.25
430  8  30  0.25  0.0625  2  0.5  56.25
651  16  30  0.25  0.0625  4  1  56.25
242  4  45  0.25  0.0625  1  0.25  126.56
352  8  45  0.25  0.0625  2  0.5  126.56
565  16  45  0.25  0.0625  4  1  126.56
247  4  60  0.25  0.0625  1  0.25  225
```

```
310  8   60  0.25  0.0625  2  0.5  225
565  16  60  0.25  0.0625  4  1  225
187  4   30  0.5  0.25  2  1  225
324  8   30  0.5  0.25  4  2  225
448  16  30  0.5  0.25  8  4  225
201  4   45  0.5  0.25  2  1  506.25
340  8   45  0.5  0.25  4  2  506.25
470  16  45  0.5  0.25  8  4  506.25
182  4   60  0.5  0.25  2  1  900
279  8   60  0.5  0.25  4  2  900
376  16  60  0.5  0.25  8  4  900
235  4   30  0.75  0.5625  3  2.25  506.25
379  8   30  0.75  0.5625  6  4.5  506.25
450  16  30  0.75  0.5625  12  9  506.25
161  4   45  0.75  0.5625  3  2.25  1139.06
264  8   45  0.75  0.5625  6  4.5  1139.06
429  16  45  0.75  0.5625  9  9  1139.06
145  4   60  0.75  0.5625  3  2.25  2025
240  8   60  0.75  0.5625  6  4.5  2025
418  16  60  0.75  0.5625  12  9  2025
FINISH
STOP SPSS
EOF..

****************************************************************************************
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***********
** Pdn    6   3199-ERF                 TERMINAL: 72                     17 DEC 81 16:
***********
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*************************************************************************************************************************
*************************************************************************************************************************
***********                                                                                              ***************
** Pdn    6   3199-ERF              TERMINAL: 72              17 DEC 81 16:39:14                          ****** V001 ***
***********                                                                                              ***************
*************************************************************************************************************************
*************************************************************************************************************************

 1STATISTICAL PACKAGE FOR THE SOCIAL SCIENCES ---  BATCH SYSTEM            17 DEC 81 16:31:38          PAGE    1
  --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
 SPSS FOR HARRIS/VULCAN 09A, VERSION H, RELEASE 8.1, AUGUST 15, 1980
-DEFAULT SPACE ALLOCATION..        ALLOWS FOR..    67 TRANSFORMATIONS
 WORKSPACE      11844 DBLWORDS                    270 RECODE VALUES + LAG VARIABLES
 TRANSPACE       1691 DBLWORDS                   1085 IF/COMPUTE OPERATIONS

                    1 RUN NAME         MULTIPLE REGRESSION RUN USING CARD INPUT AND RAW DATA
                    2 FILE NAME        FILE 4
                    3 VARIABLE LIST    FNB, MRR, VS, DL, DL2, MRRXDL, MRRDL2, VS2DL2
                    4 VAR LABELS       FNB      BASE NORMAL FORCE/
                    5                  MRR      METAL REMOVAL RATE/
                    6                  VS       WHEELSPEED/
                    7                  DL       DRESS LEAD/
                    8                  DL2      DL QUAD/
                    9                  MRRXDL   MRR AND DL INTERACT/
                   10                  MRRDL2   MRR AND DL2 INTERACT/
                   11                  VS2DL2   VS2 AND DL2 INTERACT
                   12 INPUT FORMAT     FREEFIELD(8F0.0)
                   13 PRINT FORMATS    FNB(1) MRR TO VS2DL2(0)
                   14 N OF CASES       54
                   15 REGRESSION       VARIABLES=FNB, MRR, VS, DL, DL2, MRRXDL, MRRDL2, VS2DL2/
                   16                  REGRESSION=FNB WITH MRR TO VS2DL2(1)


  ***** REGRESSION PROBLEM REQUIRES    232 DBLEWORDS WORKSPACE, NOT INCLUDING RESIDUALS *****


                   17 READ INPUT DATA
 1MULTIPLE REGRESSICN RUN USING CARD INPUT AND RAW DATA                    17 DEC 81 16:31:38          PAGE    2
   --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
 FILE      FILE   (CREATED  17 DEC 81 16:31:38)    4
0* * * * * * * * * * * * * * * * * * * * * * * *  M U L T I P L E   R E G R E S S I O N  * * * * * * * * * * * *   VARIABLE LIST
                                                                                                              REGRESSION LIST

 DEPENDENT VARIABLE..        FNB      BASE NORMAL FORCE
0VARIABLE(S) ENTERED ON STEP NUMBER  1.        MRR       METAL REMOVAL RATE

0MULTIPLE R            0.82236                  ANALYSIS OF VARIANCE    DF       SUM OF SQUARES        MEAN SQUARE            F
 R SQUARE              0.67628                  REGRESSION               1.        667442.28714       667442.28713        108.6
 ADJUSTED R SQUARE     0.67006                  RESIDUAL                52.        319485.41672         6143.95032
 STANDARD ERRCR       78.38335


 ---------------- VARIABLES IN THE EQUATION -----------------          ------------ VARIABLES NOT IN THE EQUATION ----------

 VARIABLE              B          BETA      STD ERROR B       F         VARIABLE      BETA IN      PARTIAL    TOLERANCE

   MRR           22.29472       0.82236      2.13808      108.634       VS          -0.27312     -0.48004     1.00000        15
 (CONSTANT)     146.0833                                                DL          -0.35067     -0.61633     1.00000        31
                                                                        DL2         -0.30246     -0.53160     1.00000        20
                                                                        MRRXDL      -0.41494     -0.57508     0.62180        25
```

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                                                                          MRRDL2      -0.32030     -0.51101     0.82394      18
                                                                          VS2DL2      -0.32768     -0.57593     1.00000      25



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OVARIABLE(S) ENTERED ON STEP NUMBER  2..       DL        DRESS LEAD

OMULTIPLE R          0.89401                    ANALYSIS OF VARIANCE    DF      SUM OF SQUARES        MEAN SQUARE            F
 R SQUARE            0.79925                    REGRESSION               2.       788804.49626       394402.24813        101.5
 ADJUSTED R SQUARE   0.79138                    RESIDUAL                51.       198123.20760         3884.76878
 STANDARD ERROR     62.32791


 ---------------- VARIABLES IN THE EQUATION -----------------          ------------- VARIABLES NOT IN THE EQUATION ----------

 VARIABLE               B           BETA     STD ERROR B        F          VARIABLE      BETA IN      PARTIAL    TOLERANCE

   MRR           22.28472        0.82236       1.70013     171.810          VS         -0.27312     -0.60959     1.00000      29
   DL          -159.3203        -0.35067      28.50440      31.241          DL2         0.83813      0.40755     0.04747       9
 (CONSTANT)     225.7435                                                    MRRXDL     -0.10472     -0.08758     0.14040       0
                                                                            MRRDL2      0.04709      0.04857     0.21355       0
                                                                            VS2DL2     -0.13303     -0.18025     0.36858       1



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OVARIABLE(S) ENTERED ON STEP NUMBER  3..       VS        WHEELSPEED

OMULTIPLE R          0.93480                    ANALYSIS OF VARIANCE    DF      SUM OF SQUARES        MEAN SQUARE            F
 R SQUARE            0.87385                    REGRESSION               3.       862426.27398       287475.42466        115.4
 ADJUSTED R SQUARE   0.86628                    RESIDUAL                50.       124501.42987         2490.02860
 STANDARD ERROR     49.90019


 ---------- -- --- VARIABLES IN THE EQUATION -----------------          ------------- VARIABLES NOT IN THE EQUATION ----------

 VARIABLE               B           BETA     STD ERROR B        F          VARIABLE      BETA IN      PARTIAL    TOLERANCE

   MRR           22.28472        0.82236       1.36114     268.046          DL2         0.83813      0.51412     0.04747      17
   DL          -159.3203        -0.35067      22.82083      48.739          MRRXDL     -0.10472     -0.11048     0.14040       0
   VS            -3.014815      -0.27312       0.55445      29.567          MRRDL2      0.04709      0.06127     0.21355       0
 (CONSTANT)     361.4101                                                    VS2DL2      0.30010      0.38244     0.20486       8



* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
OVARIABLE(S) ENTERED ON STEP NUMBER  4..       DL2       DL QUAD

OMULTIPLE R          0.95247                    ANALYSIS OF VARIANCE    DF      SUM OF SQUARES        MEAN SQUARE            F
 R SQUARE            0.90719                    REGRESSION               4.       895334.54812       223833.63703        119.
 ADJUSTED R SQUARE   0.89962                    RESIDUAL                49.        91593.15573         1869.24808
 STANDARD ERROR     43.23480


 ---------- ------ VARIABLES IN THE EQUATION -----------------          ------------- VARIABLES NOT IN THE EQUATION ---------

 VARIABLE               B           BETA     STD ERROR B        F          VARIABLE      BETA IN      PARTIAL    TOLERANCE

   MRR           22.28472        0.82236       1.17933     357.065          MRRXDL     -0.11927     -0.14664     0.14027
```

```
 DL              -530.9616      -1.16867     90.75384     34.229          MRRDL2    -0.11912    -0.16731    0.18310
 VS              -3.014815      -0.27312      0.48039     39.386          VS2DL2     0.16768     0.22917    0.17336
 DL2              328.2232       0.83813     78.22583     17.605
(CONSTANT)        436.0944



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OVARIABLE(S) ENTERED ON STEP NUMBER  5..      VS2DL2   VS2 AND DL2 INTERACT

                                                ANALYSIS OF VARIANCE     DF      SUM OF SQUARES      MEAN SQUARE          F
OMULTIPLE R            0.95502                  REGRESSION               5.       900144.95829     180028.99166        99.
 R SQUARE              0.91207                  RESIDUAL                48.        86782.74556       1807.97387
 ADJUSTED R SQUARE     0.90291
 STANDARD ERROR       42.52028

 ------------------ VARIABLES IN THE EQUATION ------------------        ------------- VARIABLES NOT IN THE EQUATION ---------

 VARIABLE              B            BETA      STD ERROR B        F      VARIABLE      BETA IN      PARTIAL     TOLERANCE

   MRR             22.28472       0.82236      1.15984      369.166      MRRXDL      -0.12082     -0.15260     0.14026
   DL             -530.9234      -1.16858     89.25398       35.384      MRRDL2      -0.11912     -0.17189     0.18310
   VS             -3.763715      -0.34097      0.65879       32.639
   DL2             274.7262       0.70152     83.63212       10.791
   VS2DL2       0.2457926E-01     0.16768      0.01507        2.661
 (CONSTANT)        469.7915



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OVARIABLE(S) ENTERED ON STEP NUMBER  6..      MRRDL2   MRR AND DL2 INTERACT

                                                ANALYSIS OF VARIANCE     DF      SUM OF SQUARES      MEAN SQUARE          F
OMULTIPLE R            0.95638                  REGRESSION               6.       902708.99645     150451.49941        83.
 R SQUARE              0.91467                  RESIDUAL                47.        84218.70740       1791.88739
 ADJUSTED R SQUARE     0.90377
 STANDARD ERROR       42.33069

 ------------------ VARIABLES IN THE EQUATION ------------------        ------------- VARIABLES NOT IN THE EQUATION ---------

 VARIABLE              B            BETA      STD ERROR B        F      VARIABLE   .  BETA IN      PARTIAL     TOLERANCE

   MRR             23.63912       0.87234      1.61716      213.675      MRRXDL       0.08773      0.03503     0.01360
   DL             -530.9501      -1.16864     88.85603       35.705
   VS             -3.763715      -0.34097      0.65585       32.933
   DL2             312.0918       0.79694     88.92598       12.317
   VS2DL2       0.2457927E-01     0.16768      0.01500        2.685
   MRRDL2         -4.000679      -0.11912      3.34447        1.431
 (CONSTANT)        457.1529



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OVARIABLE(S) ENTERED ON STEP NUMBER  7..      MRRXDL   MRR AND DL INTERACT

                                                ANALYSIS OF VARIANCE     DF      SUM OF SQUARES      MEAN SQUARE          F
OMULTIPLE R            0.95644                  REGRESSION               7.       902812.31470     128973.18781        70.
 R SQUARE              0.91477                  RESIDUAL                46.        84115.38915       1828.59542
 ADJUSTED R SQUARE     0.90180
 STANDARD ERROR       42.76208
```

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------- --------- VARIABLES IN THE EQUATION ------------------            ------------- VARIABLES NOT IN THE EQUATION ---------

VARIABLE              B           BETA     STD ERROR B         F          VARIABLE       BETA IN      PARTIAL   TOLERANCE

  MRR          23.00678        0.84901         3.12181    54.312
  DL          -556.6383       -1.22518       140.48536    15.699
  VS          -3.760802       -0.34071         0.66265    32.210
  DL2          333.4368        0.85144       127.01771     6.891
  VS2DL2   0.2448367E-01       0.16703         0.01516     2.608
  MRRDL2      -6.451284       -0.19208        10.84912     0.354
  MRRXDL       3.013636        0.08773        12.67830     0.057
(CONSTANT)     462.4577


MAXIMUM STEP REACHED
OSTATISTICS WHICH CANNOT BE COMPUTED ARE PRINTED AS ALL NINES.
1MULTIPLE REGRESSION RUN USING CARD INPUT AND RAW DATA                     17 DEC 81 16:31:38       PAGE    3
  --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
FILE     FILE    (CREATED  17 DEC 81 16:31:38)    4
0* * * * * * * * * * * * * * * * * * * * * * * * M U L T I P L E   R E G R E S S I O N * * * * * * * * * * * * *      VARIABLE LIS
                                                                                                                    REGRESSION LIS
DEPENDENT VARIABLE..       FNB       BASE NORMAL FORCE
0                                                         SUMMARY TABLE

VARIABLE                                            MULTIPLE R  R SQUARE  RSQ CHANGE   SIMPLE R              B                 BE

  MRR      METAL REMOVAL RATE                          0.82236   0.67628     0.67628    0.82236        23.00678               0.8
  DL       DRESS LEAD                                  0.89401   0.79925     0.12297   -0.35067       -556.6383              -1.2
  VS       WHEELSPEED                                  0.93480   0.87385     0.07460   -0.27312       -3.760802              -0.3
  DL2      DL QUAD                                     0.95247   0.90719     0.03334   -0.30246        333.4368               0.8
  VS2DL2   VS2 AND DL2 INTERACT                        0.95502   0.91207     0.00487   -0.32768   0.2448367E-01              0.1
  MRRDL2   MRR AND DL2 INTERACT                        0.95638   0.91467     0.00260    0.08114       -6.451284              -0.1
  MRRXDL   MRR AND DL INTERACT                         0.95644   0.91477     0.00010    0.24772        3.013636               0.0
(CONSTANT)                                                                                             462.4577
1MULTIPLE REGRESSION RUN USING CARD INPUT AND RAW DATA                     17 DEC 81 16:31:38       PAGE    4
  --- U N I V E R S I T Y   O F   V E R M O N T   S P S S ---
OCPU TIME REQUIRED..      3.45 SECONDS
 ELAPSED WALL TIME..        11 SECONDS



                  18 FINISH
1             NORMAL END OF SPSS RUN.
               18 COMMAND RECORDS READ
                0 ERRORS DETECTED


**************************************************************************************************************************
**************************************************************************************************************************
***********                                                                                                ***************
** Pdn    6    3199-ERF            TERMINAL. 72          17 DEC 81 16:41:28        No of Pages      4        ****** V001 ***
***********                                                                                                ***************
**************************************************************************************************************************
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Appendix 11

LIST OF TABLES

TABLE 1

Test No.	Dressing Tool	Dress Lead	Dressing Wheel Speed	Metal Removal Rate	Grinding Wheel Speed	Workhead Speed
		(mm/rev)	m/s	(mm^3/mm/sec)	m/s	m/s
1	Multi Point	0.125	30	4	30	0.80
2	"	0.125	"	8	"	"
3	"	0.25	"	4	"	"
4	"	0.25	"	8	"	"
5	"	0.25	"	8	"	"
6	"	0.25	"	16	"	"
7	"	0.375	"	16	"	"
8	"	0.375	"	8	"	"
10	"	0.375	"	4	"	"
11	"	0.500	"	4	"	"
12	"	0.500	"	8	"	"
13	"	0.500	"	16	"	"
14	"	0.750	"	16	"	"
15	"	0.750	"	8	"	"
16	"	0.750	"	4	"	"
17	"	1.000	"	4	"	"
18	"	1.000	"	8	"	"
19	"	1.000	"	16	"	"
20	Multi Point	0.125	30	4	45	0.80
21	"	0.25	"	8	"	"
22	"	0.375	"	16	"	"
23	"	0.500	"	8	"	"
24	"	0.750	"	4	"	"

Test No.	Dressing Tool	Dress Lead	Dressing Wheel Speed	Metal Removal Rate	Grinding Wheel Speed	Workhead Speed
		(mm/rev)	m/s	(mm^3/mm/sec)	m/s	m/s
25	Multi Point	1.000	30	16	45	0.80
26	Multi Point	0.125	30	8	60	0.80
27	"	0.25	"	16	"	"
28	"	0.375	"	4	"	"
29	"	0.500	"	16	"	"
30	"	0.750	"	8	"	"
31	"	1.000	"	4	"	"
32	"	1.000	"	4	"	1.23

TABLE 2

Test No.	Dressing Tool	Dress Lead	Dressing Wheel Speed	Metal Removal Rate	Grinding Wheel Speed	Workhead Speed
		(mm/rev)	m/s	(mm^3/mm/sec)	m/s	m/s
33	Blade Dresser	0.125	30	16	30	0.80
34	"	0.125	"	"	45	"
35	"	0.125	"	"	60	"
36	"	0.250	"	"	30	"
37	"	0.250	"	"	45	"
38	"	0.250	"	"	60	"
39	"	0.375	"	"	30	"
40	"	0.375	"	"	45	"
41	"	0.375	"	"	60	"
42	"	0.50	"	"	30	"
43	"	0.50	"	"	45	"
44	"	0.50	"	"	60	"
45	"	0.750	"	"	30	"
46	"	0.750	"	"	45	"
47	"	0.750	"	"	60	"
48	"	1.000	"	"	30	"
49	"	1.000	"	"	45	"
50	"	1.000	"	"	60	"

TABLE 3

Test No.	Dressing Tool	Dress Lead	Dressing Wheel Speed	Metal Removal Rate	Grinding Wheel Speed	Workhead Speed
		(mm/rev)	m/s	(mm^3/mm/sec)	m/s	m/s
51	Single Point	0.125	30	4	30	0.80
52	"	0.125	"	"	45	"
53	"	0.125	"	"	60	"
54	"	0.125	"	8	30	"
55	"	0.125	"	"	45	"
56	"	0.125	"	"	60	"
57	"	0.125	"	16	30	"
58	"	0.125	"	"	45	"
59	"	0.125	"	"	60	"
60	"	0.25	"	4	30	"
61	"	0.25	"	"	45	"
62	"	0.25	"	"	60	"
63	"	0.25	"	8	30	"
64	"	0.25	"	"	45	"
65	"	0.25	"	"	60	"
66	"	0.25	"	16	30	"
67	"	0.25	"	"	45	"
68	"	0.25	"	"	60	"
69	"	0.375	"	4	30	"
70	"	0.375	"	"	45	"
71	"	0.375	"	"	60	"
72	"	0.375	"	8	30	"
73	"	0.375	"	"	45	"
74	"	0.375	"	"	60	"

Test No.	Dressing Tool	Dress Lead	Dressing Wheel Speed	Metal Removal Rate	Grinding Wheel Speed	Workhead Speed
		(mm/rev)	m/s	(mm^3/mm/sec)	m/s	m/s
75	Single Point	0.375	30	16	30	0.80
76	"	0.375	"	"	45	"
77	"	0.375	"	"	60	"
78	"	0.500	"	4	30	"
79	"	0.500	"	"	45	"
80	"	0.500	"	"	60	"
81	"	0.500	"	8	30	"
82	"	0.500	"	"	45	"
83	"	0.500	"	"	60	"
84	"	0.500	"	16	30	"
85	"	0.500	"	16	45	"
86	"	0.500	"	"	60	"
87	"	0.750	"	4	30	"
88	"	0.750	"	"	45	"
89	"	0.750	"	"	60	"
90	"	0.750	"	8	30	"
91	"	0.750	"	"	45	"
92	"	0.750	"	"	60	"
93	"	0.750	"	16	30	"
94	"	0.750	"	"	45	"
95	"	0.750	"	"	60	"
96	"	1.000	"	4	30	"
97	"	1.000	"	"	45	"
98	"	1.000	"	"	60	"
99	"	1.000	"	8	30	"
100	"	1.000	"	"	45	"

Test No.	Dressing Tool	Dress Lead	Dressing Wheel Speed	Metal Removal Rate	Grinding Wheel Speed	Workhead Speed
		(mm/rev	m/s	(mm^3/mm/sec)	m/s	m/s
101	Single Point	1.000	30	8	60	0.80
102	"	1.000	"	16	30	"
103	"	1.000	"	"	45	"
104	"	1.000	"	"	60	"

TABLE 4 Test Series II (J Wheel)

TEST NO	DRESSING TOOL	DRESS LEAD	DRESSING WHEEL SPEED	METAL REMOVAL RATE	GRINDING WHEEL SPEED	WORKHEAD SPEED
		(mm/rev)	(m/s)	(mm^3/mm/sec)	(m/s)	(m/s)
J7	Single	0.125	30	16	60	0.80
J5	Point	0.25				
J4		0.375				
J2		0.5				
J3		0.75				
J18		1.00				
J9	Single	0.125	30	16	60	1.2
J14	Point	0.25				
J10		0.375				
J16		0.5				
J8		0.75				
J17		1.00				
J6	Single	0.125	30	16	60	0.51
J1	Point	0.25				
J11		0.375				
J15		0.5				
J12		0.75				
J13		1.00				

GRINDING WHEEL WA60JV

DRESSING TOOL Single Point Diamond

WORKPIECE MATERIAL EN9

TABLE 5 Test Series II (L Wheel)

TEST NO	DRESSING TOOL	DRESS LEAD	DRESSING WHEEL SPEED	METAL REMOVAL RATE	GRINDING WHEEL SPEED	WORKHEAD SPEED
		(mm/rev)	(m/s)	(mm^3/mm/sec)	(m/s)	(m/s)
59	Single	0.125	30	16	60	0.80
68	Point	0.25				
77		0.375				
86		0.5				
95		0.75				
104		1.00				
L9	Single	0.125	30	16	60	1.20
L14	Point	0.25				
L10		0.375				
L16		0.50				
L8		0.75				
L17		1.00				
L6	Single	0.125	30	16	60	0.51
L1	Point	0.25				
L11		0.375				
L15		0.50				
L12		0.75				
L13		1.00				

GRINDING WHEEL WA60LV

DRESSING TOOL Single Point Diamond

WORKPIECE MATERIAL EN9

TABLE 6 Test Series II (N Wheel)

TEST NO	DRESSING TOOL	DRESS LEAD (mm/rev)	DRESSING WHEEL SPEED (m/s)	METAL REMOVAL RATE (mm^3/mm/sec)	GRINDING WHEEL SPEED (m/s)	WORKHEAD SPEED (m/s)
N6	Single	0.125	30	16	60	0.51
N5	Point	0.25				
N3		0.375				
N17		0.50				
N12		0.75				
N9		1.00				
N8	Single	0.125	30	16	60	0.80
N16	Point	0.25				
N18		0.375				
N11		0.50				
N2		0.75				
N7		1.00				
N1	Single	0.125	30	16	60	1.20
N14	Point	0.25				
N4		0.375				
N15		0.50				
N10		0.75				
N13		1.00				

GRINDING WHEEL WA60NV

DRESSING TOOL Single Point Diamond

WORKPIECE MATERIAL EN9

TABLE 7 Test Results, Test 87

WORKPIECE SIZE (mm)	POWER DRAWN (KW)	GRINDING FORCE NORMAL (NEWTONS)	GRINDING FORCE TANGENTIAL (NEWTONS)	METAL REMOVED (mm^3)	WHEEL WEAR (mm^3)	SURFACE FINISH µm CLA
116.33						
116.21	1.5	245	121	589	167	1.35
116.08	1.45	235	113	1178	206	1.40
115.57	1.32	240	114	3525	279	1.45
115.06	1.43	252	126	5862	310	1.63
114.55	1.47	265	129	8189	361	1.3
114.05	1.62	279	131	10506	464	1.35
113.54	1.62	288	139	12812	515	1.38
113.03	1.70	293	142	15109		1.38
112.52	1.67	298	131	17394	618	1.15
112.01	1.76	301	137	19670	631	1.28
111.51	1.82			21935		1.13
111.00	1.83	323	144	24190	695	1.10
110.49	1.88	337	147	26434	721	1.20
109.98	1.93	339	156	28669		1.05

WHEEL	WA60LV
DRESSING TOOL	Single Point Diamond
WORKPIECE MATERIAL	EN9
WHEELSPEED	30 m/s
WORKSPEED	0.80 m/s
DRESS LEAD	0.75 mm/rev
METAL REMOVAL RATE	4 mm^3/mm/sec

TABLE 8 Grinding Ratios (Test Series I)

WHEEL SPEED	DRESS LEAD	Dressing Tool								
		Multi Point			Blade Dresser			Single Point		
		Metal Removal Rate								
		4	8	16	4	8	16	4	8	16
30	0.125	131.6	75.5					178.0	128.3	56.5
	0.25	74.0	80.7				87.7	106.0	72.1	39.1
	0.375	110.0	78.1	113.6			54.1	119.8	73.8	52.4
	0.500	83.3	32.9	77.5			48.2	94.4	44.9	28.3
	0.750	90.9	104.2	137.0			75.8	49.6	45.8	32.1
	1.00	94.3	76.9	84.0			46.1	34.4	48.4	16.0
45	0.125	141.0					172.4	90.6	99.5	95.1
	0.25		145.0				89.3	89.0	114.6	108.8
	0.375			97.0			102.0	129.4	83.9	70.2
	0.500		105.0				76.3	93.9	74.8	57.4
	0.750	115.0					117.6	65.6	53.1	62.1
	1.00			107.0			82.0	35.6	37.5	41.4
60	0.125		159.0				83.3		77.3	46.0
	0.25			48.0			73.5	86.3	91.9	64.1
	0.375	76.0					74.6	84.9	59.7	53.2
	0.50			61.2			79.4	77.7	56.6	47.1
	0.75		109.0	32.2			65.4	73.6	47.9	41.8
	1.00	67.0		35.2			67.6	37.0	39.1	35.1

Dressing wheelspeed 30 m/s

TABLE 9 Surface Finish @ 15,000 mm^3 of Metal Removed

Wheel Speed	Dress Lead	Dressing Tool: Multi Point			Blade Dresser			Single Point		
		Metal Removal Rate								
		4	8	16	4	8	16	4	8	16
	0.125	0.70	1.00	-			0.75	0.70	0.85	1.05
	0.250	1.08	1.08	-			0.95	1.00	1.20	1.45
30	0.375	0.90	1.35	1.50			1.00	0.65	1.10	1.20
	0.500	1.00	1.40	1.70			1.00	1.45	1.10	1.60
	0.750	0.80	1.35	1.30			1.00	1.20	1.55	1.50
	1.00	1.20	1.05	1.15			1.30	1.40	1.55	2.75
	0.125	0.60					0.65	0.45	0.60	0.80
	0.250		0.80				1.00	0.50	0.75	0.95
45	0.375			0.80			0.85	0.60	0.90	0.95
	0.500		0.90				1.05	0.90	0.80	1.05
	0.750	1.20					1.00	1.40	1.20	1.15
	1.000			0.80			1.50	1.50	1.65	1.25
	0.125		0.65				0.70	0.55	0.60	0.59
	0.250			0.70			0.90	0.60	0.70	0.56
60	0.375	0.60					0.80	0.65	0.80	0.86
	0.500			1.00			1.10	0.75	0.95	0.71
	0.750		1.00		-		1.25	1.35	1.00	0.74
	1.000	0.75					1.70	2.70	1.00	0.68

Dressing wheelspeed 30 m/s

TABLE 10 Normal Force (Newtons @ 15000 mm^3)
(Test Series I)

WHEEL SPEED	DRESS LEAD	Dressing Tool								
		Multi Point			Blade Dresser			Single Point		
		Metal Removal Rate								
m/s	mm/rev	4	8	16	4	8	16	4	8	16
30	0.125	394						475	510	656
	0.25	257	368				588	293	504	694
	0.375	308	462	530			560	293	427	593
	0.50	273	457	520			683	278	386	603
	0.75	410	434	588			614	291	476	488
	1.00	417	445	575			651	270	420	570
45	0.125	299					588	323	454	610
	0.25		494				511	274	407	623
	0.375			542			600	267	358	577
	0.50		415				633	242	409	497
	0.75	289					634	213	329	496
	1.00			504			533	218	386	515
60	0.125		411				611	289	473	558
	0.25			545			483	291	399	640
	0.375	317					580	216	381	496
	0.5			623			541	224	375	423
	0.75		445	581			567	201	367	487
	1.00	269		527			548	227	306	468

Dressing Wheelspeed 30 m/s

TABLE 11 Tangential Force (Newtons @ 15000 mm^3)
(Test Series I)

WHEEL SPEED	DRESS LEAD	Dressing Tool								
		Multi Point			Blade Dresser			Single Point		
		Metal Removal Rate								
m/s	mm/rev	4	8	16	4	8	16	4	8	16
30	0.125	228						241	264	317
	0.25	132	182				286	137	249	359
	0.375	156	231	257			283	151	215	301
	0.50	130	220	249			331	138	184	270
	0.75	211	211	286			316	135	231	211
	1.00	198	220	271			327	120	183	276
45	0.125	154					253	168	218	269
	0.25		238				220	138	189	287
	0.375			255			275	138	167	253
	0.50		198				281	123	185	241
	0.75	149					292	107	133	203
	1.00			240			257	92	153	189
60	0.125		250				215	131	201	219
	0.25			227			189	132	167	250
	0.375	145			-		211	110	170	207
	0.50			216			218	105	151	192
	0.75		168	153			227	97	138	177
	1.00	111		142			215	96	109	168

Dressing Wheelspeed 30 m/s

TABLE 12 Grinding Ratios (Test Series II)

WHEEL SPEED	DRESS LEAD	WHEEL GRADE								
		J			L			N		
		WORK SPEED (m/s)								
m/s	mm/rev	0.51	0.80	1.20	0.51	0.80	1.2	0.51	0.80	1.20
60	0.125	98.1	35.6	53.7	39.6	46.0	41.0	45.3	69.0	48.2
	0.25	42.3	36.9	110.0	57.7	64.1	53.3	86.7	90.5	74.7
	0.375	68.9	41.9	42.2	38.4	53.2	49.2	77.4	78.2	58.9
	0.50	122.0	56.2	117.0	51.5	47.1	57.1	73.0	47.1	71.0
	0.75	190.0	34.1	31.2	45.0	41.8	44.7	61.1	53.8	37.8
	1.00	140.0	77.0	77.0	31.7	35.1	44.1	51.4	68.1	43.6

GRINDING WHEELSPEED 60 m/s

DRESSING WHEELSPEED 30 m/s

METAL REMOVAL RATE 16 $mm^3/mm/sec$

DRESSING TOOL Single Point Diamond

TABLE 13 Overall Wear (mm^3) (Test Series II)

WHEEL SPEED	DRESS LEAD	WHEEL GRADE								
		J			L			N		
		WORK SPEED (m/s)								
m/s	mm/rev	0.51	0.80	1.20	0.51	0.80	1.20	0.51	0.80	1.20
	0.125	551	1048	812	1017	845	937	732	551	650
	0.25	878	1020	678	804	676	808	518	590	471
60	0.375	706	983	887	1006	952	929	657	569	703
	0.500	644	835	778	809	930	825	666	861	613
	0.750	621	1171	1189	889	1120	1028	763	768	925
	1.00	693	978	1104	1181	1200	1024	823	743	921

GRINDING WHEELSPEED 60 m/s

DRESSING WHEELSPEED 30 m/s

METAL REMOVAL RATE 16 mm^3/mm/sec

DRESSING TOOL Single Point Diamond

WEAR MEASUREMENTS TAKEN AFTER:- 30,000 mm^3 of metal removed

TABLE 14 Surface Finish @ 15000 mm^3 of metal removed

(Test Series II)

WHEEL SPEED	DRESS LEAD	WHEEL GRADE								
		J			L			N		
		WORK SPEED (m/s)								
m/s	mm/rev	0.51	0.80	1.20	0.51	0.80	1.20	0.51	0.80	1.20
	0.125	0.50	0.73	0.75	0.75	0.59	0.66	0.77	0.77	0.74
	0.25	0.72	0.68	0.68	1.18	0.56	0.75	0.72	0.80	0.76
60	0.375	0.76	0.63	0.78	0.63	0.86	0.71	0.70	0.78	0.77
	0.50	0.77	0.91	0.78	0.70	0.71	0.68	0.82	0.77	0.79
	0.75	0.73	0.96	0.83	0.82	0.74	0.66	0.78	0.78	0.80
	1.00	0.74	0.81	0.78	0.98	0.68	0.73	0.79	0.85	0.80

GRINDING WHEELSPEED 60 m/s

DRESSING WHEELSPEED 30 m/s

METAL REMOVAL RATE 16 mm^3/mm/sec

DRESSING TOOL Single Point Diamond

MEASUREMENTS
TAKEN AFTER:- 15,000 mm^3 of metal removed

TABLE 15 Normal Force (Test Series II)

WHEEL SPEED	DRESS LEAD	WHEEL GRADE								
		J			L			N		
		WORK SPEED								
m/s	mm/rev	0.51	0.80	1.20	0.51	0.80	1.20	0.51	0.80	1.20
	0.125	440	417	460	603	558	757	582	592	542
	0.25	438	503	477	624	640	602	536	567	546
60	0.375	423	485	426	621	496	657	542	550	572
	0.50	419	388	516	545	423	697	494	482	495
	0.75	451	374	464	625	487	718	484	480	511
	1.00	420	435	484	554	468	607	485	499	494

GRINDING WHEELSPEED 60 m/s

DRESSING WHEELSPEED 30 m/s

METAL REMOVAL RATE 16 mm^3/mm/sec

DRESSING TOOL Single Point Diamond

MEASUREMENTS TAKEN AFTER:- 15,000 mm^3 of metal removed

TABLE 16 Tangential Force (Test Series II)

WHEEL SPEED	DRESS LEAD	WHEEL GRADE								
		J			L			N		
		WORK SPEED (m/s)								
m/s	mm/rev	0.51	0.80	1.20	0.51	0.80	1.20	0.51	0.80	1.20
	0.125	150	142	159	168	219	191	172	182	173
	0.25	160	186	143	169	250	177	163	176	175
60	0.375	141	161	149	164	207	173	163	170	172
	0.500	129	140	145	153	192	195	157	145	160
	0.75	134	132	149	170	177	183	153	150	160
	1.00	128	128	138	158	168	162	150	153	157

GRINDING WHEELSPEED 60 m/s

DRESSING WHEELSPEED 30 m/s

METAL REMOVAL RATE 16 $mm^3/mm/sec$

DRESSING TOOL Single Point Diamond

MEASUREMENTS TAKEN AFTER:- 15,000 mm^3 of metal removed

TABLE 17

	STATISTICAL RESULT		
	MULTI POINT	BLADE DRESSER	SINGLE POINT
MULTI POINT			
GRINDING RATIO		$t=0.84$ $\nu=9$*	$t=3.40$ $\nu=29$***
SURFACE FINISH		$t=0.24$ $\nu=7$	$t=1.55$ $\nu=27$
NORMAL FORCE		$t=1.12$ $\nu=9$	$t=1.36$ $\nu=28$
TANGENTIAL FORCE		$t=2.88$ $\nu=9$**	$t=1.84$ $\nu=28$
BLADE DRESSER			
GRINDING RATIO	$t=0.84$ $\nu=9$		$t=5.62$ $\nu=16$***
SURFACE FINISH	$t=0.24$ $\nu=7$		$t=0.60$ $\nu=17$
NORMAL FORCE	$t=1.12$ $\nu=9$		$t=1.56$ $\nu=16$
TANGENTIAL FORCE	$t=2.88$ $\nu=9$**		$t=1.48$ $\nu=16$
SINGLE POINT			
GRINDING RATIO	$t=3.40$ $\nu=29$***	$t=5.62$ $\nu=16$***	
SURFACE FINISH	$t=1.55$ $\nu=27$	$t=0.60$ $\nu=17$	
NORMAL FORCE	$t=1.36$ $\nu=28$	$t=1.56$ $\nu=16$	
TANGENTIAL FORCE	$t=1.84$ $\nu=28$	$t=1.48$ $\nu=16$	

*** Highly significant

** Significant

* Probably significant

TABLE 18 Summary of Analysis of Variance (Test Series I)

	NORMAL FORCE $500mm^3$	NORMAL FORCE $15000mm^3$	TANGENTIAL FORCE $500mm^3$	TANGENTIAL FORCE $15000mm^3$	GRINDING RATIO	SURFACE FINISH $15000mm^3$
MAIN EFFECTS						
METAL REMOVAL RATE (M)						
L_M	60.97***	182.49***	86.45***	137.33***	22.36***	0.63
Q_M	0.08	0.02	0.03	0.09	0.07	0.09
WHEELSPEED (V)						
L_V	0.67	9.61**	8.89**	30.26***	4.36*	44.93***
Q_V	0.01	1.68	0.57	0.48	6.67**	2.74
DRESS LEAD (D)						
L_D	5.63**	15.75***	12.31***	26.90***	33.05***	23.35***
Q_D	2.61	3.14	0.83	1.11	2.29	0.02
2 FACTOR INTERACTIONS						
$L_M L_V$	0.00	0.30	2.00	3.71*	0.19	7.76**
$Q_M L_V$	0.02	0.06	0.00	0.81	0.02	1.22
$L_M Q_V$	0.02	0.00	0.02	0.00	7.10**	0.25
$Q_M Q_V$	0.04	0.20	0.09	0.84	0.12	0.48
$L_M L_D$	1.09	4.34*	2.50	10.09**	1.56	6.18**
$Q_M L_D$	0.16	1.72	0.45	1.68	0.74	0.01
$L_M Q_D$	1.86	1.21	0.33	0.28	1.10	0.05
$Q_M Q_D$	5.26**	0.13	3.67*	0.02	0.58	1.26
$L_V L_D$	0.70	0.06	0.03	0.19	1.01	1.26
$Q_V L_D$	0.01	0.01	0.03	0.07	0.13	1.67
$L_V Q_D$	1.17	0.22	1.84	0.33	1.40	0.29
$Q_V Q_D$	0.32	0.93	0.49	1.66	0.08	0.48
3 FACTOR INTERACTIONS	5070.54	2129.75	672.47	471.86	221.24	0.027
TOTAL	17284.10	18827.27	3324.33	4062.88	772.73	2.735

*** highly significant, ** significant, * probably significant

TABLE 19 Summary of Analysis of Variance (Test Series II)

	NORMAL FORCE $15000mm^3$	TANGENTIAL FORCE $15000mm^3$	SURFACE FINISH $15000mm^3$	GRINDING RATIO	WHEEL WEAR $30000mm^3$
MAIN EFFECTS					
WHEEL GRADE (C)					
L_C	11.12**	12.38***	0.01	1.04	5.84**
Q_C	51.05***	17.90***	7.46**	2.82	2.38
WORKSPEED (V)					
L_V	5.85**	6.86**	1.12	0.88	2.69
Q_V	10.56**	0.39	0.03	2.46	3.20
DRESS LEAD (N)					
L_N	4.00*	16.81***	0.26	0.30	9.55**
Q_N	4.31*	4.00*	0.01	0.27	1.48
2 FACTOR INTERACTIONS					
$L_C L_V$	0.64	0.07	0.22	0.26	0.19
$Q_C L_V$	1.17	2.83	0.56	0.46	0.34
$L_C Q_V$	0.90	1.18	0.65	2.84	1.52
$Q_C Q_V$	8.07**	6.94**	0.05	1.16	0.43
$L_C L_N$	0.11	0.56	0.81	2.05	0.25
$Q_C L_N$	0.93	1.48	1.26	0.07	0.30
$L_C Q_N$	0.25	0.77	0.08	0.71	1.64
$Q_C Q_N$	1.39	0.33	0.08	0.11	0.20
$L_V L_N$	0.59	1.07	0.95	4.10*	3.43
$Q_V L_N$	10.27**	13.44***	2.37	0.30	0.40
$L_V Q_N$	2.01	2.47	0.32	0.41	0.65
$Q_V Q_N$	3.59*	0.90	0.52	0.30	0.44
3 FACTOR INTERACTIONS	1595.31	79.40	0.013	1108.71	18833.67
TOTAL	7657.38	300.42	0.013	1217.45	31093.32

TABLE 20 Linear Regression of Normal Force (Test Series I)

TEST NO	WHEEL SPEED (m/s)	METAL REMOVAL RATE (mm^3/mm/sec)	DRESS LEAD (mm/rev)	INITIAL NORMAL FORCE (Newtons)	SLOPE ($x10^{-3}$)	CORRELATION COEFFICIENT (r)
51	30	4	0.125	498	-1.55	0.48
52	45	4		318	0.31	0.21
53	60	4		230	3.94	0.95
54	30	8		458	3.53	0.81
55	45	8		417	2.49	0.92
56	60	8		357	7.70	0.98
57	30	16		686	-1.98	0.36
58	45	16		578	2.15	0.66
59	60	16		466	6.16	0.98
60	30	4	0.25	231	4.14	0.95
61	45	4		242	2.16	0.92
62	60	4		247	2.91	0.90
63	30	8		430	4.91	0.92
64	45	8		352	3.69	0.91
65	60	8		310	5.94	0.97
66	30	16		651	2.88	0.49
67	45	16		565	3.86	0.76
68	60	16		565	5.01	0.69
69	30	4	0.375	249	2.95	0.98
70	45	4		228	2.63	0.93
71	60	4		172	2.96	0.93
72	30	8		396	2.05	0.61
73	45	8		317	2.75	0.73
74	60	8		332	3.26	0.72
75	30	16		580	0.85	0.23
76	45	16		561	1.06	0.28
77	60	16		423	4.84	0.97
78	30	4	0.50	187	6.07	0.96
79	45	4		201	2.76	0.85
80	60	4		182	2.82	0.95

continued/

Table 20 /continued

TEST NO	WHEEL SPEED (m/s)	METAL REMOVAL RATE (mm^3/mm/sec)	DRESS LEAD (mm/rev)	INITIAL NORMAL FORCE (Newtons)	SLOPE ($x10^{-3}$)	CORRELATION COEFFICIENT (r)
81	30	8	0.50	324	4.10	0.86
82	45	8		340	4.62	0.86
83	60	8		279	6.42	0.97
84	30	16		448	10.30	0.80
85	45	16		470	1.77	0.43
86	60	16		376	3.12	0.81
87	30	4	0.75	235	3.71	0.99
88	45	4		161	3.45	0.97
89	60	4		145	3.74	0.98
90	30	8		379	6.48	0.67
91	45	8		264	4.33	0.84
92	60	8		240	8.44	0.83
93	30	16		450	2.55	0.57
94	45	16		429	4.44	0.93
95	60	16		418	4.58	0.75
96	30	4	1.00	211	3.95	0.87
97	45	4		146	4.83	0.98
98	60	4		156	4.76	0.95
99	30	8		337	5.53	0.84
100	45	8		338	3.29	0.61
101	60	8		261	2.98	0.65
102	30	16		448	8.10	0.80
103	45	16		425	5.99	0.90
104	60	16		411	3.79	0.75

TABLE 21 Initial Normal Forces

Wheelspeed : 30 m/s			
Dress Lead (mm/rev)	Metal Removal Rate		
	4	8	16
	(mm^3/mm/sec)		
0.125	498	458	686
0.25	231	430	651
0.375	249	396	580
0.50	187	324	448
0.75	235	379	450
1.00	211	337	448

Wheelspeed : 45 m/s

0.125	318	417	578
0.25	242	352	565
0.375	228	317	561
0.50	201	340	470
0.75	161	264	429
1.00	146	338	425

Wheelspeed : 60 m/s

0.125	230	357	466
0.25	247	310	565
0.375	172	332	423
0.50	182	279	376
0.75	145	240	418
1.00	156	261	411

TABLE 22 Regression Analysis of Initial Normal Forces

WHEEL SPEED (m/s)	METAL REMOVAL RATE ($mm^3/mm/sec$)	LINEAR REGRESSION			EXPONENTIAL CURVE FIT			POWER CURVE FIT			WHEEL SPEED	METAL REMOVAL RATE	POLYNOMIAL REGRESSION			
		CONSTANT	SLOPE	CORRELATION COEFFICIENT	CONSTANT	EXPONENT	CORRELATION COEFFICIENT	CONSTANT	EXPONENT	CORRELATION COEFFICIENT			CONSTANT	LINEAR COEFFICIENT	QUADRATIC COEFFICIENT	CORRELATION COEFFICIENT
30	4	373.32	-209.65	0.60	348.63	-0.637	0.60	183.41	-0.358	0.78	30	4	560.16	-1139.0	820.79	0.84
30	8	448.98	-123.29	0.77	449.75	-0.314	0.76	335.99	-0.149	0.84	30	8	504.6	-399.97	244.34	0.87
30	16	690.66	-293.65	0.87	698.91	-0.535	0.87	428.97	-0.244	0.93	30	16	811.74	-895.98	531.93	0.96
45	4	305.41	-178.82	0.94	318.79	-0.846	0.97	149.17	-0.372	0.99	45	4	357.6	-438.43	229.26	0.98
45	8	384.12	-92.24	0.60	383.06	-0.269	0.59	293.98	-0.144	0.73	45	8	474.64	-542.55	397.68	0.90
45	16	606.67	-204.00	0.93	614.85	-0.412	0.94	428.25	-0.172	0.91	45	16	637.89	-359.30	137.15	0.95
60	4	240.67	-104.00	0.83	243.41	-0.548	0.84	148.48	-0.244	0.87	60	4	278.27	-291.06	165.19	0.89
60	8	355.21	-117.41	0.86	358.42	-0.398	0.86	250.24	-0.177	0.89	60	8	393.75	-309.16	169.33	0.92
60	16	498.58	-110.82	0.55	494.70	-0.237	0.55	398.18	-0.109	0.58	60	16	556.77	-400.28	255.62	0.63

TABLE 23 Summary of Analysis of Variance

(Initial Forces, Test Series I)

	BASE NORMAL FORCE	BASE TANGENTIAL FORCE
MAIN EFFECTS		
METAL REMOVAL RATE (M)		
L_M	409.77***	268.14***
Q_M	3.17	2.43
WHEELSPEED (V)		
L_V	20.84***	47.16***
Q_V	0.05	0.24
DRESS LEAD (D)		
L_D	48.26***	52.97***
Q_D	10.37**	7.44**
2 FACTOR INTERACTIONS		
$L_M L_V$	1.17	6.06**
$Q_M L_V$	3.22	2.52
$L_M Q_V$	0.05	0.12
$Q_M Q_V$	0.07	1.07
$L_M L_D$	8.86**	18.60***
$Q_M L_D$	1.91	2.55
$L_M Q_D$	4.32*	3.97*
$Q_M Q_D$	1.63	1.29
$L_V L_D$	0.48	0.19
$Q_V L_D$	0.06	0.08
$L_V Q_D$	1.36	0.99
$Q_V Q_D$	5.59**	4.44**
3 FACTOR INTERACTIONS	875.39	258.04
TOTAL	17816.44	4250.5

*** highly significant, ** significant, * probably significant

TABLE 24 Linear Regression of Tangential Forces (Test Series I)

TEST NO	WHEEL SPEED (m/s)	METAL REMOVAL RATE (mm^3/mm/sec)	DRESS LEAD (mm/rev)	INITIAL NORMAL FORCE (Newtons)	SLOPE ($x10^{-3}$)	CORRELATION COEFFICIENT (r)
51	30	4	0.125	240	0.07	0.05
52	45	4	↓	163	0.33	0.51
53	60	4	↓	106	1.68	0.96
54	30	8	↓	256	0.51	0.33
55	45	8	↓	208	0.66	0.77
56	60	8	↓	167	2.26	0.97
57	30	16	↓	348	-2.06	0.58
58	45	16	↓	263	0.39	0.10
59	60	16	↓	197	1.47	0.91
60	30	4	0.25	128	0.61	0.61
61	45	4	↓	118	1.31	0.93
62	60	4	↓	116	1.05	0.87
63	30	8	↓	228	1.38	0.71
64	45	8	↓	166	1.50	0.75
65	60	8	↓	145	1.45	0.88
66	30	16	↓	347	0.93	0.17
67	45	16	↓	281	0.39	0.22
68	60	16	↓	258	-0.53	0.34
69	30	4	0.375	133	1.19	0.94
70	45	4	↓	123	0.99	0.87
71	60	4	↓	93	1.11	0.90
72	30	8	↓	209	0.43	0.23
73	45	8	↓	153	0.91	0.67
74	60	8	↓	170	0.02	0.01
75	30	16	↓	316	-0.97	0.47
76	45	16	↓	254	-0.04	0.03
77	60	16	↓	196	0.74	0.74
78	30	4	0.5	102	2.41	0.94
79	45	4	↓	111	0.83	0.60
80	60	4	↓	92	0.83	0.86

continued/

Table 24 /continued

TEST NO	WHEEL SPEED (m/s)	METAL REMOVAL RATE (mm^3/mm/sec)	DRESS LEAD (mm/rev)	INITIAL NORMAL FORCE (Newtons)	SLOPE ($x10^{-3}$)	CORRELATION COEFFICIENT (r)
81	30	8	0.5	166	1.20	0.65
82	45	8		165	1.30	0.80
83	60	8		129	1.46	0.89
84	30	16		237	2.17	0.72
85	45	16		216	1.66	0.64
86	60	16		160	2.10	0.85
87	30	4	0.75	116	1.25	0.93
88	45	4		88	1.24	0.88
89	60	4		76	1.38	0.97
90	30	8		197	2.27	0.57
91	45	8		118	1.03	0.67
92	60	8		110	1.89	0.70
93	30	16		208	0.18	0.14
94	45	16		192	0.73	0.73
95	60	16		175	0.16	0.18
96	30	4	1.00	102	1.20	0.77
97	45	4		68	1.62	0.95
98	60	4		71	1.66	0.97
99	30	8		148	2.32	0.81
100	45	8		141	0.79	0.44
101	60	8		98	0.75	0.57
102	30	16		195	5.40	0.75
103	45	16		182	1.13	0.61
104	60	16		165	0.23	0.21

TABLE 25 Initial Tangential Forces

Wheelspeed : 30 m/s			
Dress Lead (mm/rev)	Metal Removal Rate ($mm^3/mm/sec$) 4	8	16
0.125	240	256	348
0.25	128	228	347
0.375	133	209	316
0.50	102	166	237
0.75	116	197	208
1.00	102	148	195

Wheelspeed : 45 m/s

0.125	163	208	263
0.25	118	166	281
0.375	123	153	254
0.50	111	165	216
0.75	99	118	192
1.00	68	141	182

Wheelspeed : 60 m/s

0.125	106	167	197
0.25	116	145	258
0.375	93	170	196
0.50	92	129	160
0.75	76	110	175
1.00	71	98	165

TABLE 26 Regression Analysis of Initial Tangential Force

WHEEL SPEED (m/s)	METAL REMOVAL RATE ($mm^3/mm/sec$)	LINEAR REGRESSION			EXPONENTIAL CURVE FIT			POWER CURVE FIT			WHEEL SPEED	METAL REMOVAL RATE	POLYNOMIAL REGRESSION			
		CONSTANT	SLOPE	CORRELATION COEFFICIENT	CONSTANT	EXPONENT	CORRELATION COEFFICIENT	CONSTANT	EXPONENT	CORRELATION COEFFICIENT			CONSTANT	LINEAR COEFFICIENT	QUADRATIC COEFFICIENT	CORRELATION COEFFICIENT
30	4	192.01	-110.35	0.69	186.32	-0.713	0.73	93.45	-0.369	0.88	30	4	270.0	-493.3	342.61	0.88
30	8	253.25	-105.18	0.86	258.08	-0.537	0.87	159.28	-0.237	0.89	30	8	277.49	-225.75	106.48	0.89
30	16	376.11	-201.88	0.94	391.88	-0.763	0.95	200.42	-0.319	0.92	30	16	411.77	-379.29	156.67	0.92
45	4	158.14	-88.94	0.93	167.29	-0.839	0.95	80.10	-0.350	0.92	45	4	166.67	-131.40	37.50	0.94
45	8	194.85	-72.71	0.79	195.98	-0.454	0.78	128.44	-0.216	0.87	45	8	232.02	-257.60	163.28	0.91
45	16	289.33	-116.00	0.93	295.76	-0.518	0.95	189.00	-0.209	0.89	45	16	297.88	-158.51	37.54	0.94
60	4	116.69	-48.71	0.93	119.52	-0.545	0.95	74.54	-0.221	0.89	60	4	119.91	-64.76	14.18	0.93
60	8	177.56	-82.12	0.91	183.81	-0.636	0.93	106.27	-0.254	0.86	60	8	176.46	-76.67	-4.81	0.91
60	16	226.30	-68.94	0.63	225.32	-0.348	0.65	166.46	-0.142	0.62	60	16	240.55	-139.46	62.16	0.64

TABLE 27 Linear Regression of Normal Forces (Test Series II)

TEST NO	WORK SPEED (m/s)	WHEEL GRADE	DRESS LEAD (mm/rev)	INITIAL NORMAL FORCE (Newtons)	SLOPE ($x10^{-3}$)	CORRELATION COEFFICIENT (r)
J7	0.80	J	0.125	358	3.92	0.96
J5			0.25	362	9.40	0.96
J4			0.375	414	4.74	0.96
J2			0.50	344	2.92	0.91
J3			0.75	294	5.33	0.98
J18			1.00	350	5.65	0.97
J9	1.20		0.125	397	4.22	0.96
J14			0.25	401	5.08	0.96
J10			0.375	372	3.62	0.94
J16			0.5	442	4.90	0.92
J8			0.75	403	4.05	0.93
J17			1.00	392	6.12	0.93
J6	0.51		0.125	351	5.96	0.98
J1			0.25	380	3.87	0.93
J11			0.375	340	5.51	0.95
J12			0.75	389	4.11	0.84
J13			1.00	348	4.81	0.98
L9	1.20	L	0.125	644	7.52	0.91
L14			0.25	494	6.71	0.88
L10			0.375	536	8.09	0.96
L16			0.50	547	10.00	0.95
L8			0.75	626	6.12	0.90
L17			1.00	482	8.31	0.90
L6	0.51		0.125	506	6.45	0.96
L1			0.25	528	6.38	0.96
L11			0.375	480	9.38	0.98
L15			0.50	419	8.38	0.97
L12			0.75	480	9.68	0.97
L13			1.00	418	9.05	0.97
J15			0.50	317	6.79	0.97

continued/

Table 27 /continued

TEST NO	WORK SPEED (m/s)	WHEEL GRADE	DRESS LEAD (mm/rev)	INITIAL NORMAL FORCE (Newtons)	SLOPE ($x10^{-3}$)	CORRELATION COEFFICIENT (r)
N6	0.51	N	0.125	495	5.80	0.97
N5			0.25	427	7.24	0.96
N3			0.375	454	5.84	0.98
N17			0.50	404	6.00	0.97
N12			0.75	403	5.38	0.97
N9			1.00	379	7.04	0.99
N8	0.80		0.125	525	4.46	0.94
N16			0.25	488	5.28	0.97
N18			0.375	478	4.79	0.92
N11			0.50	386	6.36	0.96
N2			0.75	391	5.91	0.95
N7			1.00	398	6.71	0.97
N1	1.20		0.125	488	3.59	0.94
N14			0.25	485	4.05	0.94
N4			0.375	507	4.31	0.95
N15			0.50	396	6.62	0.99
N10			0.75	408	6.90	0.93
N13			1.00	405	5.96	0.98

GRINDING WHEELSPEED	60 m/s
DRESSING WHEELSPEED	30 m/s
DRESSING TOOL	Single Point Diamond
METAL REMOVAL RATE	16 mm^3/mm/sec

TABLE 28 Linear Regression of Tangential Forces (Test Series II)

TEST NO	WORK SPEED (m/s)	WHEEL GRADE	DRESS LEAD (mm/rev)	INITIAL TANGENTIAL FORCE (Newtons)	SLOPE ($x10^{-3}$)	CORRELATION COEFFICIENT (r)
J7	0.80	J	0.125	170	0.42	0.56
J5			0.25	185	2.56	0.82
J4			0.375	188	0.73	0.89
J2			0.50	168	0.37	0.82
J3			0.75	145	1.05	0.95
J18			1.00	149	0.62	0.92
J9	1.20		0.125	186	0.68	0.69
J14			0.25	174	0.29	0.66
J10			0.375	180	0.31	0.39
J16			0.50	176	0.25	0.80
J8			0.75	171	0.77	0.90
J17			1.00	161	0.63	0.76
J6	0.51		0.125	160	1.44	0.87
J1			0.25	188	0.65	0.86
J11			0.375	161	0.78	0.83
J15			0.50	151	0.52	0.82
J12			0.75	169	-0.77	0.12
J13			1.00	154	0.33	0.74
L9	1.20	L	0.125	230	0.47	0.42
L14			0.25	213	0.50	0.55
L10			0.375	193	1.26	0.83
L16			0.50	225	0.98	0.91
L8			0.75	191	1.58	0.76
L17			1.00	196	0.34	0.39
L6	0.51		0.125	195	0.80	0.85
L1			0.25	206	0.26	0.30
L11			0.375	188	0.96	0.80
L15			0.50	173	0.99	0.92
L12			0.75	179	1.81	0.88
L13			1.00	181	0.86	0.86

Table 28 /continued

TEST NO	WORK SPEED (m/s)	WHEEL GRADE	DRESS LEAD (mm/rev)	INITIAL TANGENTIAL FORCE (Newtons)	SLOPE ($x10^{-3}$)	CORRELATION COEFFICIENT (r)
N6	0.51	N	0.125	203	0.65	0.73
N5			0.25	193	0.64	0.84
N3			0.375	195	0.49	0.91
N17			0.50	188	0.50	0.80
N12			0.75	190	0.75	0.31
N9			1.00	184	0.20	0.43
N8	0.80		0.125	234	-0.36	0.63
N16			0.25	214	0.33	0.49
N18			0.375	210	1.38	0.18
N11			0.50	176	0.27	0.73
N2			0.75	181	0.32	0.60
N7			1.00	179	0.69	0.86
N1	1.20		0.125	220	-0.20	0.61
N14			0.25	216	0.16	0.36
N4			0.375	209	0.34	0.70
N15			0.50	189	0.61	0.93
N10			0.75	190	0.52	0.80
N13			1.00	181	0.80	0.79

GRINDING WHEELSPEED	60 m/s
DRESSING WHEELSPEED	30 m/s
DRESSING TOOL	Single Point Diamond
METAL REMOVAL RATE	16 mm^3/mm/sec

TABLE 29 Summary of Analysis of Variance

	COEFFICIENT OF FRICTION (μ)	INTERCEPT (C)
MAIN EFFECTS		
METAL REMOVAL RATE (M)		
L_M	392.22***	310.34***
Q_M	0.08	11.14**
WHEELSPEED (V)		
L_V	782.72***	44.80***
Q_V	32.13***	3.48*
DRESS LEAD (D)		
L_D	156.72***	2.59
Q_D	9.84**	1.18
2 FACTOR INTERACTIONS		
$L_M L_V$	3.46*	17.40***
$Q_M L_V$	0.86	1.77
$L_M Q_V$	0.35	1.13
$Q_M Q_V$	1.16	0.54
$L_M L_D$	3.46*	2.72
$Q_M L_D$	0.52	0.51
$L_M Q_D$	0.73	0.74
$Q_M Q_D$	0.02	0.06
$L_V L_D$	38.7***	11.90***
$Q_V L_D$	9.33**	2.27
$L_V Q_D$	0.00	0.11
$Q_V Q_D$	0.74	0.28
3 FACTOR INTERACTIONS	0.000058	548.09
TOTAL	0.0834	230736.36

*** highly significant, ** significant, * probably significant