THE DIAMOND GRINDING OF
REACTION BONDED SILICON CARBIDE

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A thesis submitted for the degree of
MASTER of PHILOSOPHY of the University
of Aston in Birmingham

1978.

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David Steele M Phil June 1978

SUMMARY

The development of ultra-hard materials and the multiplicity of use to which they can be applied, has highlighted several problems in the machining of such materials. The solution to some of the problems, such as that associated with very high hardness numbers, has been the introduction of a diamond grinding operation. Such an operation would not only remove the desired quantity of material, but also maintain both dimensional accuracy and surface integrity.

With the development of reaction bonded silicon carbides in the order of hardness of 2000 VDH, the problems became more acute. The object of this research is to investigate the process of grinding 'Refel' silicon carbide with diamond wheels and to make recommendations for good grinding practice. A series of grinding tests are undertaken, the ranking of these tests being qualified in terms of cutting forces, surface finish and 'G' ratio, that is the volume of stock removed compared to the volume of grinding wheel lost.

Key words: Grinding
Materials - silicon carbide
Diamond Grinding

ACKNOWLEDGMENTS.

My thanks are due to both the Director, and the Head of the Department of Production Engineering, at Wolverhampton Polytechnic for their support and consideration in placing the facilities of that establishment at my disposal.

Also to British Nuclear Fuels Limited and The Henderson Diamond Tool Co. for their help in supplying materials and tools for the project.

Finally, I am particularly grateful to Dr.E.Parker of Wolverhampton Polytechnic and to Dr. T.J. Vickerstaff for their help, and encouragement and for criticisms that were always constructive and courteous.

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NOMENCLATURE

The following features of grinding and grinding machines have been identified by symbols as shown below

SYMBOL	DEFINITION	UNIT
Vw	Work Speed	m/s
Vs	Wheel Speed (peripheral)	m/s
dw	Work diameter	mm
a	Radial in feed	μm/rev
h	Maximum undeformed chip thickness	mm
k	Number of grains per unit length of wheel periphery	-
n	Wheel Speed	Revs/min
g	Rate of Work Feed	μm/rev
g^1	Grain Diameter	μm
b	Width of Workpiece	mm
b^1	Mean Chip Width	μm
h	Depth of Cut	μm
	Length of contact or cut	mm
F_t	Tangential component of cutting force	N
F_n	Radial component of cutting force	N
G	Grinding ratio i.e. $\frac{\text{Volume of stock removed}}{\text{Volume of wheel removed.}}$	-
C	Number of cutting points per unit area	-
d_s	Wheel diameter	mm
e	Specific energy	J/mm^3
S	Metal removal rate	$mm^3/sec.$

1 INTRODUCTION

In many cases where other properties are satisfactory the performance of metallic materials often falls short of the requirements of designers and engineers. This is particularly the case when the ability of a material to perform under conditions of high stress and in hostile environments is essential. The limitations in the characteristics of a metal emphasise the need for a material with good chemical stability, a high melting point and very high hardness and strength values. Such a combination can be found in non-metallic materials and particularly in the characteristics of engineering ceramics such as silicon carbide.

The machining of ultra-hard material requires a diamond grinding operation and research into the optimum machining conditions for grinding carbides has recently been carried out by Hughes (1), who observed that using a resin bond diamond grit wheel in the wet condition produced the most economic results. However the improvement in the use of resin bond wheels over wheels with a metallic bond is quantified as less than 10% and Hughes acknowledged that bond technology is an incomplete area of study. In addition Rigvall (2) has investigated the economic aspects of the process and obtained results which emphasised the importance of grinding wheel wear and the stiffness of the machining set-up in determining total costs.

The results from these studies are not consistent, particularly with regard to conclusions on wheel speed selection and depth of cut. Whilst there is a body of opinion that suggests an optimum wheel speed of approximately 27 m/s, there is an alternative view, including that held by Wicks (3), that 4 m/s to 5 m/s is a much more economic and efficient value. Successful applications of slow speed grinding appear to be rare, but this could be due to the fact that slow speed grinding machines are not available for that process. In addition it has not definitely been established whether wet or dry grinding is to be preferred for grinding hard materials.

An examination of the problems of diamond grinding silicon carbides highlights three basic factors which have to be considered; the nature of the workpiece material, the nature of the diamond abrasive grinding wheel, and the geometry of the grinding process.

2 REVIEW OF DIAMOND GRINDING PARAMETERS.

In studying the factors involved in the process of grinding silicon carbide it is necessary to examine the construction of the abrasive wheel so that the variables inherent in the design can be established. The workpiece material will also be considered, its' properties examined and quantified. Finally the grinding process is examined, the parameters defined and the relevant factors recorded.

2.1 DIAMOND GRINDING WHEELS.

Natural abrasives such as sandstone, emery and corundum were used for centuries but have largely been replaced by manufactured abrasives which have more uniform composition and performance. Silicon carbide was discovered by Asheson (4) and the patent registered in 1893. Werlien (5) suggested the use of bauxite as a source of aluminium abrasive, a patent being taken out for a method of fusing aluminium oxide by Jacobs (6) in 1900. Silicon carbide and aluminium oxide both still remain major examples of abrasive materials used in the grinding process.

The superlative hardness of diamond has long been known to man and 70/75% of the worlds diamond production is devoted to industrial uses with 36% (7) going to the manufacture of grinding wheels.

<u>2.1.1. Diamond Types.</u> Any diamond that is too small, irregularly shaped, poorly coloured, or flawed to be of value as a gem is considered for industrial use. Three variations of industrial diamonds exist; bollas, borts and carbonards. Bollas or short borts are composed of concentrically arranged spherical masses of miniature diamond crystal; extremely hard and difficult to cleave. Bort is a grey to black massive diamond, the colour being due to impurities and inclusions. A low grade diamond

bort is extensively mined, crushed and graded into abrasive powders of various sizes. Carbonard is a black opaque diamond having a slightly porous structure. It has no cleavage and is valuable for use in diamond set tools.

2.1.2. Diamond Structure. The crystal structure of diamond is cubic, each atom being surrounded by four others all at the same distance and arranged at the corners of a regular tetrahedron. An X-ray diffraction analysis of diamond crystals has highlighted a very high concentration of electrons between the atoms in diamond and it is surmised that these strong electron bonds account for the extreme hardness of the materials. Bridgeman (8) has observed that although the diamond is dense and hard the atoms are not packed in the closest possible geometric arrangement. He states that a diamond would be much harder if each atom were surrounded by twelve other equidistant atoms instead of only four. He concludes that it may be possible to synthesise a 'super-diamond' if the atoms of diamond could be compelled to assume a closer packed arrangement than at present.

2.1.3. Synthetic Diamonds. Industrial uses of diamond are so important that a deficiency in the supply of industrial diamond may cause serious problems.
J. Ballantine Hannay, a Scots chemist, submitted small specimens he obtained experimentally to the British Museum for inspection in 1880, but it was not until 1943 that they were examined and found by X-ray analysis to be genuine diamond. Moissan in 1893 attempted to produce diamond in a series of unavailing experiments that attracted wide attention (9). The work of Willard Gibbs (10) led to the prediction of conditions under which a stable form of diamond would be produced. By subjecting graphite to high pressures and temperatures it was hoped to transform graphite into diamond. Bridgeman (8) winner of the 1946 Nobel Prize for Physics, carried out several experiments for General Electric Company of America in the year immediately after the Second World War and in February 1955

that company announced the first commercially viable synthesis of diamond. During the same period Wentorf (11) succeeded in preparing the cubic form of boron nitride known as 'BORAZON' by a pressure conversion method.

The use of cemented carbide, as a metal cutting tool, with the attendant need to grind such a tool, has stimulated the development of diamond impregnated wheels. The further use of super-alloys and ceramics has accelerated this trend. The diamond abrasive wheel can be considered in terms of three components; the abrasive grit, the bond holding the grit and the hub to which the diamond matrix is fixed.

2.1.4. Diamond Grit. It is possible to classify diamond grains into several types according to their geometric form. Grains may be of cubic block, irregular block, needle, flat and plate types. Irregular form grains having a large surface area are suitable for resin bond wheels while cubic form grains, because they are friable and more difficult to crush, are used for metal bond wheels. It is claimed (7) that the efficiency of wheels used to grind glass or graphite can be improved by up to 25% if the sharp edges of the diamond grit are removed and their surfaces polished before being incorporated into a wheel. Several investigations into the qualities of a diamond have been made by Komine and Obara (12) using a test grain, statically loaded whilst placed between two carbide plates. The strength of the grain was determined by recording the load level at which the particle broke down. The results indicated that a near perfect diamond crystal has the highest strength although a diamond grit selected for a metal bond wheel has a higher average strength than a diamond selected for resin bond wheels. Thus a wheel made with the former grit is used mainly for heavy grinding and a resin bond wheel would be selected for light grinding.

The results of an examination into the resistance of a diamond to impact loading, carried out by Tanaka and Ikawa (13), made it evident that the impact strength of a natural diamond was approximately twice that for aluminium oxide grains of the same size, and the conclusion was drawn that diamond is more suitable than aluminium oxide for impulsive grinding. The rapid rise and fall of the temperature of a grain during grinding must be considered because the thermal conductivity of a diamond is comparatively high. By subjecting diamond grains to successive thermal shocks and testing the compressive strength between each shock application it was found that the compressive strength diminished in direct ratio to the number of shocks. However Tanaka and Ikawa (13) conceded that the number of cyclic temperature changes in a typical grinding operation were not capable of being reproduced under laboratory conditions. The effect of thermal shock is thus very difficult to determine in quantitative terms.

2.1.5. Coated Abrasives. Metal coated abrasives have been developed (4) and it is reported that by applying a nickel coating of 30% by volume to each particle the resultant surface permits a more effective adhesion between grits and resin bond. The nickel coating acts as a heat sink and conducts heat away from diamond particle. The coated grit tends to be retained in the wheel longer than an uncoated specimen thus making the wheel act harder. Because of the somewhat limiting application of nickel coated diamond wheels to grinding situations requiring a coolant, an alternative coating suitable for dry grinding was developed, using copper. The copper coated diamond wheel is used only on carbide workpieces under dry conditions. Contact with steel usually results in premature diamond pull out due to a reaction between copper and steel. Metal coated synthetic diamond grains may be supplied in more controlled dimensional forms than can natural diamonds and can be adopted for grinding both brittle and ductile work pieces.

2.1.6. Wheel Bond. A wide range of matrices or bonds have been used for holding the diamond particles in the wheels. They include rubber, alkali-silicate, magnesium oxychloride, bronze, vitreous, graphite and resinoid (15). Only the last four are of any significance, although rubber-bonded diamond wheels are still used for polishing operations. The metal bond category includes the conventional sintered bronze, iron and steel bonds, single layer electroplated and sintered bonds as well as the newer free-cutting metal bonded wheels.

In the manufacture of metal bonds, two processes, sintering and infiltration are used. In the sintering process the diamond grit is mixed with the metal constituents in the powdered form, together with a wetting agent to improve bonding. The mixture is moulded at a pressure of 118 - 177 MN/m^2 (8 - 12 tons per square inch) and heated to sintering temperature under full load. A high-frequency induction method of heating is used and temperatures of 70 - 80% of the melting point of the metal matrix are required. To reduce the problems of oxidisation of the bond, sintering is usually carried out in either a vacuum or in a hydrogen atmosphere. During the infiltration process, a pre-pressed relatively porous skeleton consisting of a diamond grit and metal powder is covered with a suitable low melting point binder and heated to a temperature 15% higher than the melting point of the binder. The completely molten binder then infiltrates the porous skeleton by capillary action to form a solid matrix on cooling. A water soluble component may be incorporated in the matrix to produce a metal bonded wheel even cooler and more rapid cutting. During wet grinding the soluble component is leached from the bond by the coolant thus producing a porous wheel.

2.1.7. Hub Type The diamond grinding wheel consists of an abrasive layer incorporated on to a hub. Conradi (15) has stated that the performance of the diamond wheel can be related to the hub. His results showed that a decreasing 'G' ratio was accompanied by an increase in modulus of elasticity as shown in the table (a) of Fig 1. The effect of varying hub type in terms of surface finish was also investigated and the results obtained are shown below. They appear to indicate a reasonable correlation between surface finish and hub rigidity for a carbide workpiece.

Hub Type	·03 downfeed	·06 downfeed	
Fibre filled Phenolic	1.05	1.4	Surface Finish C L A µ m.
Aluminium/Phenolic	1.30	2.7	
Aluminium	1.45	3.2	
Mild Steel	1.65	2.05	
Carbide	1.22	7.5	

2.1.8. Classification of Diamond Wheels. Diamond wheels are manufactured in a variety of forms and sizes to suit differing grinding conditions. To enable test data to be related from one wheel to another some reference must be made to diamond wheel classification.

B.S. 2064 (16) provides a comprehensive system of classification by form and size. However in contrast to the case of aluminium oxide and silicon carbide wheels, no attempt is made to produce a complete system of identification for diamond wheels. Manufacturers employ widely differing methods and techniques, and a manufacturers name, reference number, bond type and size of diamond grit is the limit of many identifying systems. A more detailed system could include the following information :-

i Diamond grain size
ii Bond group
iii Concentration
iv Bond detail
v Bond type
vi Layer thickness.

Natural diamond sizes are graded according to BS 410 (1962) (17), and extend in a numerical range from 18 to 350. The British Standard can be compared directly with the German DIN 848 range, the equivalent ASTME 11 standard and Federation Europeinne de Fabricants de Products Abrasifs (FEPA) designation. Synthetic diamonds are graded to ASTME 11 standards.

The bond groups are:- M - metal, the most durable and least susceptable to accidental damage. N.P - electrometallic deposition of diamond and metal mix on to a formed metal base enabling complex wheel shapes to be developed. R - resinoid bonds which provide a free cutting wheel. RM - resinmet, the diamond is held in a porous metal bond infiltrated with resin.

The concentration of diamond grit within the matrix is an important factor and is represented by a number 100, 75, 50 or 25.

100 = 4.4 Carats (8.8 grams per cubic centimetre of bond matrix)
= 72 carats per cubic inch
= 25% diamond by volume of impregnation, thus 25 = 1.1 carats/cm^3
and 50 = 2.2 carats/cm^3

Bond layer is a maker designation relating to bond-application characteristics.

Bond type relates to the formal hub and reference to a manufacturers technical brochure must be made for this information.

Layer depth is usually indicated by a number representing a value of M representing metric measure, e.g. 2.5 M is 2½ millimetres.

2.2 SILICON CARBIDE

Silicon carbide is found in its natural state in meteoric irons such as Moissonite and occurs only in Arizona U.S.A. It can be pale yellow, green or black in colour. In its manufactured form it is a block crystalline material capable of withstanding temperatures up to its decomposing point of 4175° k. and is used both as a refractory and as an abrasive. Silicon carbide is manufactured by heating high grade silica sand and coke in an electric furnace at temperatures between 2250° k and 2900° k (18). The carbon monoxide produced burns on the surface of the charge. Thus it can be seen that :-

$$SiO_2 + 3\,C \qquad SiC + 2CO$$

The crystals obtained in this way are crushed and cleaned by acid and alkali washing treatments.

2.2.1. Refel. 'Refel' silicon carbide is made by a proprietary reaction bonding technique. Fine silicon carbide and graphite powders are mixed with a plasticiser and formed into shapes by extrusion, die pressing or isostatic pressing. These 'green' shapes are then siliconised in a furnace to produce a fully dense, completely impermeable product. When removed from the furnace the silicon carbide parts are covered with small nodules of silicon which have been exuded from the main body of the material while cooling through the melting point of silicon. The main body of the component may be wholly or partially covered with a layer of crystalline silicon carbide that is thought to be formed by reaction between carbon-monoxide and the surface free-silicon. Beneath this layer, typically 20 - 50 μm thick is a silicon-rich layer about 150 - 200 μm thick. This is formed by the partial burn-out of carbon by silicon monoxide. Below this silicon-rich layer is the denser bulk material. After siliconising, the silicon nodules, and as much of the fine silicon carbide layer as possible, are removed by shot-blasting with a fine alumina grit. The manufacturing process produces only slight dimensional changes in the material and consequently products can be formed to ± 0.25 mm without machining and it is claimed that "a finish better than 0.25 μm can be achieved". (20)

2.2.2. Applications of Refel. The material was first developed in 1965 by British Nuclear Fuels Limited, for cladding high temperature rod-type nuclear reactors with a product that was compatible with CO_2. The development of helium cooled reactors has made Refel redundant as a cladding material but several other industrial applications have been suggested. The low coefficient of thermal expansion, high thermal conductivity and high chemical stability of Refel suggest refractory applications for kiln and muffle fittings, with working temperatures above 1400°k. Messrs. Sealol Limited (19) have developed silicon carbide mechanical seals that show an improvement in working life over previous materials of the order x 10. Thin silicon carbide tiles have been made up into protective armour against high velocity armour piercing bullets and the material seems to have an application for rocket nose cones and flame tubes for gas turbines. It is the potential for industrial application of Refel that has stimulated this investigation into the machining characteristics with respect to diamond grinding.

2.2.3. Properties of Refel. The properties of Refel can be optimised by adjusting the proportion of graphite, so varying the free silicon content. Thus high strength applications requiring low silicon contents or alternatively high electrical conductivity and higher levels of free carbon can be obtained. A summary of the mechanical properties of Refel in comparison with other materials is shown in Table 1.A review of its physical and mechanical properties yields the following information (20) :-

i. Density :- 3.03 grm/cc maximum falling into the region of 2.82/2.95 grm/cc when free silicon is removed by a vacuum heat treatment or chemical leaching.

ii. Expansion coefficient:- $4.4 \times 10^{-6}/^{\circ}c$ between $0^{\circ}c$ and $1000^{\circ}c$.

iii. Specific Heat:- Estimated at between 1.03 and 1.4 within the temperature range 300° - $1200^{\circ}c$.

iv. Youngs Modulus:- This varies directly with silicon content and at room temperature is 430 GN/m^2 with 6% silicon and 380 GN/m^2 for Refel with 2% silicon.

v. Emissivity:- A total normal emissivity of 85% has been observed up to $1500^{\circ}c$.

vi. Poisson Ratio:- The mean value obtained from rosette strain gauge measurement is 0.24.

vii. Hardness:- Vickers hardness values of 2500 have been obtained using micro-hardness equipment.

viii. Strength:- For a ceramic this factor depends upon the largest flaw in the volume under stress, and for Refel it also depends on the presence, or lack of, free silicon. Fig 1b shows how bend strength will vary relative to these features under a range of temperatures.

ix. Compressive Strength:- The limited data available suggests a value for Refel of about 3.5 GN/m^2.

2.3 THE GRINDING PROCESS

Grinding can be defined as the use of a multi-point tool to remove material from a workpiece, the tool consisting of non-metallic abrasive particles retained in a suitable matrix. Shaw (21) defined the three basic qualities of primary importance in grinding operations as chip geometry, grinding force, and grinding temperature. The functions of the process include stock removal, generation of precise size and the production of a desired finish.

2.3.1. Grinding Geometry. Operational analysis is made difficult by the random shape of the abrasive particles, the minute chips produced and the rapidity with which they are formed. The earlier analysis of grinding referred to cylindrical grinding, and Alden (22) expressed the view that the abrasive grits each remove a chip from the workpiece and in doing so gradually wear, together with some of the bonding matrix in which they are supported. Alden further suggested that the ratio of the rate of grit wear relative to the rate of wear of bond is critical. If the bond wears too quickly the wheel will appear soft, and wear too rapidly. If the bond does not wear fast enough the grits will become glazed or polished. The efficiency of grinding action was thus related to the action of the workpiece on the bond, and this was, in turn related to the chip thickness.

Assuming the chip thickness to be 'a key' factor in grinding wheel performance then the relationship of work speed to wheel speed is important and could be used to predict the optimum working conditions for a particular operation. With reference to the action of a single grit 0 shown in the diagram fig 2 a general expression for grain depth of cut was obtained by Alden

$$h = \frac{v_W}{k.l} \text{ Sin } (\theta + \phi). \quad - - - - \quad \text{①}$$

where k is the number of grains per unit length of wheel periphery.

Guest (23) produced a theoretical analysis of work and wheel relationships that enabled chip dimensions to be calculated for a particular form of grinding. In his view the maximum force on a simple grit was assumed to be proportional to $v_w^2 . a. \left(\frac{1}{d_w} + \frac{1}{d_s} \right)$.

A fuller investigation into chip dimension and type was carried out by Mayer (24). A classification of chip type into five groups based on thickness to length ratios was produced for all types of grinding. Two parameters considered to be of utmost importance were the specific energy u^1, and the metal removal rate z. Both parameters were investigated and a series of tests indicated that they were both dependent on chip thickness. The previous assumptions of Alden and Guest were found to hold, with maximum force on a single grit varying with h^2 in fine grinding and $h^{1.1}$ in coarse grinding.

Shaw (21) compared grinding with micro-milling and concluded that in plunge cut grinding with no longitudinal feed of the work, the maximum penetration of the grain into the work is given by $t = \frac{a}{n.K}$.

If there are C grains per square millimetre of wheel surface and if the average grain width is b_1 then the number of grains ranged one behind the other around the circumference of the wheel is $K = \pi.d_s.b_1.C$. The ratio of the width of cut by a grain to the depth of cut by a grain is

$$r = \frac{b_1}{h} \quad - - - \quad ③$$

The terms C and r are difficult to evaluate and the number of cutting grains per sq cm has been estimated as

300 per cm^2 for a 48 grit wheel of 8 structure. Shaw obtained this value by rolling a grinding wheel over a soot-blackened glass plate and counting the number of points where the soot had been removed. A ground tapered reference plate was used to find the width to depth ratio r. A value of 15 for r was considered a good average for fine grinding.

In surface grinding operations the wheel and work are arranged as shown in fig 3, the depth of cut being greatly exaggerated. The path ABH traced by the tool point is a trochoid generated by a combination of circular movement of the wheel and horizontal movement of the work.

Referring to figs 3a and 3b

$$l = ABH \bumpeq BH$$

As θ is small when grinding,

curve BH $\bumpeq$ chord BH

$$\text{thus } l = BH = \sqrt{(HG)^2 + a^2}$$

$$= \sqrt{\left[\left(\frac{d_s}{2}\right)^2 - \left(\frac{d_s}{2} - a\right)^2\right] + a^2}$$

If a is considered small then a^2 can be neglected and

$$l \bumpeq \sqrt{(d_s . a)} \; - - - - \; ④$$

Shaw determined chip thickness with reference to its approximately flattened form shown in figs 3b and 3c

$$\text{Thus } h = EF = HE \sin\theta$$

$$\sin\theta = \frac{HG}{d_s/2} \text{ (from fig 3a)}$$

$$\text{But } HG = \sqrt{\left(\frac{d_s}{2}\right)^2 - \left(\frac{d_s}{2} - a\right)^2}$$

$$= \sqrt{d_s . a - a^2}$$

$$\text{hence } h = HE . \frac{2}{d_s} \sqrt{d_s . a - a^2}$$

$$= 2 . HE . \sqrt{\frac{a}{d_s} - \left(\frac{a}{d_s}\right)^2}$$

and as a^2 can be neglected $\left(\left[\frac{a}{d_s}\right]^2 = 0\right)$
then $h = 2.HE.\sqrt{\frac{a}{d_s}}$.

HE is the work feed per grit. If the grains are equally spaced and there are K in line/rev then $HE = \frac{V_W}{K \cdot n}$ where V_W is the rate of work feed/min

Substituting for HE

$$h = \frac{2\,V_W}{K.n}\sqrt{\frac{a}{d_s}} \quad - - - - \quad ⑤$$

In surface grinding the depth of cut changes from zero to $h_{max.}$ Referring to ③ and using the average depth of cut

$$b_1 = \frac{h.r}{2} \quad - - - - \quad ⑥$$

Now $K = \pi.d_s.C.b_1 = \frac{\pi.d_s.C.h.r}{2}$ and substituting for K in (5)

$$h = \frac{2\,V_{W}.\,2}{n.\pi.d_s.C.h.r}\sqrt{\frac{a}{d_s}}$$

$$\therefore\ h = \left(\frac{4.\,V_W}{.\pi.d_s.C.n.r.}\ . \ x\sqrt{\frac{a}{d_s}}\right)^{\frac{1}{2}} \quad - - - - \quad ⑦$$

Attempts to formulate basic concepts of the grinding process have been confined to grinding parameters that depend upon the undeformed chip. No consideration is given to chip deformation, or to the effect of interference of successive grits on previously cut chips.

2.3.2. Grinding Forces. Marshall and Shaw (25) reported a more extensive investigation in which relationships between undeformed chip length, cross-sectional area and volume for various shapes were examined, using schematic diagrams. They identified the radial, tangential and friction forces acting on a grit and chip during cutting and produced a relationship between Ft and e_1, the specific energy. Fig 3d shows a section through an abrasive grit as it removes a particle from the workpiece. The tangential and radial forces exerted by the grit on the work are balanced by the normal and frictional forces between the chip and the grit. For a given rake angle the ratio of radial to tangential force is indicative of the coefficient of friction on the grit face. The magnitude of Ft can be related to the specific energy of metal removal thus:- Ft = e.A where A is the instantaneous undeformed chip area.

Grisbrook (30) considered that the cutting forces were a function of speed of wheel and work, and expressed specific energy in the form $e = \frac{V_s}{V_w} . \frac{F_t}{b.a.}$ - - - - ⑧

The specific energy is seen to be of fundamental importance in grain kinematics; it is related to chip thickness and cutting speed. Reduction in chip thickness leads to an increase in specific energy whilst an increase in cutting speed will yield a lower grain/chip interface friction and consequently a reduction in specific energy.

The value of specific energy can be evaluated in terms of geometrical parameters of the chip as follows ---

$$- - - - - \quad e = \frac{\int_0^{l_m} \mu A \, dl}{\int_0^{l_m} A \, w \, dl} \quad - - - -$$ ⑨

where l_m = maximum chip length
and l = contact length

The quantity e was found by Marshall and Shaw to be very much larger than its counterpart in metal cutting and to vary with undeformed chip thickness 'h'.

$$e(\text{energy/unit volume}) = 30h \text{ if } h < \cdot 001 \text{ mm}$$

$$e = \frac{.0092}{h^{\cdot 8}} \quad \text{if } h > .001 \text{ mm}$$

2.3.3. Wear Theory. The analogy between single point cutting and grinding was questioned by Buttery (26). In his view grinding should be considered in terms of the interaction between surfaces. Buttery develops the view that rake angle of the grits is critical and states that most grits on a grinding wheel have a negative rake. He also emphasised that the inconsistency between Ft and Fn in the previous work, compared to conventional machining, tends to confirm the view that forces observed when grinding hard or soft materials are the same. The variation indicated by Buttery between predicted and observed forces in grinding lead to the development of an assessment in terms of volume wear ratio per unit of sliding distance.

$$\frac{\text{Volume wear}}{\text{Sliding distance}} = \frac{0.5\,\alpha\,\beta\,\underline{\text{Cot }\theta}}{H}$$

where α = proportion of grits cutting
β = proportion of groove removed
W = load
θ = ½ angle of scratches
H = hardness of work piece

β Cot θ is termed the 'k' factor and each parameter is of definite physical significance. Buttery's work tended to confirm the views of Stroud (27) that only a portion of the groove volume was removed by cutting. Wetton and Rowe (28) developed a theory of metal displacement by grinding that was analogous to bulge formation in strip drawing. It was predicted that material could be removed in the form of continuous swarf or be displaced without being removed from the surface being ground. A major factor in this concept was the geometry of the grit. Quantitative predictions were made about the deformation and were verified by experiments with a large scale grit sliding in plasticine. It was considered more realistic to assume that the rake angle would be negative rather than assume a particular angle for that rake. The analysis pointed out the apparent inadequacy of previous work in the failure to appreciate that work piece material will be displaced laterally as well as forwards by the grits and that there will be interaction between neighbouring and following grits. It was suggested that only 10% of all the chips obtained by grinding were the result of direct cutting; the remainder were sheared from the walls by succeeding grits. Hahn (29) attempted a reconciliation of the distinct views on metal cutting and metal displacement. i) Rubbing where grits are forced against the work and cause elastic and/or plastic deformation ii) Ploughing where the grits cause plastic flow of the work material in the direction of grinding with extruded metal being forced up and broken off along the sides of the groove, and iii) cutting, where fracture takes place in a plastically stressed zone just ahead of the grit. This latter forms a chip and results in rapid stock removal rates. Hahn examined the effects of different depth of cut and found that the increase in depth of penetration of the grit produced a transition from elastic deformation through ploughing to chip formation as shown in fig 4a together with a reduction in the force increment required to produce a unit increase of depth of metal removed. It was further proposed by Hahn that chip formation was initiated by minute imperfections in the metallic structure of the workpiece and that the presence of a flat on the grit inhibited the formation of chips and tended to result in metal removal by elastic deformation.

In 1960 Grisbrook (30) made an extensive investigation into surface grinding and his results substantiated much of the work done by Marshall and Shaw. He performed tests which indicated that the dulling of grits increased both Ft and Fn and also showed that optimum speeds for work and wheel produced constant forces with long periods of free cutting. The magnitude of cutting force can be related to specific energy by the following expression

$$\text{Power} = F_t \cdot v_s = b.a.v_w.e$$

$$\text{thus} \quad Ft = \frac{b.a.v_w.e}{v_s} \quad - - - - \quad (11)$$

The specific energy has been shown by Backer (31) to vary as follows:-

when maximum chip thickness $h > 1$ mm, $e = \frac{k_1}{h^{0.8}}$

when maximum chip thickness $h < 1$ mm, $e = k_2$

The value k can be related to the specific energy for turning. $k_1 = 0{\cdot}0092\ eh$; $k_2 = 30\ e_t.h$. where $e_t h$ is the specific energy for turning a similar material using a feed of 0.025 mm/rev and a 15° rake.

Backer and Shaw (34) have used micro-milling techniques to simulate the grinding process. Their test results illustrated an idea of 'size effect', which is analogous to the increase in strength of wires as their diameter is decreased. They suggest that due to the small size of grinding chips a similar effect would occur in grinding and, using small cuts, they have shown that as the undeformed thickness of the chip is reduced, so the energy per unit volume required to remove the material increases to a maximum limiting value.

2.3.4. Surface Finish A prediction of the surface finish obtainable in a grinding operation was made by Shaw (21) who produced an expression for the maximum peak-to-valley distance 't' in fig 4. The value of the pitch 'p' of the pattern left on the surface is given by the work velocity divided by the number of grains that cut a given path of width b^1 per unit of time.

$$\text{Thus}\quad p = \frac{v_s}{v_w.b^1.c} = \frac{2v_s}{v_w.c.r.h}$$

Applying the approximation used in equation ④

$$p = \sqrt{d_s.a}$$

and by combining the above with ⑦

$$t = \frac{h^2}{16a} \quad - - - - \quad ⑫$$

The maximum peak to valley distance actually measured could differ from the figure obtained in ⑫ due to

i vibration of the wheel and work,
ii built up edge on certain grits and,
iii deviation in the actual situation from the anticipated situation

From this review it can be seen that grinding, like most other machining operations has certain parameters which govern the overall efficiency of the process and determine its nature. An example of the effect of the parameters is shown in the results presented by Krabacher (33) from a series of tests and set out in table 2.

Reference to the range of variables shown in table 3 shows that, although not all the factors shown need be critical, it would be a vast task to investigate every factor independently. Thus an experiment was devised that was economic and yet comprehensive.

3 ANALYTICAL TECHNIQUES

The review of the many research investigations into grinding parameters emphasised the extreme difficulty of examining a single feature of the grinding process in isolation. Several variables are involved as shown in Table 3, and during a grinding operation any of these variables, singly or in combination could influence wheel behaviour. A possible solution proposed by Wetton (37) to the problem caused by the number of variables would be the development of standard test rigs. If such a procedure was not possible, any investigation must be considered as relating only to those conditions appertaining during the test. Some attempt to provide a basis for comparison purposes has been made by Peters (38), using C.I.R.P symbols and units.

It may not be possible to determine in advance whether a series of factors are independent of each other, but factorial experiments provide a test of the assumption of interdependence. Information is thus obtained on the responses to the different factors and also on the effects of changes in the level of each factor on the responses to others.

3.1. FACTORIAL EXPERIMENTS.

It is convenient to begin the discussion of the design of experiments by introducing some definitions and an example (34). Each basic grinding parameter is called a 'factor' and the number of quantities of a factor are called the number of 'levels' for that factor. A particular combination of one level from each factor determines the 'treatment' and the experiment is called a 'factorial experiment' if all, or nearly all, the factor combinations are of interest.

3.1.1. Notation.

It is proposed to use the notation adopted by Yates (35) in which the letters A, B, C, D ---- etc denote the factors. A factor appearing at a high level in any treatment is identified by a lower case letter a, b, c, d, - - - etc. The absence of a lower case letter in any treatment combination indicates that in the treatment considered, that particular factor is at a low level. Thus in a 2^5 experiment with factors A, B, C, D and E, the treatment combination 'ab' indicates that factors A and B are at a high level and factors C, D and E are at a low level. The treatment combination of all factors at a low level is indicated by 'l'. The letters A, B, and AB when they refer to numbers, represent the main effects of factor A, factor B and the interaction of A with B respectively.

An example relating to the composition of metals may be used to illustrate the use of these definitions. In a trial on a cutting tool material, the steel contained three factors for examination; chromium 'A', vanadium 'B', and molybedenum 'C'. In eight steel specimens the constituents were either present in a standard amount or absent, as shown in the following table:

Specimens	Factor A	Factor B	Factor C	Specimen
1	No	No	No	l
2	Some	No	No	a
3	No	Some	No	b
4	Some	Some	No	ab
5	No	No	Some	c
6	Some	No	Some	ac
7	No	Some	Some	bc
8	Some	Some	Some	abc

The example relates to an experiment with three factors, each on two levels. It is convenient to describe it as a 2 x 2 x 2 (or 2^3) experiment. A factorial experiment in which each combination of factor levels is used the same number of times is called a complete experiment and the estimation of separate effects of interest is simple only when the experiment is complete or the experimental design has a high degree of symmetry.

3.1.2. Analysis of experiments. The simple effect A is measured four times in the example, by the following pairs of observations :-

$(a) - (1)$; $(ab) - (b)$; $(ac) - (c)$; $(abc) - (bc)$.

The main effect of A is defined as the average of these simple effects.

Thus:- $A = \frac{1}{4}\left[(a) + (ab) + (ac) + (abc) - (1) - (b) - (c) - (bc)\right]$.

Similarly the main effects of B and C may be expressed as

$$B = \tfrac{1}{4}\left[(b) + (ab) + (bc) + (abc) - (1) - (a) - (c) - (ac)\right]$$

and $$C = \tfrac{1}{4}\left[(c) + (ac) + (bc) + (abc) - (1) - (a) - (b) - (ab)\right]$$

The interaction of two factors is known as a first-order effect. To compute first-order interactions, use is made of a basic rule called 'Evens versus Odds'. The yields for units that contain an even number of letters in common with the interaction are considered positive and those having an odd number of letters are considered negative. Thus for interaction AB :

$$AB = (ab) + (abc) - (a) - (b) + (c) - (bc) - (ac) + (1).$$

3.1.3. Significance Tests Any conclusions to be drawn from the experiment are based on the difference between samples and if such a difference could have arisen by pure chance, it would be incorrect to assume that it arose through interaction of the factors. The samples used are drawn from populations and if the difference in samples is valid then there will be a difference in the populations.

A particular test known as an 'F' test can be used to check the population for difference. This test is termed a variance ratio test and the variance ratio can be developed as $F = \dfrac{\text{Greater estimate of the variance of population}}{\text{Lesser estimate of the variance of population.}}$

The variance is defined as the mean square deviations of several items taken from their grand average. If $\bar{X}$ is the

grand average (the individual items being denoted by $\bar{x}$) then for a number of items N, the variance is given by
$V = \frac{1}{N} (\bar{x} - \bar{X})^2$.

Yates carried out an analysis (36) in order to establish the significance of the estimates made from the response to factors. The treatment combinations were set down in order, the introduction of any letter being followed by its combinations with all previously introduced treatment combinations. The corresponding treatment responses were then placed in the next column. The data was analysed in stages using a particular technique and explanation will be simplified if a numerical example is introduced at this stage relating to the definitions given in 3.1.1. The table below shows the responses in terms of Brinell Hardness Number obtained from specimens having three factors at two levels.

Combinations	Responses	I	II	III	IV
l	242	473	1190	2427	-
a	231	717	1237	67	561
b	361	508	16	465	27028
ab	356	729	51	11	15
c	268	-11	244	47	276
ac	240	-5	221	-55	378
bc	376	-28	6	-23	66
abc	353	-23	5	1	0.125

In the top half of column I the responses are added in pairs i.e. 242 + 231 = 473; 361 + 356 = 717. In the lower half of column I the first response is subtracted from the second i.e. -242 + 231 = -11. The same process is applied to column I to obtain column II, then to column II to obtain column III. In a 2^n experiment, 'n' columns would be used and column 'n' would contain the effective totals. Column IV in the table contains the effect mean square values which are obtained by dividing the square of the total in the previous column by the number of treatments considered. Each of the quantities in column IV of the table is the algebraic sum of eight observations and the totals may be checked using the equations

$$\Sigma(I^2) - \frac{(\Sigma I)^2}{n} = \Sigma \text{Col III}$$

viz : $$242^2 + 231^2 + 361^2 ---- + 353^2 - \frac{(2427)^2}{8}$$

$$= 28100$$

The sum of column IV agrees with this total within rounding off errors.

The results of the above computation can be used as a basis for an analysis of variance. The data is set out in the following table.

Combinations		Mean Square Values		Degrees of Freedom
a	Main effects	561		1
b		27028		1
c		276		1
ab	Two factor interactions	15	459	4
ac		378		
bc		66		
abc	- others	.13		

When all interactions are combined the estimate of error variance, based on four degrees of freedom, is equal to 459.

The number of degrees of freedom in any variance calculation is one less than the total number of combinations (in example there are eight combinations with seven degrees of freedom). Three levels of confidence can be assigned to any result depending on the probability level associated with the judgement. Three such levels are in normal use:-

(i) 'Probably significant' - results which would only arise once in twenty trials by chance.

Probability $p = 0.05$

(ii) 'Significant' - results which would only arise once in one hundred trials by chance.
Probability $p = 0.01$.

(iii) 'Highly significant' - results which would only arise once in one thousand trials by chance
Probability $p = 0.001$

Fisher and Yates (39) tabulated 'F' values for three levels of probability for various combinations of degrees of freedom. It is possible to use these tables to assign statistical significance and confidence limits to the results of various combinations of levels. By combining all but the main effects in the table of results an error variance of $\frac{459}{4} = 114.7$, is obtained, based on four degrees-of-freedom. From the statistical tables (39) the 5% value of 'F' is 7.71 and the 1% value of 'F' is 21.2. Mean square values in excess of $7.71 \times 114.7 = 884.4$ are probably significant and mean square values in excess of $21.2 \times 114.7 = 2431.6$ are significant.

From this analysis the size of the 'F' value can be used to give an indication of the significance of the treatment effects. It can also be seen that the addition of factor B (vanadium) to the steel has a significant effect on the hardness of the steel. The combinations of the three factors considered are probably insignificant. The main effect of 'b' is expressed as

$$B = \tfrac{1}{4}\left[b + ab + bc + abc - \lfloor - a - c - ac\right]$$

$$= \tfrac{1}{4}\left[361 + 356 + 376 + 353 - 242 - 231 - 268 - 240\right]$$

$$= 116.25$$

Thus it is concluded that the addition of factor B to the steel increased the hardness of the steel by 116·25 on the Brinell hardness scale.

<u>3.1.4. Design of factorial experiment.</u> When the design of factorial experiments is considered, the following questions are usually involved

a) What factors should be included ?
b) At what levels should the factors be taken ?
c) How many experimental units should be used ?

d) What measures should be adopted to reduce the effect of uncontrolled variations

In considering those factors which may be included in an experiment, any decision will be guided to some extent by questions of economy and simplicity. However for initial consideration a comprehensive list of factors likely to be relevant is drawn up although some of them may be neglected until a later work and a less ambitious list produced from within the initial one.

Treatment factors are selected from those factors of direct interest; factors which modify the action of the main factors and factors connected with experimental technique. Classification factors are of two types, i) variations in experimental material and ii) deliberately inserted variations in the experimental units designed to examine interactions.

Sufficient levels of factors must be provided to satisfy statistical considerations and at the same time the levels must be kept as small as possible for experimental convenience. The extreme levels are governed by the limitations of experimental equipment but should reflect commercial practice.

3.2. 'ECONOMIC' ANALYSIS

The total cost of producing machined components consists of raw material costs, together with machining costs and factory overheads. For many components the volume of material used is only a small proportion of the volume of the product. In such cases the adoption of metal forming or casting processes is recommended, rather than the use of metal cutting techniques. Silicon carbides are comparatively costly as well as having mechanical properties that preclude the selection of many machining methods. Diamond grinding is, in many cases, the only suitable machining method but the high capital cost of diamond grinding wheels emphasises the need for an examination of the mechanics of material removal and of costing techniques.

3.2.1. Costing Techniques. Weimann (41) has identified the factors that give an indication of costs related to the grinding process. These are - volumetric removal rate (N_V), and the specific total costs (K_G). The volumetric removal rate N_V is defined as the volume removed from the workpiece in unit time.

$$\text{Therefore } N_v = a.b.v_w \quad - - - - \quad (13)$$

The costs of grinding wheels together with machining costs resulting from the removal of a unit volume of workpiece material are described as specific total costs.

$$\text{Thus } K_G = K_m + K_D \quad - - - - - \quad (14)$$

$$\text{where } K_m = f(N_v) + \frac{Kmz}{a.b.v_w} \quad - - - - \quad (15)$$

$$\text{and } K_D = C_1.N_v = S_3\, K_{DV} \quad --- \quad (16)$$

$$\text{Thus } K_G = \frac{Kmz}{a.b.v_w}. + S_3\, K_{DV} \quad - - - \quad (17)$$

where K_m is machine costs in relation to the removal of a unit volume of work,

K_D is the cost of diamond wheel,

K_{mz} is the cost of unit time of grinding work,

K_{DV} is the cost of unit volume of diamond layer,

N_v is the volume removal rate

S_3 is the related volumetric wear of diamond layer,

and C_1 is the constant depending on conditions.

K_G, K_m and K_D are all expressed in £ per cm^3

S_3 and N_v provide a relationship, shown in fig 5, which leads to the conclusion that any increase of the removal rate (i.e. a decrease in production time) will lead to a reduction in K_m and an increase in K_D. The trend of the curve for K_G shows that for a certain value of removal rate N_v, a minimum value of specific costs K_G is reached. The example shows that under certain conditions, manufacturing problems, especially time problems can be solved on available machines without the costs rising at a rate which is proportional to the higher output achieved.

Tarasov (42) showed that changes in the size of wheel and workpiece had relatively small effects on K_G unless the process resulted in high wheel wear. Thus if a diamond wheel is found to be more economically viable than an aluminium oxide wheel for a particular operation, changes in work size or wheel size will not effect specific costs. If however an aluminium oxide wheel is found to be more economical, then changes in wheel wear will effect K_G in relation to workpiece size.

Any economic appreciation of the process must be designed to use the information available and relevant to the problem involved. From the data used in this investigation it was considered that a simplified cost equation used by Ratterman (43) would provide evidence of the most economic rate of material removal.

$$\text{So} \quad K_G = K_m + K_D$$

$$K_m = \frac{Ct}{S} \quad \text{and } K_D = \frac{Y}{G}$$

where C_t is the time cost, and Y is the cost per unit volume of the diamond. In the results the values for C_t and Y are the latest available. However, the values are subject to inflation and only provide the form of the cost- material removal relationship without a specific price being stated.

4. EXPERIMENTAL TEST EQUIPMENT

The test equipment can be considered in terms of four distinct units; the machine tool, the cutting tool, the workpiece material and the force measuring equipment.

4.1. MACHINE TOOL.

The tests described in chapter 5 were performed on an Elliot 921 hydraulic surface grinding machine which was modified to take a 360 mm diameter wheel. The existing drive system incorporated a two-speed pulley system which provided speeds of 2140 RPM and 2850 RPM. The hydraulically-operated worktable produced an infinitely-variable workpiece velocity in the range 5.8 m/min to 21 m/min.

4.1.1. Modifications to the machine tool. In order to take full advantage of the characteristics of the diamond wheel provided, a special machine guard was designed and constructed, to incorporate the coolant outlet and dust extractor system. In addition modified pulleys were fitted so that the available speed range then included three further speeds of 1200 RPM, 1400 RPM and 2000 RPM. Details of manufactured items are shown in plates 1 and 6. The spindle speed was measured by means of a Smiths Instrument tachometer.

4.1.2. Coolant Supply. A function of the cutting fluid is to reduce the effect of the thermal shock caused by the impact of successive grits upon the workpiece. As the wheel speeds were increased, the application of coolant became more difficult due, in part, to the failure of the fluid to penetrate the air blanket that was developed around the fast running wheel. An insert was then fitted to the pipe to decrease the internal diameter. In this way the pressure of the liquid was increased to ensure improved penetration into the grinding area. The coolant used was a 40 to 1 solution of water and Shell Dromus 'B' flowing at a rate of 1 litre per minute.

4.2. GRINDING WHEEL.

Wheels were supplied by Henderson Diamond Tool Ltd. and Norton Grinding Wheels Limited. The selection of grit size and concentration was such that the resin bond wheel and metal bond wheel were compatible. The wheel width was always greater than the width of the workpiece so that a transverse wheel profile would give an indication of wheel wear. The particular wheels used in the test were

i) A 355 mm Henderson wheel with metal bond.
Ref D 180/200 - N 75 - KM 3 - $\frac{1}{8}$
ϕ 355 x 75 x 12.5

ii) A 250 mm Norton wheel with resin bond.
Ref A.S.D. - 180 - R - 500 - B $\frac{1}{16}$
ϕ 250 x 75 x 9

4.2.1. Preparation of the grinding wheels.

Three stages can be considered in the preparation of a diamond grinding wheel (44). Separate operations have to be carried out before any stock removal is contemplated and may be described as

i) Setting up : ii) Trueing : iii) Conditioning the wheel.

A check was first carried out on the condition of the flanges. In good condition the flanges should be free from burrs and irregularities, and close on the diamond wheel. The balance weights were spaced equally, the wheel fitted in position on the flange and the bolts tightened to hold the wheel. The wheel was then placed on a balancing frame and the position of the weights adjusted until static balance was obtained, i.e. when the wheel remained stationary in any position on the frame.

The object of trueing the wheel is to bring the wheel to a state of roundness so that every point on the periphery can take part in the grinding operation. To achieve this condition an aluminium oxide wheel (WA6OKVSG) was mounted in a brake-controlled trueing device. The device was mounted on the magnetic table so that the diamond wheel and the trueing wheel were parallel to each other. The machine was switched on and with the spindle rotating, the cross feed was engaged so that the trueing wheel passed slowly backwards and forwards beneath the diamond wheel (plate 2). The diamond wheel was then fed down vertically until the two wheels engaged, after which down-feed continued at a rate of 0.01 mm at every table reversal. The grinding machine was stopped after every ten cycles to check the surface of the grinding wheel. Trueing continued until it was apparent that the whole of the diamond wheel periphery had been in contact with the trueing wheel. The balance of the wheel was then re-tested and adjustments made as required. Metal bond diamond abrasive wheels required a further dressing operation which was effected using a stick of soft aluminium oxide held against the diamond wheel for a few seconds. Care was taken to see that the stick was applied evenly over the whole surface of the wheel.

A diamond wheel is in its optimum condition when the surface texture has been so altered that the wheel performs to its best advantage on any material. After setting up, and trueing, the diamond wheel was required to make ten passes at a depth of 0.015 mm over a workpiece, before recorded tests were taken, as this was found to produce the best surface condition on the wheel.

4.3. WORKPIECE MATERIAL

Bonded silicon carbide strip (trade name Refel) was provided by British Nuclear Fuels Limited in rectangular sections approximately 12 mm x 6 mm. It was cut into lengths of 75 mm on a Struers Abrasive Slotting machine fitted with a resin bonded diamond wheel of size 200 x 21 x 1 mm and reference ASD180 R75 ·B$\frac{1}{8}$ .B56. Initially it was found that a clean cut was difficult to achieve and the silicon carbide tended to chip or splinter whilst being sliced. Reference to the work of Shaw (40) on abrasive cutting indicated that an improvement in efficiency could be obtained by clamping the work on one side only. This proved to be the case and subsequent test pieces were cut from the strips provided without further difficulty. The hardness of the material was tested on a Vickers Pyramid Hardness Testing machine. Three specimens were tested from each strip and each specimen was tested in six positions, three per side.

The average hardness numbers were	I	1951 VDH
	II	2044 VDH
	III	1916 VDH

4.4. FORCE MEASURING EQUIPMENT

The equipment consisted of a measuring platform, a charge-amplifier, a galvo-amplifier manufactured by Kistler Limited, and an ultra-violet recording device manufactured by Southern Instruments Limited. The workpiece was mounted in a special clamp which was itself fixed to the top of the measuring platform (Plate 1).

4.4.1. Measuring Platform. The platform incorporated piezo-electric transducers for measuring component forces in mutually perpendicular directions. For each of the three force components a proportional electric charge was set up. The charges were fed into a charge amplifier where they were converted into proportional voltages which were measured and recorded as required. A diagram of the measuring platform is shown in Fig. 6. The platform was capable of recording forces in all three axes up to a maximum of 5000 N, within a temperature operating range of ± 100°c. Sensitivity in the two planes used in the tests was ± 3.5p C/N.

4.4.2. Charge Amplifier. The Kistler charge amplifier was a mains-operated D.C. amplifier of high impedance, intended to convert the electrical charge from the piezo-electric transducer into a proportional voltage at the low impedance amplifier output. Standard amplifier sensitivities of from 1 mV per unit of force in stages, up to a maximum of 500 V per mechanical unit were available and it was possible for sensitivity to be indicated directly as a measuring range. Thus a range of 100 N per volt when used with a sensitivity of 1 volt per centimetre, provided a scale on the recording paper of 100 N to 1 cm.

4.4.3. Galvo-Recorder. The galvo recorder was a mains fed D.C. unit, with a variable sensitivity of from 1 mA per volt to 100 mA per volt. The direction of the signal could be reversed and an overload protection unit was fitted. A calibration signal of either ± 1 volt or ± 5 volt was set up in the signal generator so that sensitivity could be checked periodically and corrected if necessary.

4.4.4. Ultra-Violet Recorder. A 10-300 series Southern Instruments Oscilloscope was used and twelve channels were provided with frequencies up to 10 K.Hz. Each signal was fed to a miniature tubular galvanometer which reflected a spot of intense ultra-violet light onto photosensitive recording paper. The deflection of the galvanometer, and hence the movement of the light spot, was a function of the amplitude of the input signal. The images became visible shortly after exposure to light and were then lacquered to provide a permanent record. The recorder operated from a single phase A.C input, and the maximum power requirement was approximately 425 VA. A choice of twelve paper speeds was available; together with a dimming device and a timer.

4.5. MACHINE TABLE SET UP

The workpiece was held in a holding device (plate 7) fixed to the measuring platform. The device could be adjusted horizontally and vertically and also permitted the workpiece to be lined up with the axes of the machine table.

A shield under the workholding fixture screened the platform connections from a direct flow of coolant and was found to prevent any change in scale or datum on the galvonometers when alternating test readings between wet and dry conditions.

5. TEST PROCEDURES

The test programme began with two complete 2^5 factorial experiments with cutting forces as the output by which performance was assessed. The results of these experiments were processed and two sets of cutting tests were then completed using those factors found to be significant in the previous work. A further 2^5 factorial experiment was carried out with surface finish as the measure of performance. Two sets of tests enabling the grinding ratio 'G' to be calculated for a resin bond wheel and a metal bond wheel completed the experimental work and the results were used to estimate comparative economic costs.

5.1. FACTORIAL EXPERIMENT (OUTPUT-CUTTING FORCE)

The machine tool inputs of wheel speed, work speed, depth of cut and use of coolant, together with equivalent wheels of a resin and a metal bond provided five factors which were examined for significance by means of a factorial experiment. The outputs by which each factor would be assessed were tangential cutting force, radial cutting force and the grinding coefficient (F_t/F_n). The Kistler Dynamometer (4.4) recorded the cutting forces and enabled an instantaneous value to be obtained without altering the setting of the work and machine tool.

The factorial experiment was run twice to give integrity to the results, the conditions being identical in each case. The factors were identified as shown in the following table.

FACTOR	IDENTIFICATION	HIGH LEVEL	LOW LEVEL
BOND	A	METAL	RESIN
WHEEL SPEED	B	2199 m/min	1540 m/min
WORK SPEED	C	21 m/min	5.8 m/min
DEPTH OF CUT	D	0.055 mm	0.015 mm
COOLANT	E	Wet run	Dry run

Thirty minutes free running of the machine tool spindle and hydraulic system was allowed before any recorded tests were conducted; a procedure similar to that adopted by Grisbrook (30). Each new test piece was machined until a completely ground surface was exposed so that comparable surface conditions were obtained for successive pieces. When these conditions had been fulfilled, with the workpiece in position and cutting depth and table feed set, a test run was made. Three unrecorded cycles were first completed to ensure that the test piece was straight and to reduce the effect of a fully dressed wheel. Three recorded cycles were then made for each test run. No discernable difference in wheel speed was recorded when either up-cutting or down cutting. Similarly, no change in wheel speed was found between the conditions of idling or cutting. The test results are shown in tables 4, 5, 7 and 8.

5.2. CUTTING TESTS.

From the results of the factorial experiment, it was found that the factors of work speed bond type and depth of cut were probably significant in determining cutting forces. A further two series of experiments were carried out in order to examine the relationship between cutting forces, minimum chip thickness and specific energy. Each series comprised 25 tests and the tangential and radial forces were recorded by the Kistler dynamometer. The tests were conducted using a cutting fluid to aid the extractor unit in the task of dispersing silicon carbide dust which would have made operating conditions unpleasant. The two series of test were carried out in random order to minimise any possible bias.

Test Details

Resin bond wheel : Speed of wheel 2199 m/min
Depth of cut : 0.015 mm, 0.025 mm, 0.035mm, 0.045 mm, 0.055 mm
Work speed : 6.25 m/min, 7.56 m/min, 11.6 m/min, 18.2 m/min, 21 m/min

The results are shown in tables 12 and 13.

5.3. SURFACE FINISH FACTORIAL EXPERIMENT.

The machine tool inputs of wheel speed, work speed, depth of cut, wheel bond and use of coolant provided five factors for a 2^5 factorial experiment where surface finish was used as the output for comparison of performance.

The work holding platform from the previous factorial experiment was used, and mounted directly on the magnetic chuck. The platform was positioned with a set square to ensure uniformity of horizontal work axis.

The surface finish of each specimen was measured on a Rank Talysurf 4 and the average values of three measurements in three positions on the specimen were used in the variance estimate. The results are shown in tables 6 and 9. Each specimen was marked so that the feed direction relative to the grinding wheel rotation was known and the measurement of surface finish was made in the same direction on each specimen (plate 5). The test conditions were identical to those shown in 5.1.

5.4. ECONOMIC TESTING

The grinding ratio G is a key factor in any assessment of grinding costs. In order to obtain a value for G it was neccessary to determine the amount of wheel wear. A thin section of low carbon steel was mounted in a jig and a replica of the grinding wheel profile was duplicated onto the strip by feeding the grinding wheel into the strip, (plates 3 and 5). The jig was then transferred to the table of a Talysurf 4 machine, and a surface trace taken across the copy of the work-profile. It was possible to calculate the cross-section of area worn on the wheel by taking replicas before and after a grinding test. A work speed and depth of cut were selected as shown below:-

Test No.	1	2	3	4	5
Depth of cut mm	.015	.025	.035	.045	.055
Work speed m/min	6.09	7.92	10.66	17.67	21

Resin bond and metal bond wheels were both run at a speed of 1649 m/min and a coolant was used. The results are shown in tables 29 and 30 and a typical set of profile traces obtained on the Talysurf is shown in Fig.13.

6. TEST RESULTS AND DISCUSSION

The initial tests carried out in this work were aimed at providing information on the process of grinding Refel, which would lead to recommendations for the cutting that give the most acceptable conditions in terms of measured factors.

Further work examined the cutting requirements for obtaining optimum finish and optimum economic performance.

6.1. CUTTING TESTS.

The results of the factorial experiments indicated the significance of the factors, in terms of tangential cutting force, radial cutting force and the ratio of tangential force to cutting force $(\frac{Ft}{Fn})$, which is called the grinding coefficient. It was suggested by Shaw (21) that grinding coefficient is an indication of cutting efficiency, and that a value of 0.5 tends to show that optimum cutting efficiency is attained. The values obtained for tangential force, radial force and grinding coefficient were programmed to obtain a computer readout of the variance estimate. The details of the programme are quoted in Appendix I and the results of the 'F' test for significance are shown in tables 7a, 7b, 7c, 8a, 8b, and 8c. The last two columns in each of the tables indicate the significance of the factors and combinations of factors. Main effects are shown in tables 10 and 11.

<u>6.1.1. Wheel Bond.</u> The variance test provided the probably significant result that the wheel bond influenced the tangential cutting force. The use of a metal bond wheel in place of a resin bond wheel increased the tangential force by 53 N.

The metal bond retains the diamond grit in the wheel and has a higher strength than resin. Thus it may be expected that the tangential force will increase when a metal bond wheel is used. However Conradi (15) questions the validity of bond comparisons in general, and points out the difficulty of obtaining a consistent value for resin bond strength. The shape of a diamond grit will affect the ease with which it can be removed, as will the amount of bond forming the bridge around an individual grit. The degree of polymerization of the resin can also vary with a consequent variation in bond characteristics. Thus the connection between wheel bond and tangential cutting force is considered to be of somewhat minor significance.

In the factorial experiment, the wheel bond was found to be a significant factor in terms of effect on radial cutting force. The metal bond wheel produced a higher radial cutting force than a resin bond wheel under the same grinding conditions, by amounts up to 401 N. Despite Conradi's comments the significance of wheel bond in relation to radial cutting force is important and is due to the more elastic nature of a resin bond wheel. The impact between wheel and work as each grit strikes the work is more easily absorbed by the resin bond, and not transmitted directly as is the case when using a metal bond wheel.

The stiffness of a metal bond wheel becomes even more apparent when increased rates of material removal are used. During the factorial experiment three specimens fractured at a work speed of 21 m/min and with a depth of cut of 0.055 mm. It is possible that at the higher work speed any slight out of roundness of the 350 mm diameter wheel that may remain despite the trueing operation became a factor, but it is also felt that a critical point was reached in terms of material removal rate and the assault of the diamond grits on Refel was so great as to exceed the stress limit of that specimen.

In both runs of the factorial experiment the type of bond was found to be a significant factor and the use of a metal bond wheel was found to reduce the grinding coefficient from the 0.5 norm by values of 0.142 to 0.316. The efficiency of grinding relative to the 0.5 norm specified by Shaw (21) was more readily achieved with a resin bond wheel.

6.1.2. Wheel speed. The range of wheel speeds used in the factorial experiment was from 1540 m/min to 2100 m/min., and covered the speeds available on most grinding machine tools. The wheel speed was not found to be a factor of significance and it was concluded that the wheel efficiency was not altered by changes of wheel speed within the range of the experiment.

6.1.3. Work speed and depth of cut. It was found that workspeed had a significant effect on tangential force and an increase of the work speed from 5.8 m/min to 21 m/min produced a corresponding increase in tangential force from 159 N to 224 N.

The depth of cut also effected tangential force and the tests showed that the greater the depth of cut, the greater the tangential force. An increase of the depth of cut from 0.015 mm/pass to 0.055 mm/pass generated force changes of 164 N to 196 N. The combined effect of both work speed and depth of cut also produced a significant increase in tangential force of the order 114 N to 152 N.

The importance of both work speed and depth of cut was also shown in its significant effect on radial cutting force. An increase of work speed from 5.8 m/min to 21 m/min produced an increase in radial cutting force of from 557 N to 597 N as shown in tables 10 and 11. An increase in depth of cut from 0.015 mm/pass to 0.055 mm/pass was accompanied by increase in radial cutting force from 503 N to 555 N. The significant effect of work speed and depth of cut in combination was to increase radial cutting force by 411 N to 459 N. Depth of cut had a significant effect on the grinding coefficient and increased the factor by 0.089 towards the optimum value of 0.5.

The importance of depth of cut and work speed in the generation of grinding forces is not unexpected, for as the volume of material being ground is increased, so the force required to remove that material should increase.

6.1.4. Cutting Fluid. The use of a cutting fluid in the grinding process was discussed by Chalkley (47) in a recent paper. A report published by M.I.T.R.A (48) also examined the question of the proper use of cutting fluids in high speed grinding.

The significance of a fluid as a lubricant to reduce the forces between the grit and the workpiece was not established in the factorial experiment, although the use of a cutting fluid was found to decrease the grinding coefficient by 0.085 to 0.094 from the optimum value of 0.5. However without the use of a cutting fluid the debris from the grinding operation was rapidly dispersed into the air around the machine despite the action of a dust extractor. After a few moments some discomfort was noticed around the eyes and lips, and when the material was handled and then the hand brushed against the mouth, the irritation was also felt. The use of a cutting fluid tended to keep the particles of ground Refel within the area of the machine tool table and improved the working conditions for the operator. It is felt that some note should be made of this possible source of discomfort to operators when grinding reaction-bonded silicon carbide.

6.1.5. Chip Thickness and Energy. From the results of the cutting tests shown in tables 12 and 13 a series of values for chip thickness 'h' were calculated. In section 2.3 a review of the work of Grisbrook (30) and Shaw (21) noted that the minimum undeformed chip thickness was given by :-

$$\left(\frac{4.V_w}{\pi.d_s.n.C.r.}\sqrt{\frac{a}{d_s}}\right)^{\frac{1}{2}}$$

If the average diameter of a 180 grit is taken as 0.14 mm (17) we can estimate the value of C as being 50 per mm^2. A sample calculation using the data shown in the first row of table 14 shows that :-

$$h = \left(\frac{4 \times 6.25 \times 1000}{\pi \times 250 \times 2000 \times 50 \times 15} \sqrt{\frac{.015}{250}} \right)^{\frac{1}{2}}$$

$$= 0.00039 \text{ mm.}$$

The values of 'h' obtained in tables 14 and 15 were then used to compute test values for specific energy 'e' applying the formula used by Grisbrook (30).

A sample calculation can then be compiled using the data in the first row of table 14 as follows:-

$$e = \frac{V_s . F_t}{V_W . ba}$$

$$= \frac{2199 \times 13}{6.25 \times 6 \times .015}$$

$$= 50.821 \text{ KN/mm}^2$$

A BASIC programme on a Hewlett Packard Model 2000 computer was available for correlation and regression problems, and was used to consider the relationship between 'h' and 'F_t'. The programme performed an analysis based on a series of observations between two variables. The correlation coefficient was calculated and up to four regression equations were estimated using the method of least squares.

The four equations were

i) Variable 2 = A x B (Variable 1)
ii) Variable 2 = A x B (Natural log of variable 1)
iii) Natural log of variable 2 = A x B (Variable 1)
iv) Natural log of variable 2 = A x B (Natural log of variable 1)

Tables 17 to 22 show the variation of minimum chip thickness (h) with tangential force (F_t). When a resin bond wheel was used with a coolant, the correlation coefficient lay between 0.87 and 0.91 and under these conditions it can be stated that :-

$$F_t = K_1 . h \quad - - - - \quad ⑬$$

where K_1 is a constant between 20×10^3 and 35×10^3. When a metal bond wheel was used with a coolant the correlation coefficient lay between 0.78 and 0.9 and under these conditions

$$F_t = K_2 . h \quad - - - \quad ⑭$$

where K_2 is a constant between 100×10^3 and 200×10^3

The correlation coefficient when using a metal bond wheel without a coolant was lower, being between 0.54 and 0.78 and the relationship between tangential force and chip thickness was identical to that found in ⑭.

It can be concluded from the above results that tangential cutting force is directly proportional to undeformed chip thickness. Thus the views of Alden (22), Guest (23) and Shaw (21), that geometric considerations have a considerable influence on cutting conditions are strengthened by the evidence produced when diamond grinding silicon carbide.

However, the cutting force is not as accurate an indicator of performance as are observations in terms of force per unit area of cut, so that specific energy is a more acceptable measure of efficiency. Depth of cut, work speed and a combination of the two have been identified as significant factors in the grinding operation in tables 7 and 8, and an examination was carried out of the relationship between these factors and specific energy.

From the data shown in tables 15 and 16, diagrams showing the relationship between specific energy (e) and depth of cut (d) were drawn as presented in figures 7 and 8. The figures show that over the range of cutting conditions used a minimum energy level is apparent when the depth of cut is between 0.02 mm and 0.04 mm.

An examination of the relationship between work speed (Vw) and specific energy (e) shown in fig 14 has a similar graphical form, with a minimum energy level in the middle range of the work speeds i.e. 10 m/min to 18 m/min. Thus energy developed tended to diminish with increases in both depth of cut and work speed up to an optimum level. Energy then increased with further increases of depth of cut or work speed.

At the lower end of the removal rate scale the cutting process is not efficient in terms of energy generated. The diamond grit may be pressed into the matrix to some degree and cutting potential is effectively reduced. When the rate of material removal is increased beyond 2.4 cm^3/min then the flexibility of the bond becomes of relatively less importance and the wheel cuts more efficiently. At the upper range of metal removal rates, external factors such as the rigidity of wheel and workpiece are probably critical when features such as wheel spindle vibration can reduce cutting efficiency so that specific energy values will be greater. The middle range of depth of cut and work speed provides an optimum condition where the best results in terms of minimum energy are achieved.

The relationship between minimum chip thickness (h) and specific energy (e) was tested under the same conditions, in an attempt to verify the relationship suggested by Backer (31). However, when the data was processed and presented in tables 23 to 28, it was found that the correlation coefficient varied from 0.87 to 0.0069 so that no conclusions could be drawn from these tests as to the connection between chip thickness and specific energy.

It was also apparent that neither depth of cut nor work speed had a paramount effect on energy developed in cutting but that an optimum condition existed for both factors, singly and as a product.

6.2 SURFACE FINISH.

A single 2^7 factorial experiment was carried out using surface finish as the measured output. The results yielded uniformly high values for surface texture, of approximately two to three times the values excepted as good commercial finish. The results are set out in table 6. Tests of significance were made using the standard computer programme (Appendix I). The readout in table 9 showed no evidence of a significant connection between the five factors examined and surface finish.

In his examination of the effects of vibrations on diamond grinding wheels (Busch (14) concluded that the stiffness of the grinding wheel spindle was a major factor in the standard of finish obtained and that vibrations between wheel and workpiece lead to poor work piece finish. These vibrations could be reduced by stiffening the work piece mounting and using a more rigid machine tool system where possible.

In view of the remarks made by Busch (14) and of the results of the factorial experiment, it is suggested that under the conditions used factors external to the diamond grinding elements examined have a more direct influence on the surface finish than the five grinding factors tested.

6.3. ECONOMIC TESTING.

The comparatively high cost of diamond grinding wheels makes economic analysis a most valid consideration in the examination of good grinding practice. The high initial cost of the diamond wheel may be such that economic factors become the prime consideration in determining the effeciency of a process.

Table 29 shows the results of cutting tests from which the amount of Refel ground was calculated relative to the equivalent wear of diamond grinding wheel (G). The total specific cost (K_G) is defined as the sum of the machine costs (Km) and the cost of the diamond wheel (K_D). Using the definitions suggested by Ratterman (43) :-

$$\text{the machine costs (Km)} = \frac{\text{Time Costs}}{\text{Rate of matl. removal (S)}}$$

$$\text{and the diamond costs } (K_D) = \frac{\text{Cost/Unit volume of diamond}}{\text{Grinding Ratio (G).}}$$

Reference to local industry suggested that the time costs should be £7/hour and that the cost of the abrasive diamond was £17.65 per cm^3.

A sample calculation using the data from test 1 in table 30 is as follows :-

$$S = \text{Work speed x depth of cut x width of cut}$$

$$= 6.09 \times 0.015 \times 6 = 0.5481 \text{ cm}^3/\text{min.}$$

$$\text{Hence Km} = \frac{7}{60} \times \frac{1}{.5481} = £0.212/\text{cm}^3$$

$$\text{and } K_{DR} = \frac{17.65}{59.4} = £0.297/\text{cm}^3$$

$$\therefore \quad K_{GR} = 0.212 + 0.297$$

$$= £0.509/\text{cm}^3$$

The resultant costs for all cases are presented in table 30 and a graphical representation of these costs, and of the volumetric grinding ratio (G) relative to the rate of material removal, are shown in figures 10, 11 and 12.

These results exhibit an inverse relationship to that produced by Busch (45) and Ratterman (43) when diamond grinding tool steels. The 'G' ratio falls to a minimum at approximately 4 cm^3/min and then increases as the rate of material removal increases. The total cost curves show a positive increase over the range of cutting conditions in contrast to curves having a minimum turning point in references (43) and (45).

At the lower rates of material removal the grinding wheels did not work efficiently and grits were subject to attritious wear and did not fracture or become torn from the bond. At higher cutting rates the efficiency of grinding was also reduced as the rigidity of the wheel spindle and the workpiece became more critical. This tends to be borne out by the shape of figs 10, 11 and 12, particularly as the wheel stopped or the workpiece cracked when the material removal rate exceeded 0.7 cm^3/min.

It would appear that a condition of minimum economic cutting exists between the same limits of material removal as minimum cutting force and specific energy. The effectiveness of the grinding operation in terms of removing stock without either loading the wheel or fracturing and overheating the workpiece is found to be greatest between the values $S = 0.24$ cm^3/min and $S = 0.48$ cm^3/min. Thus it is found that the highest values of grinding ratio G, being an indication of wheel wear, occur when the greatest amount of efficient work is being completed.

The relatively small variation of cost over the range tested compared with the high initial cost of the wheel is an important consideration when prolonged grinding is not anticipated. The range for a resin wheel is £ 0.338, compared with £0.112 for a metal bond wheel, with wheels costing over £100 each.

The cost level for a resin bond wheel appears to be higher than for a metal bond wheel operating under similar conditions. The softer bond wheel would be expected to wear more rapidly and hence be more costly although the total costs between them differ by only 16% at most. This is not considered a critical point of difference.

The variation of costs in terms of the range and of the differences when a metal bond or a resin bond wheel are used appear to be minor factors and economic considerations are not expected to be of primary importance when grinding such a hard material as Refel, because alternative methods of machining are not available.

7. CONCLUSIONS

This work is presented as an initial study of the machining characteristics of reaction bonded silicon carbide. Because of the intense hardness of the material, production of components was previously limited to extruded or pressed sections with very little machining. The tests carried out in the course of this research showed that Refel can be machined at acceptable rates of material removal by the diamond grinding process, thus extending the range of application for the material.

The cutting forces recorded during the tests were of the same order as those quoted by Grisbrook (30) below a material removal rate of approximately 0.6 cm^3/min. At removal rates above that figure both tangential and radial forces became greater than those found using ceramic wheels to grind steels.

The bond had a considerable effect on radial cutting force, a metal bond wheel generating much higher radial forces than when a resin bond wheel was used. A resin bond wheel permitted a higher removal rate to be used without any chipping or fracture of the very brittle Refel.

Within the experimental range of 1400 RPM to 2800 RPM, wheel speed was not found to have a significant effect on performance in terms of cutting forces.

It must also be concluded that material removal rates between 3.00 and 4.80 cm^3/min are likely to produce the best results related to specific energy.

The significance of the lubricant in the grinding of silicon carbide has not been established. However, the use of the coolant is considered important as a means of dispersing debris from the grinding area.

The surface finish of the workpiece was found to be independent of any of the five grinding parameters tested and it is concluded that the rigidity of the workpiece and of the machine tool is of prime importance in producing a high quality finish.

The need for diamond grit wheels in the operation of grinding Refel introduces a high capital cost to the operation. The economic tests indicated that the greatest total cost occurs where the cutting conditions are optimum. However, the comparatively small variations over the cost range and the small scale of that range compared to the high initial cost of a wheel (£0.4 to approximately £100) tends to reduce the relevance of the variations in the economic factors to the industrial situation.

As a result of this work it is recommended that a resin bond wheel running at a wheel speed within the range 1500 m/min to 2000 m/min should be used for diamond grinding silicon carbide. A material removal rate of between 3 to 5 cm^3/min should be employed together with a cutting fluid to clear the grinding area.

Surface finish will depend upon the rigidity of the workpiece and wheel spindle.

8. FUTURE WORK

Busch and Theil (45) carried out a series of extended tests in their work on the diamond grinding of steels. In the present work the number of passes per test rarely exceeded ten and the effect of longer grinding runs on the forces developed and on the rate of wear of the grinding wheel is a feature that could be considered for further investigation.

The low power of the grinding machine also limited the range of the investigation and a machine tool having a motor rating greater than 2.5 Kw may enable the range of depth of cut to be extended beyond the maximum value of 0.05 mm permitted by the Elliot DS 921, possibly at much lower wheel speeds.

In an investigation into machine tool vibrations and the effect on diamond wheel performance, Busch (14) found that the vibrations decreased and hence surface finish improved when a rubber disc was inserted between the wheel and flange behind the grinding wheel hub. The dampening effect of this device on self-excited vibrations could be a factor in reducing the tendency of Refel to chip under the greater rates of material removal. Thus the feature is considered worth investigating in any future work.

This research was confined to the use of diamond grinding wheels and it is possible that cubic boron nitride wheels would possess sufficient hardness to enable silicon carbides to be ground.

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Material	Density g/cc	Hardness Kg/mm^2	Youngs Modulus GM/m^2	Thermal Expansion Coeff. x 10^{-6} /^{o}c	Thermal Conductivity at 1200^{o}c W/m^{o}c	Rupture Modulus MN/m^2
REFEL	3.10	$^{2500}/_{3500}$	413	4.3	83.6	525
HOT PRESSED SILICON NITRIDE	3.20	$^{2500}/_{3500}$	310	3.2	17.5	689
REACTION BONDED SILICON NITRIDE	2.60	900/1000	220	3.2	15	241
HOT PRESSED BERYLLIA	3.03	-	400	8.5	62.7	207
HOT PRESSED ALUMINA	3.90	2500	365	9.0	8.4	480
TUNGSTEN CARBIDE (6% Co)	15	1500	606	4.9	86	1412

TABLE 1.

Comparative properties of REFEL and other materials
(from ref. 20)

	GRINDING RATIO	NET POWER	SURFACE FINISH
Increase rate of metal removal	Decreased	Increased	Poorer
Increased workpiece diameter	Increased	Slight increase	No significant change
Increase wheel speed	Increased	Slight increase	Improved
Increase concentration of coolant	Increased	Decrease	Improved
Increase hardness of workpiece	Optimum hardness exists for each grade of wheel		Improved

EFFECT OF GRINDING RATIO, SURFACE FINISH,
and POWER ON VARYING FACTORS
(From ref 33) TABLE 2.

OPERATOR	SKILLS - PERSONALITY - SAFETY
FORCES	NORMAL
	AXIAL
	TANGENTIAL
WORKPIECE MATERIAL	ANALYSIS
	STRUCTURE
	PROPERTIES
	TEMPERATURE
	RIGIDITY
WHEEL	GRIT - SIZE - NATURE
	BOND - NATURE - GRADE
	SPEED
	CONDITION - LOADING - TRUEING
	DRESSING METHOD
	MOUNTING
DEPTH OF CUT	CONDITION OF SERVICE
MACHINE	TYPE
	TRAVERSE - GENERAL - HYDRAULIC
	SPINDLE BEARINGS
	CONDITION
LUBRICANT	TYPE - APPLICATION
	FILTER - SAFETY
	FLOW-RATE - TEMPERATURE

VARIABLES IN GRINDING
(from ref 37)

TABLE 3

Wheel Bond	:	Metal	a	:	Resin
Wheel Speed	:	2199 m/min	b	:	1540 m/min
Table Speed	:	21 m/min	c	:	5.8 m/min
Depth of cut	:	0.05 mm	d	:	0.015 mm
Coolant	:	Wet	e	:	Dry

Forces in Newtons

SYMBOL	Ft	Total	Fn	Total	Ft/Fn
ab	4, 4, 4	12	14, 14, 14	42	.285
abd	17, 17, 18	52	60, 60, 60	180	.288
abc	39, 39, 39	117	52, 52, 60	164	.714
abcd	55, 58, 64	177	700, 780, 600	2080	.08
abcde	145, 110, 125	380	500, 380, 270	1150	.33
abe	4, 4, 4	12	19, 19, 19	57	.21
abde	16, 16, 16	48	52, 52, 54	158	.303
abce	36, 36, 36	108	72, 72, 72	216	.48
ace	35, 35, 36	108	64, 58, 58	180	.6
ae	5, 5, 4	14	11, 11, 10	32	.43
ade	16, 16, 16	48	45, 40, 40	125	.384
acde	240, 230, 160	620	850, 700, 570	2120	.3113
a	5, 5, 5	15	17, 17, 17	51	.293
ac	8, 8, 8	24	15, 15, 15	45	.540
acd	270, 260, 220	750	890, 750, 560	2200	.34
ad	22, 26, 25	73	60, 60, 65	185	.394

FACTORIAL EXPERIMENT 1

(Grinding Forces)

TABLE 4.

Forces in Newtons

SYMBOL	Ft	Total	Fn	Total	Ft/Fn
de	20, 20, 20	60	35, 35, 40	110	.545
e	5, 5, 5	15	14, 14, 13	41	.36
ce	18, 14, 16	48	40, 38, 38	116	.43
1	5, 5, 5	15	9, 9, 9	27	.55
d	18, 18, 19	55	32, 32, 31	95	.58
cd	110, 110, 120	340	165, 155, 155	475	.715
c	30, 30, 25	85	47, 37, 27	111	.765
bcde	45, 45, 45	135	105, 105, 125	335	.402
bce	10, 10, 10	30	36, 36, 34	106	.283
bde	12, 12, 12	36	30, 31, 28	89	.404
be	4, 4, 4	12	12, 12, 12	36	.33
b	5, 5, 6	16	10, 10, 10	30	.533
bcd	95, 85, 80	260	130, 130, 120	380	.68
bd	18, 18, 18	54	32, 30, 30	92	.586
bc	18, 21, 20	59	32, 35, 34	101	.584
ced	60, 60, 60	180	120, 120, 120	360	.50

TABLE 4

Cont'd.

Wheel Bond : Metal a : Resin
Wheel Speed : 2199 m/min b : 1540 m/min
Table Speed : 21 m/min c : 5.8 m/min
Depth of cut : 0.05 mm d : 0.015 mm
Coolant : Wet e : Dry

Forces in Newtons

SYMBOL	Ft	Total	Fn	Total	Ft/Fn
ab	12, 10, 8	30	32, 32, 25	89	.34
abd	20, 20, 20	60	60, 60, 60	180	.33
abc	20, 20, 20	60	62, 62, 60	184	.33
abcd	200, 180, 180	560	600, 600, 500	1700	.33
abcde	130, 120, 120	380	380, 370, 420	1170	.324
abe	11, 11, 10	32	25, 27, 28	80	.4
abde	25, 28, 22	72	105, 105, 95	305	.24
ace	15, 15, 15	45	64, 64, 64	192	.234
ae	4, 4, 4	12	20, 20, 20	60	.2
ade	20, 20, 20	60	90, 90, 100	280	.214
acde	90, 80, 100	270	300, 300, 250	850	.317
a	5, 5, 5	15	14, 13, 14	41	.36
ac	26, 24, 22	72	55, 60, 66	181	.397
acd	250, 260, 230	740	1130, 1000, 1000	3130	.236
ad	20, 20, 20	60	60, 60, 50	170	.353

FACTORIAL EXPERIMENT 2
(Grinding Forces)

TABLE 5

Forces in Newtons

SYMBOL	Ft	Total	Fn	Total	Ft/Fn
de	14, 14, 14	42	26, 26, 26	78	.538
e	3, 3, 3	9	6, 5, 6	17	.529
ce	10, 10 10	30	22, 21, 22	65	.462
1	5, 5, 5	15	8, 8, 8	24	.625
d	18, 18, 18	54	28, 28, 28	84	.642
cd	125, 120, 130	370	150, 150, 160	460	.804
c	16, 17, 18	51	27, 26, 24	77	.662
bcde	80, 90, 100	270	110, 120, 130	360	.75
bce	13, 14, 15	42	31, 29, 24	104	.404
bde	13, 13, 13	39	20, 20, 20	60	.65
be	3, 3, 3	9	9, 9, 9	27	.333
b	3, 3, 3	9	4, 4, 4	12	.75
bcd	105, 85, 100	290	140, 110, 125	375	.773
bd	14, 14, 14	42	21, 21, 21	63	.666
bc	15, 15, 15	45	21, 22, 20	63	.714
ced	120, 125, 125	370	145, 145, 145	435	.85

TABLE 5

Cont'd.

Wheel Bond	:	Metal	a	:	Resin
Wheel Speed	:	2199 m/min	b	:	1540 m/min
Table Speed	:	21 m/min	c	:	5.8 m/min
Depth of cut	:	0.05 mm	d	:	0.015 mm
Coolant	:	Wet	e	:	Dry

Finish μm

SYMBOL	Finish	Average Total/3	SYMBOL	Finish	Average Total/3
1	.29, .32, .33	.31	a	.3, .4, .4	.33
cd	.4, .55, .52	.47	acd	.41, .41, .41	.41
c	.56, .44, .57	.52	ac	.39, .49, .45	.45
d	.59, .51, .59	.56	ad	.35, .32, .36	.34
e	.31, .22, .30	.28	ae	.42, .40, .38	.40
cde	.50, .43, .50	.48	acde	.40, .45, .38	.41
ce	.48, .45, .50	.48	ace	.45, .36, .36	.40
de	.38, .38, .42	.39	ade	.40, .40, .32	.37
b	.49, .48, .47	.48	ab	.53, .63, .62	.59
bcd	.56, .52, .56	.55	abcd	.64, .72, .50	.62
bc	.54, .52, .49	.52	abe	.32, .28, .37	.34
bd	.50, .42, .46	.46	abd	.54, .48, .49	.50
be	.38, .36, .32	.35	abe	.38, .48, .45	.44
bcde	.78, .68, .60	.69	abcde	.46, .44, .36	.41
bce	.52, .52, .45	.50	abce	.30, .25, .32	.29
bde	.35, .33, .3	.33	abde	.50, .44, .48	.51

FACTORIAL EXPERIMENT -

SURFACE FINISH

TABLE 6

MODEL TERM	SUM OF SQUARES x 10^6	RES. 'F'	VARIANCE x 10^5	VARIANCE RATIO	SIGNIFICANCE 5%	1%
A	.4462	26	.172	4.076	-	-
B	.4462	26	.172	0.989	-	-
C	.4462	26	.172	24.284	Yes	Yes
D	.4462	26	.172	19.468	Yes	Yes
E	.4462	26	.172	0.125	-	-
AB	.1760	16	.110	2.739	-	-
AC	.1760	16	.110	3.928	-	-
AD	.1760	16	.110	2.499	-	-
AE	.1760	16	.110	0.786	-	-
BC	.1760	16	.110	0.995	-	-
BD	.1760	16	.110	2.091	-	-
BE	.1760	16	.110	0.121	-	-
CD	.1760	16	.110	11.226	Yes	Yes
CE	.1760	16	.110	0.038	-	-
DE	.1760	16	.110	0.135	-	-

COMPUTER READOUT OF 'F' TEST

TANGENTIAL FORCE (F_t) TEST 1

TABLE 7A

MODEL TERM	SUM OF SQUARES x 10^7	RES. 'F'	VARIANCE x 10^5	VARIANCE RATIO	SIGNIFICANCE 5%	1%
A	.558	26	2.15	14.608	Yes	Yes
B	.558	26	2.15	0.388	-	-
C	.558	26	2.15	26.879	Yes	Yes
D	.558	26	2.15	26.806	Yes	Yes
E	.558	26	2.15	0.368	-	-
AB	.1437	16	.898	0.183	-	-
AC	.1437	16	.898	11.946	Yes	Yes
AD	.1437	16	.898	12.708	Yes	Yes
AE	.1437	16	.898	0.217	-	-
BC	.1437	16	.898	0.415	-	-
BD	.1437	16	.898	0.640	-	-
BE	.1437	16	.898	0.233	-	-
CD	.1437	16	.898	18.753	Yes	Yes
CE	.1437	16	.898	0.294	-	-
DE	.1437	16	.898	0.733	-	-

COMPUTER READOUT OF 'F' TEST
RADIAL FORCE (F_n) TEST 1

TABLE 7B

MODEL TERM	SUM OF SQUARES x 10^4	RES 'F'	VARIANCE	VARIANCE RATIO	SIGNIFICANCE 5%	1%
A	.4566	26	175.64	9.91	Yes	Yes
B	.4566	26	175.64	2.477	-	-
C	.4566	26	175.64	2.312	-	-
D	.4566	26	175.64	0.599	-	-
E	.4566	26	175.64	4.786	Yes	Yes
AB	.184	16	115	0.004	-	-
AC	.184	16	115	0.435	-	-
AD	.184	16	115	6.957	Yes	-
AE	.184	16	115	7.853	Yes	-
BC	.184	16	115	0.053	-	-
BD	.184	16	115	0.132	-	-
BE	.184	16	115	0.435	-	-
CD	.184	16	115	5.175	Yes	-
CE	.184	16	115	1.409	-	-
DE	.184	16	115	1.257	-	-

COMPUTER READOUT OF 'F' TEST

GRINDING COEFFICIENT (F_t/F_n) TEST 1

TABLE 7C

MODEL TERM	SUM OF SQUARES x 10^6	RES. 'F'	VARIANCE x 10^5	VARIANCE RATIO	SIGNIFICANCE 5%	SIGNIFICANCE 1%
A	.352	26	.136	4.529	Yes	-
B	.352	26	.136	0.247	-	-
C	.352	26	.136	59.546	Yes	Yes
D	.352	26	.136	60.702	Yes	Yes
E	.352	26	.136	3.168	-	-
AB	.809	16	.0506	0.223	-	-
AC	.809	16	.0506	2.270	-	-
AD	.809	16	.0506	2.225	-	-
AE	.809	16	.0506	2.122	-	-
BC	.809	16	.0506	0.411	-	-
BD	.809	16	.0506	0.556	-	-
BE	.809	16	.0506	0.810	-	-
CD	.809	16	.0506	39.622	Yes	Yes
CE	.809	16	.0506	3.046	-	-
DE	.809	16	.0506	2.406	-	-

COMPUTER READOUT OF 'F' TEST
TANGENTIAL FORCE (F_t) TEST 2

TABLE 8A

MODEL TERM	SUM OF SQUARES x 10^7	RES. 'F'	VARIANCE x 10^6	VARIANCE RATIO	SIGNIFICANCE	
					5%	1%
A	.6372	26	.245	8.437	Yes	Yes
B	.6372	26	.245	0.293	-	-
C	.6372	26	.245	13.609	Yes	Yes
D	.6372	26	.245	13.013	Yes	Yes
E	.6372	26	.245	1.223	-	-
AB	.248	16	.155	0.147	-	-
AC	.248	16	.155	5.182	Yes	Yes
AD	.248	16	.155	5.008	Yes	-
AE	.248	16	.155	1.200	-	-
BC	.248	16	.155	0.222	-	-
BD	.248	16	.155	0.529	-	-
BE	.248	16	.155	8.715	Yes	Yes
CE	.248	16	.155	1.709	-	-
DE	.248	16	.155	1.605	-	-

COMPUTER READOUT OF 'F' TEST

RADIAL FORCE (F_n) TEST 2

TABLE 8B

MODEL TERM	SUM OF SQUARES x 10^4	RES 'F'	VARIANCE	VARIANCE RATIO	SIGNIFICANCE 5%	1%
A	.2764	26	106.291	110.274	Yes	Yes
B	.2764	26	106.291	0.526	-	-
C	.2764	26	106.291	0.869	-	-
D	.2764	26	106.291	7.819	Yes	Yes
E	.2764	26	106.291	13.138	Yes	Yes
AB	.1165	16	72.84	1.596	-	-
AC	.1165	16	72.84	4.376	-	-
AD	.1165	16	72.84	5.674	Yes	-
AE	.1165	16	72.84	1.298	-	-
BC	.1165	16	72.84	1.926	-	-
BD	.1165	16	72.84	0.313	-	-
BE	.1165	16	72.84	0.155	-	-
CD	.1165	16	72.84	1.813	-	-
CE	.1165	16	72.84	0.412	-	-
DE	.1165	16	72.84	4.376	-	-

COMPUTER READOUT OF 'F' TEST
GRINDING COEFFICIENT (Ft/Fn) TEST 2.

TABLE 8C.

MODEL TERM	SUM OF SQUARES x 10^4	RES 'F'	VARIANCE	VARIANCE RATIO	SIGNIFICANCE	
					5%	1%
A	.2026	26	77.913	1.223	–	–
B	.2026	26	77.913	3.635	–	–
C	.2026	26	77.913	3.077	–	–
D	.2026	26	77.913	2.565	–	–
E	.2026	26	77.913	1.991	–	–
AB	.1375	16	85.969	0.118	–	–
AC	.1375	16	85.969	5.410	Yes	–
AD	.1375	16	85.969	0.118	–	–
AE	.1375	16	85.969	0.006	–	–
BC	.1375	16	85.969	0.471	–	–
BD	.1375	16	85.969	0.372	–	–
BE	.1375	16	85.969	0.525	–	–
CD	.1375	16	85.969	0.285	–	–
CE	.1375	16	85.969	0.246	–	–
DE	.1375	16	85.969	0.013	–	–

COMPUTER READOUT OF 'F' TEST
SURFACE FINISH

TABLE 9

MODEL TERM A	NEWTONS F_n	$\frac{F_t}{F_n}$	MODEL TERM C	NEWTONS F_t	NEWTONS F_n
ab-b	12	-.254	abc-ab	105	122
abd-bd	88	-.298	abcd-abd	125	2028
abc-bc	63	.13	abcde-abde	332	992
abcd-bcd	1700	-.60	abce-abe	96	159
abe-be	21	-.072	ace-ae	94	148
abcde-bcde	715	-.12	bcde-bde	99	246
ace-ce	64	.17	bcd-bd	206	286
ae-e	-9	.07	bc-b	38	71
ade-de	15	-.161	bce-be	18	70
acde-cde	1760	-.19	acde-ade	612	1995
a-1	24	-.26	ac-a	9	-6
ac-c	-66	-.215	cde-de	120	220
acd-cd	1725	-.375	ce-e	33	65
ad-d	90	-.186	cd-d	295	380
abde-bde	69	-.141	c - 1	70	84
abce-bce	110	.197	acd-ad	287	2015
TOTAL	+6381	-2.265	TOTAL	+2539	+8875
÷ 16	+399	-.142	÷ 16	+159	+557

MAIN EFFECTS - GRINDING TEST 1
FACTORIAL EXPERIMENT

TABLE 10.

MODEL TERM D	NEWTONS Ft	NEWTONS Fn	MODEL TERM E	$\frac{Ft}{Fn}$
bd-b	38	62	abcde-abcd	.25
bcd-bc	201	279	abe-ab	-.075
bde-be	24	53	abde-abd	.015
bcde-bce	105	229	abce-abc	-.234
abde-abe	36	101	ace-ac	.06
abcde-abce	272	834	ae-a	.14
abcd-abc	60	2116	bcde-bcd	-.178
abd-ab	40	138	bce-bc	-.301
ade-ae	34	93	bde-bd	-.182
acde-ace	552	1940	be-b	-.20
acd-ac	726	2155	ade-ad	-.01
ad-a	58	134	acde-acd	-.03
de-e	45	69	de-d	-.035
cde-ce	132	244	cde-cd	-.215
d-1	40	68	e-1	-.19
cd-c	265	364	ce-c	-.335
TOTAL	2628	8879	TOTAL	-1.51
÷ 16	+164	+555	÷ 16	-.094

TABLE 10
Cont'd.

MODEL TERM	F_t		F_n	
	CD.	CD	AC	AD
ab	+12	+42	-42	-42
abd	-52	-180	-180	+180
abc	-117	-164	+164	-164
abcd	+177	+2080	+2080	+2080
abcde	+380	+1150	+1150	+1150
abe	+12	+57	-57	-57
abde	-48	-158	-158	+158
abce	-108	-216	+216	-216
ace	-108	-180	+180	-180
ae	+14	+32	-32	-32
ade	-48	-125	-125	+125
acde	+660	+2120	+2120	+2120
a	+15	+51	-51	-51
ac	-24	-45	+45	-45
acd	+750	+2200	+2200	+2200
ad	-73	-185	-185	+185
de	-60	-110	+110	-110
e	+15	+41	+41	+41
ce	-48	-116	-116	+116
1	+15	+27	+27	+27
d	-55	-95	+95	-95
cd	+340	+475	-475	-475
c	-85	-111	-111	+111
bcde	+135	+335	-335	-335
bce	-30	-106	-106	+106
bde	-36	-89	+89	-89
be	+12	+36	+36	+36
b	+16	+30	+30	+30
bcd	+260	+380	-380	-380
bd	-54	-92	+92	-92
bc	-54	-101	-101	+101
cde	+180	+360	-360	-360
TOTAL	+1824	+7343	+5861	+6043
÷ 16	+114	+459	+366	+377

FIRST ORDER EFFECTS
FACTORIAL EXPERIMENT
GRINDING TEST 1.

TABLE 10A.

MODEL TERM	$\frac{F_t}{F_n}$		
	AD	AE	CD
ab	-.285	-.285	+.285
abd	+.288	-.288	-.288
abc	-.714	-.714	-.714
abcd	+.08	-.08	+.08
abcde	+.33	+.33	+.33
abe	-.21	+.21	+.21
abde	+.303	+.303	-.303
abce	-.48	+.48	-.48
ace	-.60	+.60	-.60
ae	-.43	+.43	+.43
ade	+.354	+.354	-.354
acde	+.31	+.31	+.31
a	-.29	-.29	+.29
ac	-.54	-.54	-.54
acd	+.34	-.34	+.34
ad	+.394	-.394	-.394
de	-.545	-.545	-.545
e	+.36	-.36	+.36
ce	+.43	-.43	-.43
1	+.55	+.55	+.55
d	-.58	+.58	-.58
cd	-.715	+.715	+.715
c	+.765	+.765	-.765
bcde	-.402	-.402	+.402
bce	+.283	-.283	-.283
bde	-.404	-.404	-.404
be	+.33	-.33	+.33
b	+.53	+.53	+.53
bcd	-.68	+.68	+.68
bd	-.586	+.586	-.586
bc	+.584	+.584	-.584
cde	-.50	-.50	+.50
TOTAL	-1.73	+1.822	-1.508
÷ 16	-0.108	+0.113	-0.094

TABLE 10 A
Cont'd.

MODEL TERM D	Ft	Fn	Ft/Fn	MODEL TERM E	Ft/Fn
bd-b	33	51	.024	abcde-abcd	-.006
bcd-bc	245	312	.059	abe-ab	+.06
bde-be	30	33	.317	abde-abd	0
bcde-bce	228	256	.346	ace-ac	-.163
abde-abe	43	145	-.067	ae-a	-.16
abcde-abce	308	865	.084	bcde-bcd	-.023
abcd-abc	500	1516	0	bce-bc	-.31
abd-ab	30	31	.16	bde-bd	-.016
ade-ae	48	220	.014	be-b	-.036
acde-ace	235	658	.099	ade-ad	-.139
acd-ac	668	2949	-.161	acde-acd	+.081
ad-a	45	129	-.007	de-d	-.104
de-e	33	59	.009	cde-cd	+.046
cde-ce	340	370	.388	e-1	-.096
d-1	39	60	.015	ce-c	-.20
cd-c	319	393	.142	abce-abc	-.07
TOTAL	+3144	+8047	1.422		-1.366
TOTAL ÷ 16	196	+503	+.089		-.085

MAIN EFFECTS - GRINDING TEST 2
FACTORIAL EXPERIMENT

TABLE 11.

MODEL TERM A	Ft	Fn	Ft/Fn	MODEL TERM C	Ft	Fn
ab-b	21	77	-.41	abc-ab	30	95
abd-bd	18	57	-.16	abcd-abd	50	1580
abc-bc	15	121	-.384	abcde-abde	305	945
abcd-bcd	270	1325	-.443	abce-abe	40	225
abcde-bcde	110	810	-.436	ace-ae	33	132
abe-be	23	53	+.07	bcde-bde	341	300
ace-ce	15	127	-.228	bce-be	63	77
ae-e	3	43	-.329	bc-b	248	332
ade-de	18	202	-.324	acde-ade	36	51
acde-cde	-100	415	-.533	ac-a	210	570
a-1	0	-24	-.265	acd-ad	7	0
ac-c	21	104	-.272	cde-de	328	357
acd-cd	370	2670	-.568	ce-e	21	48
ad-d	6	86	-.289	cd-d	686	376
abde-bde	26	155	-.317	c-1	57	53
abce-bce	30	201	-.164	bcd-bd	680	2960
TOTAL	+846	+6422	-5.055		+3585	+8108
TOTAL ÷ 16	+53	+401	-.316		+224	+597

TABLE 11
Cont'd.

	Ft CD	Fn CD	Fn AC	Fn AD	Ft/Fn AD
ab	+30	+89	-89	-89	-.34
abd	-60	-120	-120	+120	+.50
abc	-60	-184	+184	-184	-.33
abcd	+560	+1700	+1700	+1700	+.33
abcde	+380	+1170	+1170	+1170	+.32
abe	+32	+80	-80	-80	-.4
abde	-75	-225	-225	+225	+.33
abce	-72	-305	+305	-305	-.24
ace	-45	-192	+192	-192	-.23
ae	+12	+60	-60	-60	-.20
ade	-60	-280	-280	+280	+.21
acde	+270	+850	+850	+850	+.32
a	+15	+41	-41	-41	-.36
ac	-72	-181	+181	-181	-.4
acd	+740	+3130	+3130	+3130	+.24
ad	-60	-170	-170	+170	+.35
de	-42	-78	+78	-78	-.54
e	+9	+17	+17	+17	+.53
ce	-30	-65	-65	+65	+.46
1	+15	+24	+24	+24	+.63
d	-54	-84	+84	-84	-.64
cd	+370	+460	-460	-460	-.804
c	-51	-77	-77	+77	+.662
bcde	+270	+360	-360	-360	-.75
bce	-42	-104	-104	+104	+.404
bde	-39	-60	+60	+60	+.65
be	+9	+27	+27	+27	+.33
b	+9	+12	+12	+12	+.75
bcd	+290	+375	-375	-375	-.77
bd	-42	-63	-63	-63	-.714
bc	-45	-63	-63	-63	-.66
cde	+370	+435	-435	-435	-.85
	+2432	+6579	+5073	+5541	-1.932
	+152	+411	+317	+346	-.121

FIRST ORDER EFFECTS -
GRINDING TEST 2

TABLE 11A.

TEST No.	DEPTH OF CUT (mm)	SPEED OF WORK(m/min)				AVERAGE Ft				AVERAGE Fn
1	.045	21	50	50	50	50	210	195	210	203
2	.015	7.56	7	7	7	7	29	28	29	29
3	.025	11.6	18	18	18	18	74	72	72	73
4	.035	18.2	40	45	50	45	178	177	176	177
5	.055	6.25	32	32	32	32	110	110	115	111
6	.045	7.56	25	25	25	25	115	120	120	117
7	.045	18.2	51	45	47	48	210	185	190	193
8	.035	21	50	50	50	50	210	210	205	208
9	.025	18.2	32	34	34	34	142	148	138	143
10	.055	7.56	35	35	35	35	150	150	150	150
11	.045	11.6	40	50	45	45	160	175	185	168
12	.015	11.6	15	16	16	16	65	66	66	66
13	.025	6.25	17	16	17	17	65	67	68	67
14	.055	18.2	60	75	75	70	285	265	235	251
15	.035	11.6	30	35	33	33	115	135	130	123
16	.035	7.56	26	26	26	26	108	108	108	108
17	.015	6.25	12	13	13	13	64	64	63	64
18	.015	21	32	32	31	32	124	128	134	129
19	.045	6.25	27	27	27	27	126	126	126	126
20	.025	7.56	22	21	22	22	92	94	94	93
21	.055	11.6	55	55	55	55	225	220	220	222
22	.025	21	50	50	50	50	200	200	200	200
23	.055	21	65	65	70	67	320	370	370	353
24	.015	18.2	22	22	22	22	92	92	94	93
25	.035	6.25	22	22	24	23	98	98	98	98

CUTTING TEST NO.1.
RESIN BOND WHEEL, WITH COOLANT
SPEED 2199 m/min

TABLE 12.

TEST No.	DEPTH OF CUT (mm)	SPEED OF WORK(m/min)				AVERAGE Ft				AVERAGE Fn
1	.035	11.6	38	37	37	37	80	80	80	80
2	.055	21	95	85	80	85	260	220	200	230
3	.035	18.2	40	45	50	45	80	80	90	84
4	.015	11.6	12	12	12	12	24	24	24	24
5	.045	6.25	24	24	24	24	48	48	48	48
6	.025	6.25	13	13	15	13	27	27	32	30
7	.025	21	56	58	54	56	100	100	100	100
8	.025	11.6	22	22	20	21	44	44	42	43
9	.045	11.6	37	37	38	37	74	74	78	75
10	.045	7.56	27	28	27	27	56	56	56	56
11	.045	18.2	70	65	65	66	125	115	115	119
12	.015	21	29	27	27	28	55	53	48	53
13	.015	7.56	9	10	10	10	20	21	22	21
14	.015	6.25	9	10	9	9	19	19	19	19
15	.055	11.6	70	70	70	70	120	120	120	120
16	.035	21	50	50	50	50	165	160	155	160
17	.055	6.25	32	32	32	32	69	66	66	65
18	.025	7.56	18	18	17	18	36	38	36	36
19	.055	18.2	110	100	90	100	190	190	190	190
20	.045	21	50	50	50	50	200	190	175	190
21	.035	7.56	20	20	21	20	42	42	46	44
22	.015	18.2	24	24	22	24	50	50	50	50
23	.035	6.25	20	20	20	20	40	40	38	39
24	.055	7.56	35	35	35	35	70	70	70	70
25	.025	18.2	38	38	38	38	76	76	76	76

CUTTING TEST No. 2
RESIN BOND WHEEL, WITH COOLANT
SPEED 2199 m/min

TABLE 13.

Depth of Cut. a mm	Work Speed. V w m/min	Wheel Speed. V s m/min	Undeformed chip thickness h $\times 10^{-4}$ mm	Tangential Cutting Force Ft N	Normal Cutting Force Fn N	$Ft/_{Fn}$	Specific Energy e kN/mm^2
.015	6.25	2199	3.875	13	64	.203	50.82
.025	6.25	"	4.39	17	67	.253	39.82
.035	6.25	"	4.79	23	98	.234	38.53
.045	6.25	"	5.09	27	126	.214	35.18
.055	6.25	"	5.35	32	110	.29	34.12
.015	7.56	"	4.19	7	29	.241	22.62
.025	7.56	"	4.76	22	93	.236	42.66
.035	7.56	"	5.17	26	108	.240	36.01
.045	7.56	"	5.51	25	117	.214	26.93
.055	7.56	"	5.79	35	150	.233	30.08
.015	11.6	"	5.19	16	66	.242	33.7
.025	11.6	"	5.88	18	73	.242	22.75
.035	11.6	"	6.39	33	123	.268	29.79
.045	11.6	"	6.81	45	168	.267	31.6
.055	11.6	"	7.16	55	222	.247	31.6
.015	18.2	"	6.61	22	93	.236	29.53
.025	18.2	"	7.49	34	143	.237	27.38
.035	18.2	"	8.15	45	177	.254	25.89
.045	18.2	"	8.68	48	193	.248	21.48
.055	18.2	"	9.13	70	251	.278	25.63
.015	21	"	7.1	32	110	.248	37.23
.025	21	"	8.05	50	200	.25	34.90
.035	21	"	8.75	50	208	.240	24.93
.045	21	"	9.32	50	203	.246	19.39
.055	21	"	9.80	67	332	.278	21.26

RESIN BOND WHEEL IN WET CONDITION

TEST 1

TABLE 14.

Depth of Cut a mm	Work Speed V_w m/min	Wheel Speed V_s m/min	Undeformed Chip Thickness h (h) $x10^{-4}$mm	Tangential Cutting Force Ft N	Normal Cutting Force Fn N	$^{Ft}/_{Fn}$	Specific Energy e kN/mm^2
.015	6.25	2199	3.875	9	19	.473	35.18
.025	6.25	"	4.39	13	30	.43	30.49
.035	6.25	"	4.79	20	39	.454	33.50
.045	6.25	"	5.09	24	48	.50	31.27
.055	6.25	"	5.35	32	65	.49	34.12
.015	7.56	"	4.19	10	21	.476	32.31
.025	7.56	"	4.76	18	36	.472	34.90
.035	7.56	"	5.17	20	44	.51	27.7
.045	7.56	"	5.51	27	56	.48	29.08
.055	7.56	"	5.79	35	70	.50	30.08
.015	11.6	"	5.19	12	24	.50	25.26
.025	11.6	"	5.88	21	43	.48	26.54
.035	11.6	"	6.39	37	80	.463	33.4
.045	11.6	"	6.81	37	75	.493	25.98
.055	11.6	"	7.16	70	120	.58	40.21
.015	18.2	"	6.61	24	50	.48	32.21
.025	18.2	"	7.49	38	76	.50	30.6
.035	18.2	"	8.15	45	84	.535	25.89
.045	18.2	"	8.68	66	119	.51	29.53
.055	18.2	"	9.13	100	190	.526	36.61
.015	21	"	7.1	28	53	.53	32.57
.025	21	"	8.05	56	100	.56	39.09
.035	21	"	8.75	50	160	.31	24.93
.045	21	"	9.32	50	190	.263	19.39
.055	21	"	9.80	85	230	.369	26.97

RESIN BOND WHEEL IN WET CONDITION

TEST 2

TABLE 15.

a mm	V_w m/min	n	h^2 $\times 10^{-4}$ mm	h $\times 10^{-4}$ mm	Test 1 Ft N	Test 2 Ft N	Test 1 e KN/mm^2	Test 2 e KN/mm^2
.015	6.25	2000	9.85	3.14	12	32	46.87	124.95
.015	21	2000	32.6	5.71	117	60	136	69.74
.055	6.25	1400	26.7	5.17	73	60	57.39	47.17
.055	21	1400	89.6	9.46	750	740	175.52	173.15
.015	6.25	1400	13.9	3.73	15	15	43.24	43.24
.015	21	1400	46.6	6.83	24	72	20.59	61.79
.055	6.25	2000	18.6	4.32	52	60	55.44	63.91
.055	21	2000	62.8	7.92	177	560	56.09	177.5

a) Dry Condition.

.015	6.25	2000	9.85	3.14	12	30	46.87	117.13
.015	21	2000	32.6	5.71	108	72	125.5	83.69
.055	6.25	1400	26.7	5.17	48	60	37.72	47.17
.055	21	1400	89.6	9.46	660	270	154.5	63.19
.015	6.25	1400	13.9	3.73	14	12	40.34	34.59
.015	21	1400	46.6	6.83	108	45	92.68	38.61
.055	6.25	2000	18.6	4.32	48	75	51.13	79.88
.055	21	2000	62.8	7.92	380	380	120.4	120.43

b) Wet Condition.

CUTTING TEST ON METAL
BOND WHEEL WITH
AND WITHOUT COOLANT.

TABLE 16.

```
                                  DATA

        OBSERVATION               VARIABLE 1              VARIABLE 2

        1                         .000387                 13
        2                         .000439                 17
        3                         .000479                 23
        4                         .000509                 27
        5                         .000535                 32
        6                         .000419                 7
        7                         .000476                 22
        8                         .000517                 26
        9                         .000551                 25
        10                        .000579                 35
        11                        .000519                 16
        12                        .000588                 18
        13                        .000639                 33
        14                        .000681                 45
        15                        .000716                 55
        16                        .000661                 22
        17                        .000749                 34
        18                        .000815                 45
        19                        .000868                 48
        20                        .000913                 70
        21                        .00071                  32
        22                        .000805                 50
        23                        .000875                 50
        24                        .000932                 50
        25                        .00098                  70

THE AVERAGE VALUE OF VARIABLE 1 IS                       6.53680E-04
THE AVERAGE VALUE OF VARIABLE 2 IS                       34.6
THE STANDARD DEVIATION OF VARIABLE 1 IS                  1.75455E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS                  16.9337
THE CORRELATION COEFFICIENT BETWEEN VARIABLES 1 AND 2 IS      .897604

EQUATION 1
VARIABLE 2 =    -22.0286           +          86630.5        * VARIABLE 1
 80.5693        PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED

EQUATION 2
VARIABLE 2 =     443.35            +          55.477
*LOG OF VAR 1
 78.6656        PERCENT OF THE VARIANCE IN  VARIABLE 2 EXPLAINED

EQUATION 3
LOG(VAR 2) =     1.6471            +          2701.9         * VARIABLE 1

EQUATION 4
LOG(VAR 2) =     16.5472           +          1.7826         * LOG(VAR 1)
```

RESIN BOND WHEEL - WET CONDITION. TEST 1

CHIP THICKNESS (1) vs TANGENTIAL FORCE (2)

TABLE 17.

```
                              DATA

      OBSERVATION                VARIABLE 1             VARIABLE 2

      1                          .000387                9
      2                          .000439                13
      3                          .000479                20
      4                          .000509                27
      5                          .000535                25
      6                          .000419                10
      7                          .000476                17
      8                          .000517                20
      9                          .000551                27
      10                         .000579                35
      11                         .000519                12
      12                         .000588                21
      13                         .000639                37
      14                         .000681                45
      15                         .000716                70
      16                         .000661                24
      17                         .000749                38
      18                         .000815                45
      19                         .000868                66
      20                         .000913                100
      21                         .00071                 28
      22                         .000805                56
      23                         .000875                50
      24                         .000932                50
      25                         .00098                 85

THE AVERAGE VALUE OF VARIABLE 1 IS                 6.53680E-04
THE AVERAGE VALUE OF VARIABLE 2 IS                 37.2
THE STANDARD DEVIATION OF VARIABLE 1 IS            1.75455E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS            23.7837
THE CORRELATION COEFFICIENT BETWEEN VARIABLES 1 AND 2 IS       .867813

EQUATION 1
VARIABLE 2  =     -39.6964             +           117636.  *VARIABLE 1
 75.3099          PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2  =     589.092              +           74.9064
*LOG OF VAR 1
 72.7009          PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG(VAR 2)  =     1.22322              +           3360.15   *VARIABLE 1


EQUATION 4
LOG(VAR 2)  =     19.7197              +           2.21234   *LOG(VAR 1)
```

RESIN BOND WHEEL - WET CONDITION, TEST 2
CHIP THICKNESS (1) vs TANGENTIAL FORCE (2) TABLE 18.

```
                                DATA

     OBSERVATION              VARIABLE 1                VARIABLE 2

     1                        .000314                   12
     2                        .000571                   117
     3                        .000517                   73
     4                        .000946                   750
     5                        .000373                   15
     6                        .000683                   24
     7                        .000432                   52
     8                        .000792                   177


THE AVERAGE VALUE OF VARIABLE 1 IS                     5.78500E-04
THE AVERAGE VALUE OF VARIABLE 2 IS                     152.5
THE STANDARD DEVIATION OF VARIABLE 1 IS                2.16811E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS                247.976
THE CORRELATION COEFFICIENT BETWEEN VARIABLES 1 AND 2 IS     .788314


EQUATION 1
VARIABLE 2  =     -369.092           +          901628.    * VARIABLE 1
 62.1439          PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2  =     3644.37            +          464.531
*LOG OF VAR 1
 50.1987          PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG(VAR 2)  =     1.02069            +          5403.1     * VARIABLE 1


EQUATION 4
LOG(VAR 2)  =     27.1064            +          3.05443    * LOG(VAR 1)
```

METAL BOND WHEEL - DRY CONDITION.   TEST 1.

CHIP THICKNESS (1)   vs   TANGENTIAL FORCE (2)

TABLE 19.

```
                        DATA

   OBSERVATION          VARIABLE 1          VARIABLE 2

   1                    .000314             32
   2                    .000571             60
   3                    .000517             60
   4                    .000946             740
   5                    .000373             15
   6                    .000683             72
   7                    .000432             60
   8                    .000792             560


THE AVERAGE VALUE OF VARIABLE 1 IS          5.78500E-04
THE AVERAGE VALUE OF VARIABLE 2 IS          199.875
THE STANDARD DEVIATION OF VARIABLE 1 IS     2.16811E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS     282.548
THE CORRELATION COEFFICIENT BETWEEN VARIABLES 1 AND 2 IS   .873467


EQUATION 1
VARIABLE 2  =  -458.631          +        1.13830E+06   * VARIABLE 1
 76.2944       PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2  =  4701.27           +        598.829
*LOG OF VAR 1
 64.2549       PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG(VAR 2)  =  1.17027           +        5684.08        * VARIABLE 1


EQUATION 4
LOG(VAR 2)  =  28.0334           +        3.13623        *LOG(VAR 1)
```

METAL BOND WHEEL - DRY CONDITION. TEST 2

CHIP THICKNESS (1) vs TANGENTIAL FORCE (2)

TABLE 20.

```
                                DATA

     OBSERVATION                VARIABLE 1            VARIABLE 2

     1                          .000314               12
     2                          .000571               108
     3                          .000517               48
     4                          .000946               660
     5                          .000373               14
     6                          .000683               108
     7                          .000432               48
     8                          .000792               380


THE AVERAGE VALUE OF VARIABLE 1 IS                5.78500E-04
THE AVERAGE VALUE OF VARIABLE 2 IS                172.25
THE STANDARD DEVIATION OF VARIABLE 1 IS           2.16811E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS           230.191
THE CORRELATION COEFFICIENT BETWEEN VARIABLES 1 AND 2 IS     .910592


EQUATION 1
VARIABLE 2  =   -387.036          +         966785     * VARIABLE 1
 82.9177        PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2  =   4022.72           +         512.238
*LOG OF VAR 1
 70.8355        PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG(VAR 2)  =   .634736           +         6392.64    *VARIABLE 1


EQUATION 4
LOG(VAR 2)  =   31.9551           +         3.67463    *LOG(VAR 1)
```

METAL BOND WHEEL - WET CONDITION. TEST 1

CHIP THICKNESS (1) vs TANGENTIAL FORCE (2)

TABLE 21

```
                                 DATA

     OBSERVATION                  VARIABLE 1                 VARIABLE 2

     1                            .000314                    30
     2                            .000571                    72
     3                            .000517                    60
     4                            .000946                    270
     5                            .000373                    12
     6                            .000683                    45
     7                            .000432                    75
     8                            .000792                    380


THE AVERAGE VALUE OF VARIABLE 1 IS                   5.78500E-04
THE AVERAGE VALUE OF VARIABLE 2 IS                   118
THE STANDARD DEVIATION OF VARIABLE 1 IS              2.16811E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS              132.765
THE CORRELATION COEFFICIENT BETWEEN VARIABLES  1 AND 2 IS   .791281


EQUATION 1
VARIABLE 2    =    -162.308            +           484543.    *VARIABLE 1
 62.6126           PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2    =    2106.59             +           264.546
*LOG OF VAR 1
 56.7962           PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG(VAR 2)    =    1.7843              +           4244.91    *VARIABLE 1


EQUATION 4
LOG(VAR 2)    =    22.3038             +           2.40305    *LOG(VAR 1)
```

METAL BOND WHEEL - WET CONDITION. TEST 2

CHIP THICKNESS (1) vs TANGENTIAL FORCE (2)

TABLE 22.

```
                         DATA

  OBSERVATION                 VARIABLE 1             VARIABLE 2

  1                           .000387                50.82
  2                           .000439                39.82
  3                           .000479                38.53
  4                           .000509                35.18
  5                           .000535                34.12
  6                           .000419                22.64
  7                           .000476                42.66
  8                           .000517                36.01
  9                           .000551                26.93
  10                          .000579                30.08
  11                          .000519                33.7
  12                          .000558                22.75
  13                          .000639                29.29
  14                          .000681                31.6
  15                          .000716                31.6
  16                          .000661                29.53
  17                          .000749                27.38
  18                          .000815                25.89
  19                          .000868                21.48
  20                          .000913                25.63
  21                          .00071                 37.23
  22                          .000805                34.9
  23                          .000875                24.93
  24                          .000932                19.39
  25                          .00098                 21.26

THE AVERAGE VALUE OF VARIABLE 1 IS              6.52480E-04
THE AVERAGE VALUE OF VARIABLE 2 IS              30.934
THE STANDARD DEVIATION OF VARIABLE 1 IS         1.76024E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS         7.53642
THE CORRELATION COEFFICIENT BETWEEN VARIABLES 1 AND 2 IS     .650158

EQUATION 1
VARIABLE 2  =    49.0965             +         -27836.3      * VARIABLE 1
 42.2705      PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED

EQUATION 2
VARIABLE 2  =  -103.026              +         -18.177
*LOG OF VAR 1
 42.8845       PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED

EQUATION 3
LOG(VAR 2)  =   3.98561              +         -891.333      * VARIABLE 1

EQUATION 4
LOG(VAR 2)  =  -.795619              +         -.569864      * LOG(VAR 1)
```

RESIN BOND WHEEL - WET CONDITION. TEST 1

CHIP THICKNESS (1) vs SPECIFIC ENERGY (2)

TABLE 23.

```
                          DATA

     OBSERVATION          VARIABLE 1          VARIABLE 2

     1                    .000387             35.18
     2                    .000439             30.49
     3                    .000479             33.5
     4                    .000509             31.27
     5                    .000535             34.12
     6                    .000419             32.31
     7                    .000476             34.9
     8                    .000517             27.7
     9                    .000551             29.08
     10                   .000579             30.08
     11                   .000519             25.26
     12                   .000558             26.54
     13                   .000639             33.4
     14                   .000681             25.98
     15                   .000716             40.21
     16                   .000661             32.21
     17                   .000749             30.6
     18                   .000815             25.89
     19                   .000868             29.53
     20                   .000913             36.61
     21                   .00071              32.57
     22                   .000805             39.09
     23                   .000875             24.93
     24                   .000932             19.39
     25                   .00098              26.97


THE AVERAGE VALUE OF VARIABLE 1 IS               6.52480E-04
THE AVERAGE VALUE OF VARIABLE 2 IS               30.7124
THE STANDARD DEVIATION OF VARIABLE 1 IS          1.76024E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS          4.78651
THE CORRELATION COEFFICIENT BETWEEN VARIABLES 1 AND 2 IS    .239012


EQUATION 1
VARIABLE 2  =    34.9531             +        -6499.29     * VARIABLE 1
 5.71268         PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2  =    .986393             +        -4.03321
*LOG OF VAR 1
 5.23421         PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG(VAR 2)  =    3.58311             +        -261.596     * VARIABLE 1


EQUATION 4
LOG (VAR 2) =    2.21834             +        -.16203      *LOG(VAR 1)
```

RESIN BOND WHEEL - WEST CONDITION. TEST 2

CHIP THICKNESS (1) vs SPECIFIC ENERGY (2)

TABLE 24.

```
                              DATA

OBSERVATION                VARIABLE 1               VARIABLE 2


1                          .000314                  46.87
2                          .000571                  136
3                          .000517                  57.39
4                          .000946                  175.52
5                          .000373                  43.24
6                          .000683                  20.59
7                          .000432                  55.44
8                          .000792                  56.09

THE AVERAGE VALUE OF VARIABLE 1  IS                 5.78500E-04
THE AVERAGE VALUE OF VARIABLE 2  IS                 73.8925
THE STANDARD DEVIATION OF VARIABLE 1  IS            2.16811E-04
THE STANDARD DEVIATION OF VARIABLE 2  IS            52.9504
THE CORRELATION COEFFICIENT BETWEEN VARIABLES 1 AND 2 IS   .555937




EQUATION 1
VARIABLE 2    =    -4.6521        +           135773.     *VARIABLE
 30.9066           PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2    =    613.91         +           71.8391
*LOG OF VAR 1
 26.3311           PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG (VAR 2)   =    3.38212        +           1243.41     * VARIABLE


EQUATION 4
LOG(VAR 2)    =    8.94161        +          .643911      *LOG(VAR 1)
```

METAL BOND WHEEL - DRY CONDITION. TEST 1

CHIP THICKNESS (1) vs SPECIFIC ENERGY (2)

TABLE 25.

```
                         DATA

    OBSERVATION                VARIABLE 1               VARIABLE 2

    1                          .000314                  124.95
    2                          .000571                  69.74
    3                          .000517                  47.17
    4                          .000946                  173.15
    5                          .000373                  43.24
    6                          .000683                  61.79
    7                          .000432                  63.91
    8                          .000792                  177.5


THE AVERAGE VALUE OF VARIABLE 1  IS           5.78500E-04
THE AVERAGE VALUE OF VARIABLE 2  IS           95.1813
THE STANDARD DEVIATION OF VARIABLE 1 IS       2.16811E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS       55.4008
THE CORRELATION COEFFICIENT BETWEEN VARIABLES  1 AND 2 IS    .633487


EQUATION 1
VARIABLE 2  =   1.53829          +         161872.      * VARIABLE 1
 40.1306        PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2  =   681.663          +         78.0202
*LOG OF VAR 1
 28.3705        PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG(VAR 2)  =   3.53117          +         1525.1       * VARIABLE 1


EQUATION 4
LOG(VAR 2)  =   9.87175          +         .726137      *LOG(VAR 1)
```

METAL BOND WHEEL - DRY CONDITION. TEST 2

CHIP THICKNESS (1) vs SPECIFIC ENERGY (2)

TABLE 26.

```
                          DATA

    OBSERVATION           VARIABLE 1          VARIABLE 2


    1                     .000314             46.87
    2                     .000571             125.5
    3                     .000517             37.72
    4                     .000946             154.46
    5                     .000373             40.34
    6                     .000683             92.68
    7                     .000432             51.13
    8                     .000792             120.43



THE AVERAGE VALUE OF VARIABLE 1 IS                5.78500E-04
THE AVERAGE VALUE OF VARIABLE 2 IS                83.6412
THE STANDARD DEVIATION OF VARIABLE 1 IS           2.16811E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS           45.6625
THE CORRELATION COEFFICIENT BETWEEN VARIABLES     1 AND 2 IS    .876212



EQUATION 1
VARIABLE 2  =   -23.1141           +            184538.     * VARIABLE
 76.7748        PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2  =   860.368            +            103.329
*LOG OF VAR 1
 73.2506        PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG(VAR 2)  =   2.99542            +            2233.87     * VARIABLE


EQUATION 4
LOG(VAR 2)  =   13.7937            +            1.2646      *LOG(VAR 1)
```

METAL BOND WHEEL - WET CONDITION. TEST 1

CHIP THICKNESS (1) vs SPECIFIC ENERGY (2)

TABLE 27.

```
                              DATA

     OBSERVATION                 VARIABLE 1          VARIABLE 2

     1                           .000314             117.13
     2                           .000571             83.69
     3                           .000517             47.17
     4                           .000946             63.19
     5                           .000373             34.59
     6                           .000683             38.61
     7                           .000432             79.88
     8                           .000792             120.43


THE AVERAGE VALUE OF VARIABLE 1 IS                  5.78500E-04
THE AVERAGE VALUE OF VARIABLE 2 IS                  73.0863
THE STANDARD DEVIATION OF VARIABLE 1 IS             2.16811E-04
THE STANDARD DEVIATION OF VARIABLE 2 IS             33.3381
THE CORRELATION COEFFICIENT BETWEEN VARIABLES  1 AND 2 IS   6.94335E-03


EQUATION 1
VARIABLE 2  =    73.7039         +         -1067.65        * VARIABLE 1
.004821         PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 2
VARIABLE 2  =    35.9517         +         -4.93966
*LOG OF VAR 1
 .314048        PERCENT OF THE VARIANCE IN VARIABLE 2 EXPLAINED


EQUATION 3
LOG(VAR 2)  =   4.14504          +         86.1554         * VARIABLE 1


EQUATION 4
LOG(VAR 2)  =   4.14312          +        -6.88772E-03     * LOG(VAR 1)
```

METAL BOND WHEEL - WET CONDITION.   TEST 2
CHIP THICKNESS (1) vs SPECIFIC ENERGY (2)

TABLE 28.

RESIN BOND WHEEL, WHEEL SPEED 1649 M/MIN WITH COOLANT.

TEST NO.		1	2	3	4	5
AREA OF WORN WHEEL	mm^2	0.035	0.036	0.11	0.05	0.07
VOLUME OF WORN WHEEL	mm^3	27.96	28.72	87.77	39.26	55.85
VOLUME OF REFEL GROUND	mm^3	1663	1646	2368	1142	2508
FEED PER PASS	mm	0.015	0.025	0.035	0.045	0.055
RATE OF MATERIAL REMOVAL	cm^3/min	0.548	1.18	2.239	4.77	6.93
GRINDING RATIO		59.4	57.34	26.97	29.1	44.9
TABLE SPEED	m/min	6.09	7.92	10.66	17.67	21

METAL BOND WHEEL, WHEEL SPEED 1649 M/MIN WITH COOLANT.

TEST NO.		1	2	3	4	5
AREA OF WORN WHEEL	mm^2	0.0325	0.0435	0.043	0.085	0.0525
VOLUME OF WORN WHEEL	mm^3	36.34	48.60	48.1	95.06	58.76
VOLUME OF REFEL GROUND	mm^3	2331	2136	2170	3441	3274
FEED PER PASS	mm	0.015	0.025	0.035	0.045	0.055
RATE OF MATERIAL REMOVAL	cm/min	0.548	1.18	2.239	4.77	6.93
GRINDING RATIO		64.14	43.9	45.1	36.19	55.75
TABLE SPEED	m/min	6.09	7.92	10.66	17.67	21

CUTTING TEST DATA FOR ECONOMIC ANALYSIS.

TABLE 29.

TIME COST (Ct) £ 7 per hour
DIAMOND COST (Y) £ 17.65 per cm^3

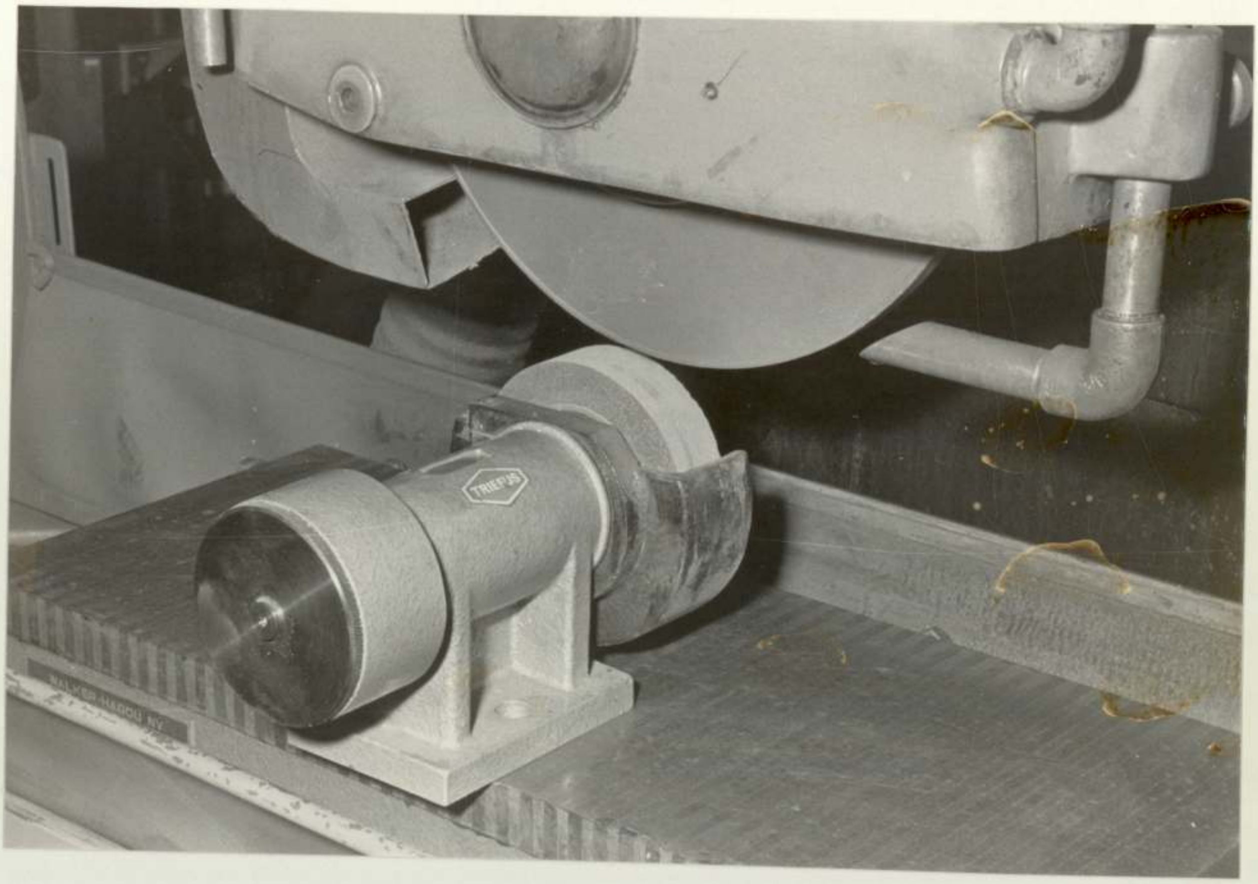
TEST NUMBER	1	2	3	4	5
VOLUMETRIC REMOVAL RATE (S) cm^3/min	0.548	01.18	2.239	4.77	6.93
GRINDING RATIO (G) RESIN WHEEL	59.4	57.34	26.97	29.1	44.9
GRINDING RATIO (G) METAL WHEEL	64.14	43.9	45.1	36.19	55.75
K_M TIME COST/VOLUMETRIC REMOVAL RATE £/cm^3.	0.212	0.0985	0.0519	0.0245	0.016
K_{DR} DIAMOND COST/G (RESIN WHEEL) £/cm^3	0.297	0.307	0.6546	0.606	0.352
K_{DM} DIAMOND COST/G (METAL WHEEL) £/cm^3	0.275	0.401	0.391	0.487	0.393
K_{GR} TOTAL SPECIFIC COSTS (RESIN) £/cm^3	0.509	0.4055	0.706	0.631	0.368
K_{GM} TOTAL SPECIFIC COSTS (METAL) £/cm^3	0.487	0.499	0.442	0.511	0.409

COMPARATIVE COSTS FOR RESIN BOND AND METAL BOND WHEELS

TABLE 30.

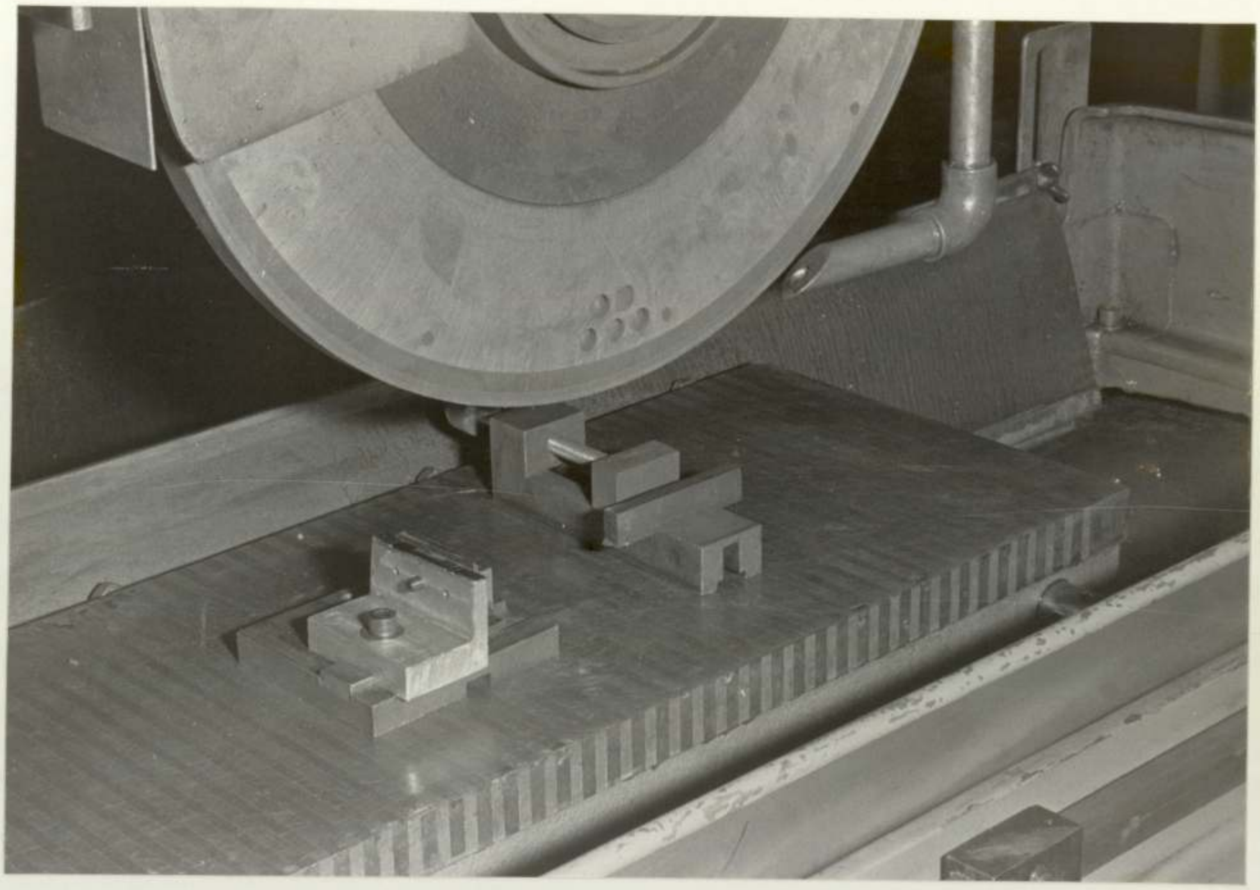
GRINDING MACHINE with DYNAMOMETER
and MONITORING DEVICE.

PLATE 1



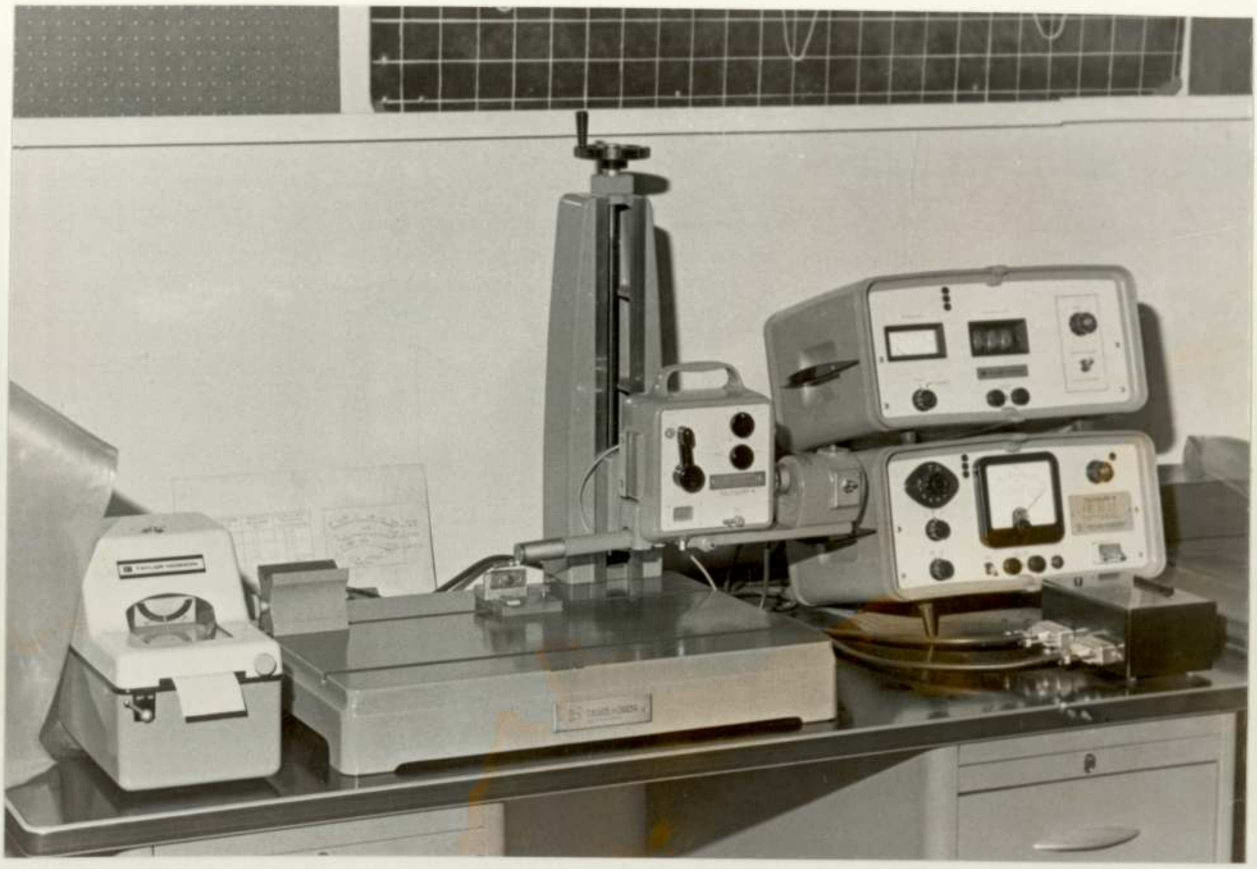
TRUEING DEVICE

PLATE 2



METAL BOND WHEEL ON ECONOMIC TEST RUN

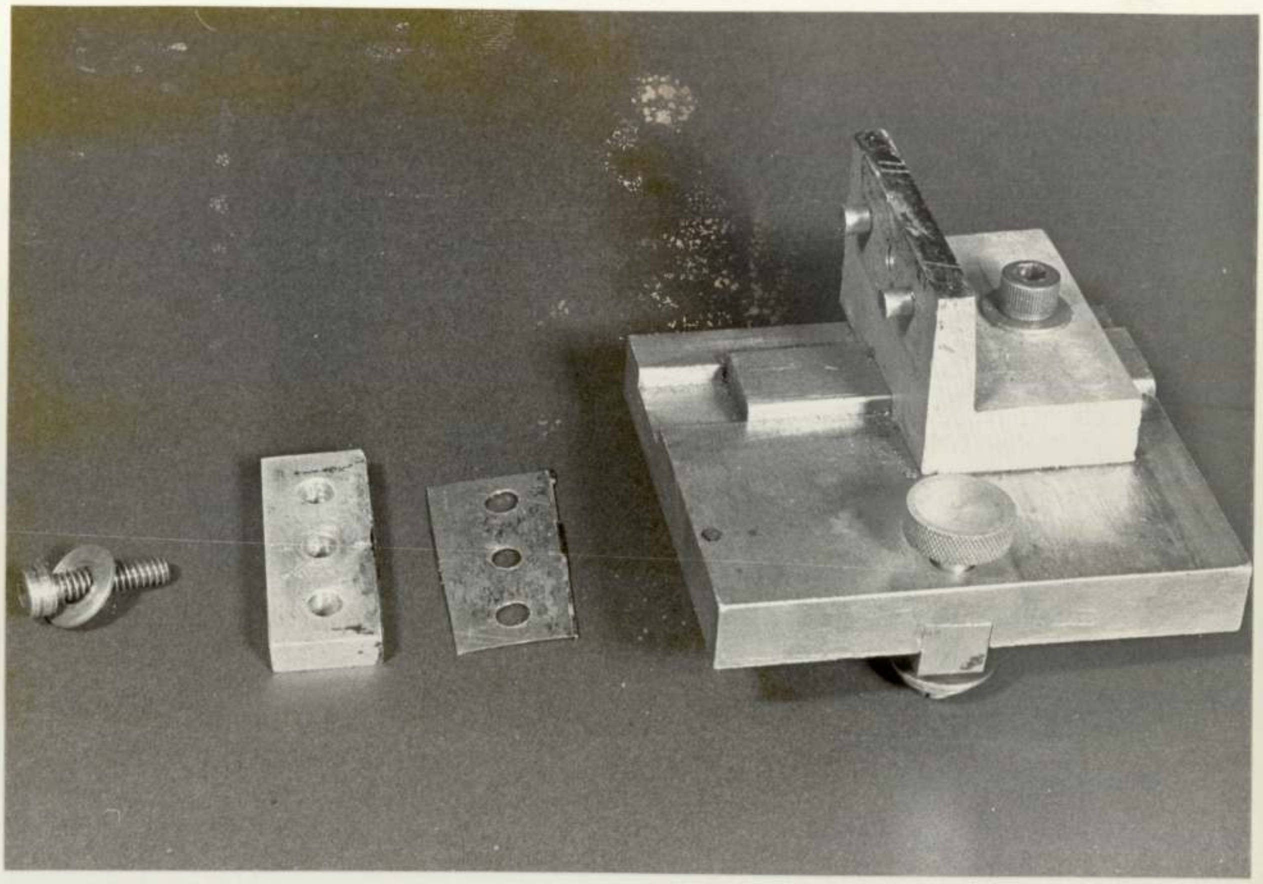
PLATE 3



GENERAL LAYOUT OF

TALYSURF AND 'RAZOR-BLADE' JIG

PLATE 4

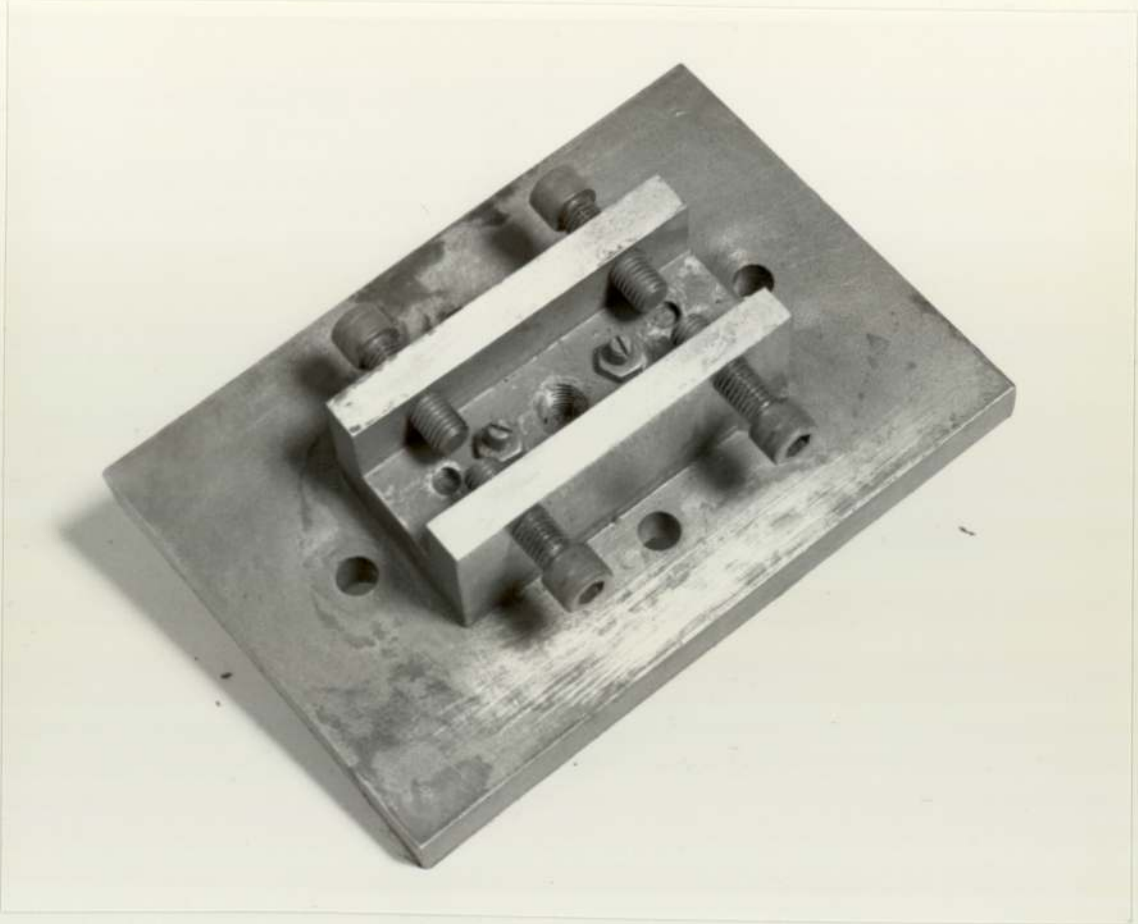


DETAILS OF RAZOR-BLADE JIG

PLATE 5

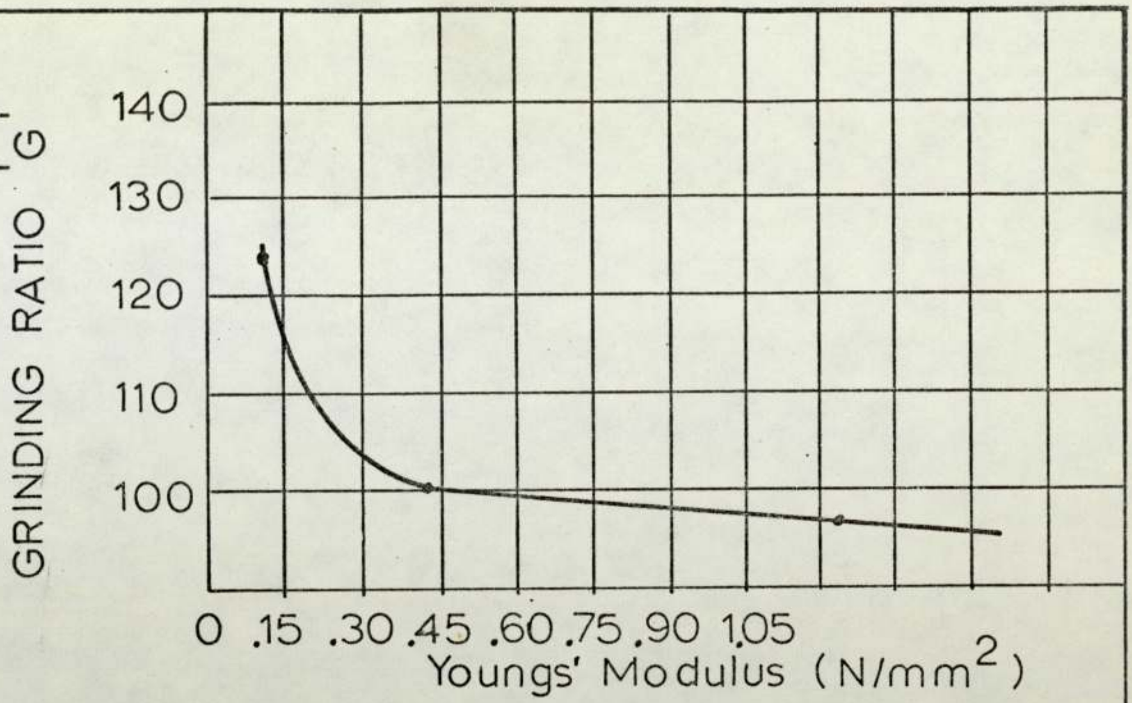
EXTRA PULLEY WHEELS

PLATE 6

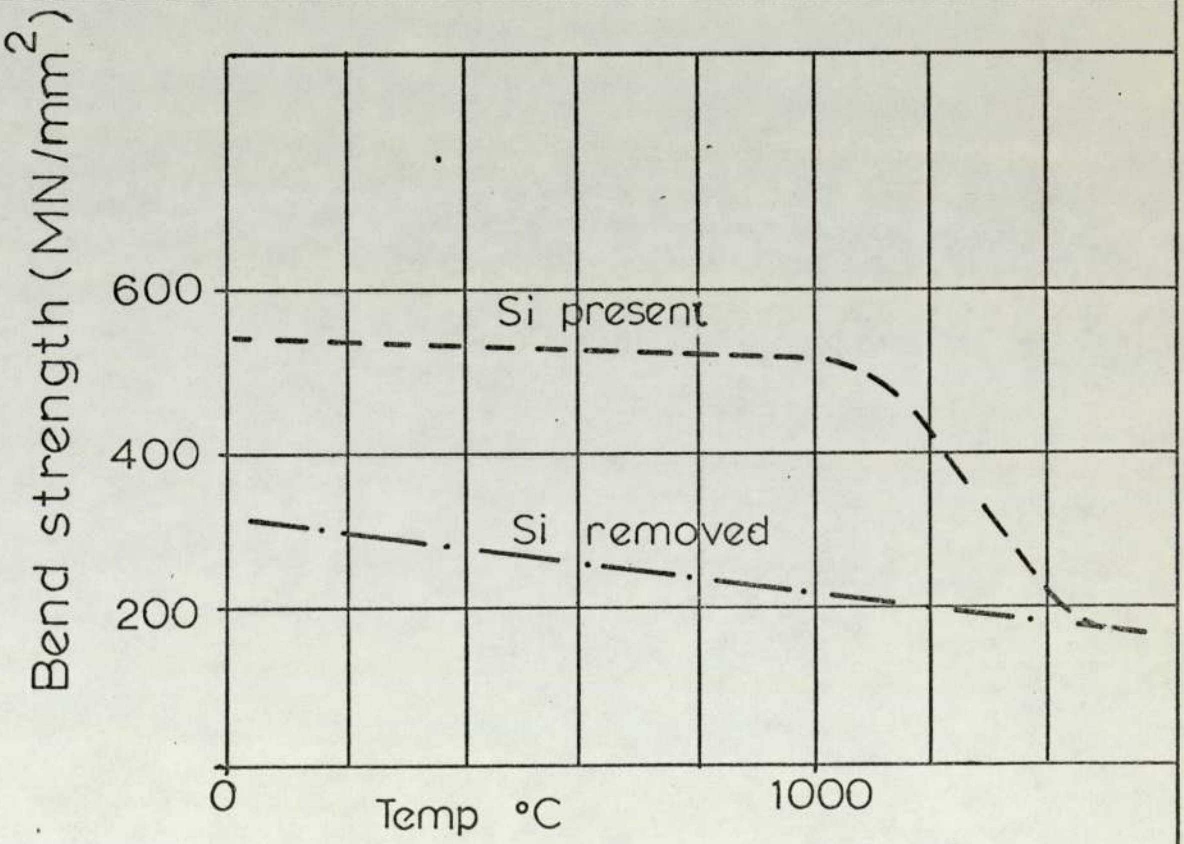


WORKHOLDING PLATE FOR ECONOMIC TEST RUN

PLATE 7

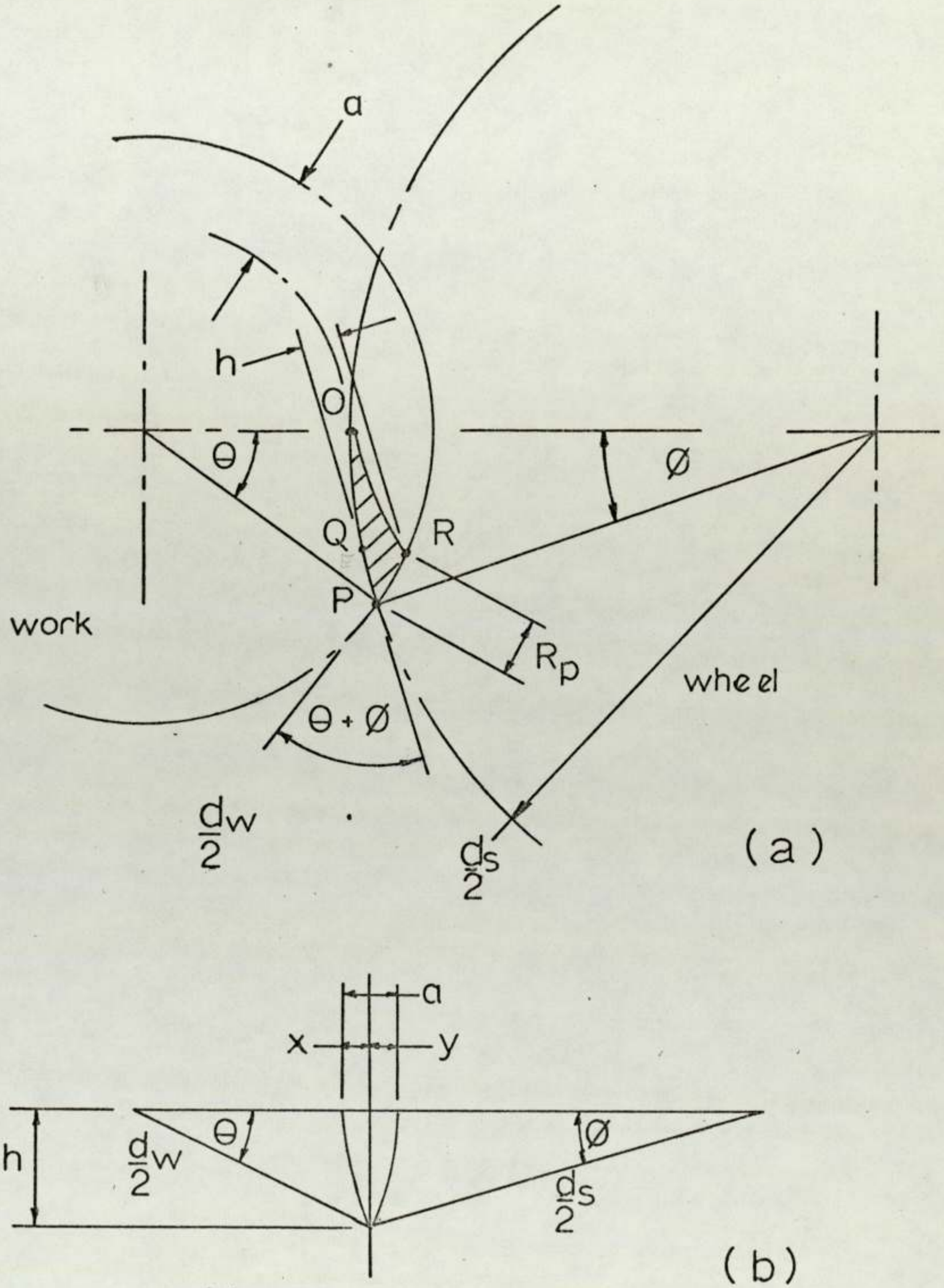


(a) EFFECT of HUB ELASTICITY on G RATIO
(from ref. 30)



(b) VARIATION of STRENGTH with TEMP
(from ref. 20)

FIG 1



GRINDING WHEEL GEOMETRY
(from ref. 21)

FIG 2

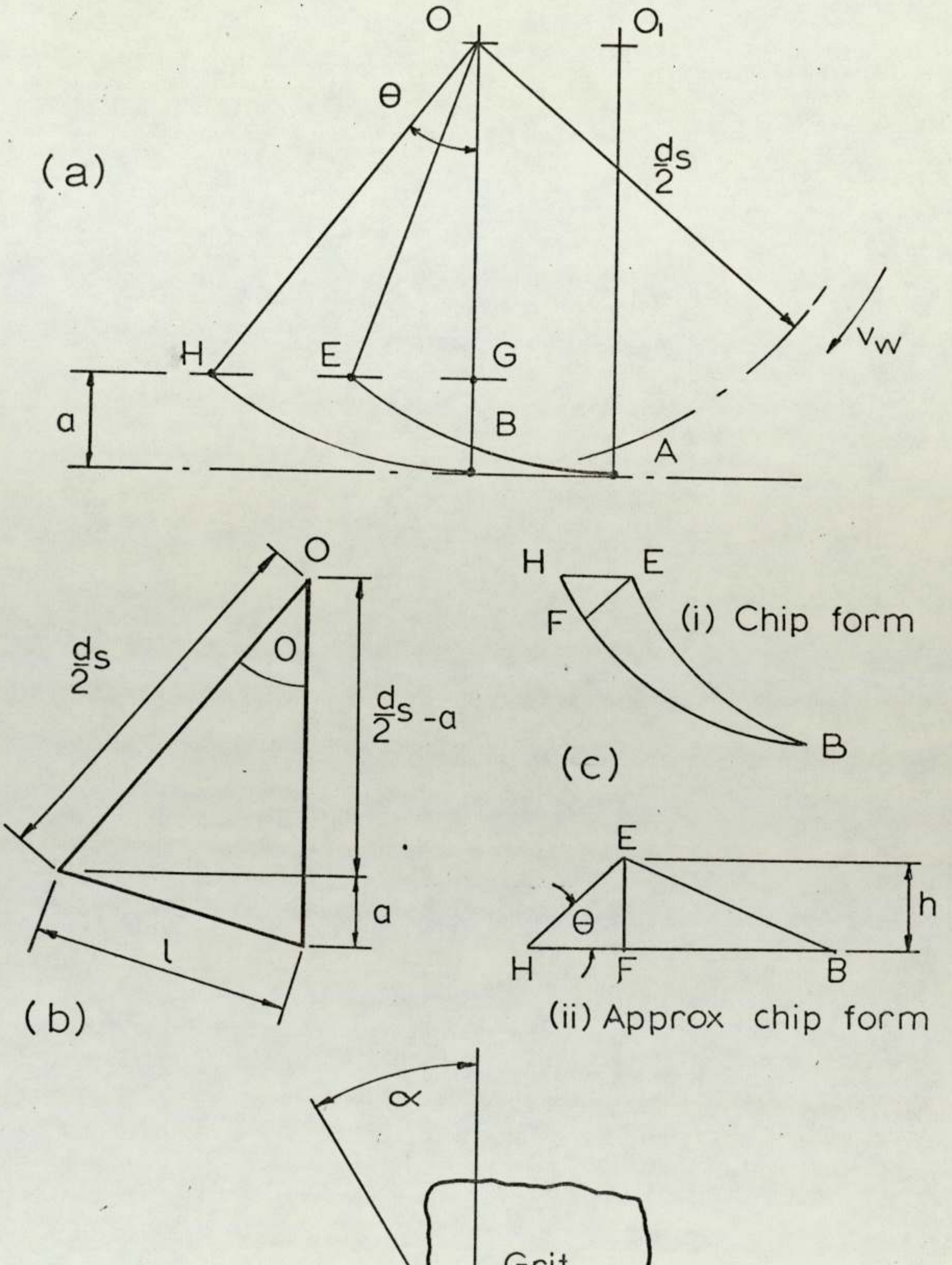
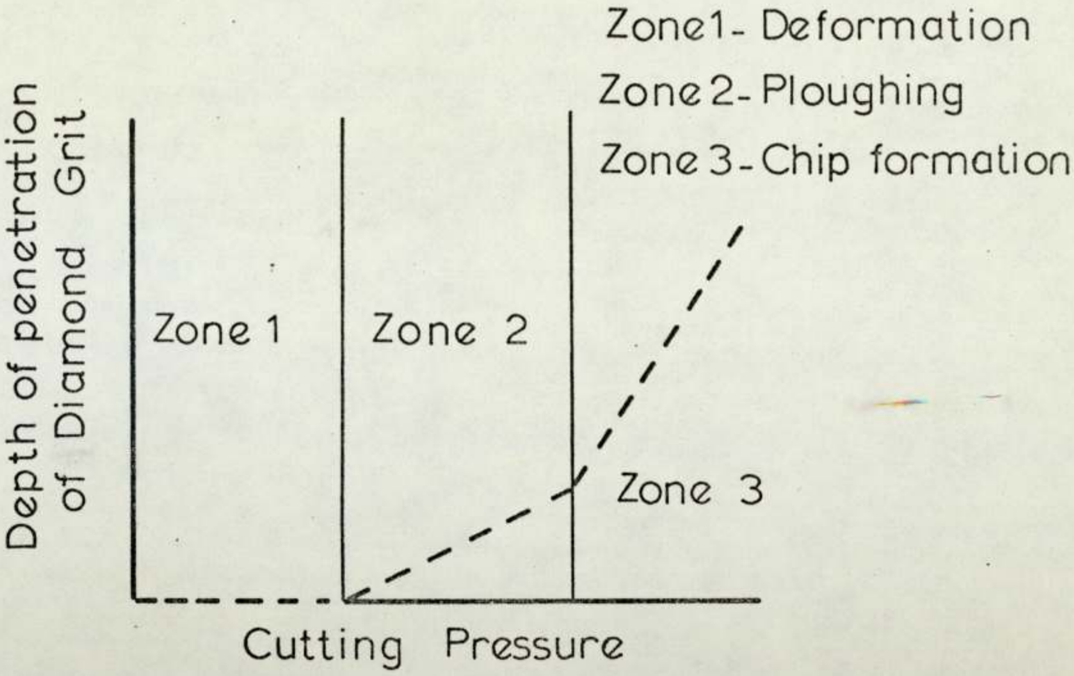
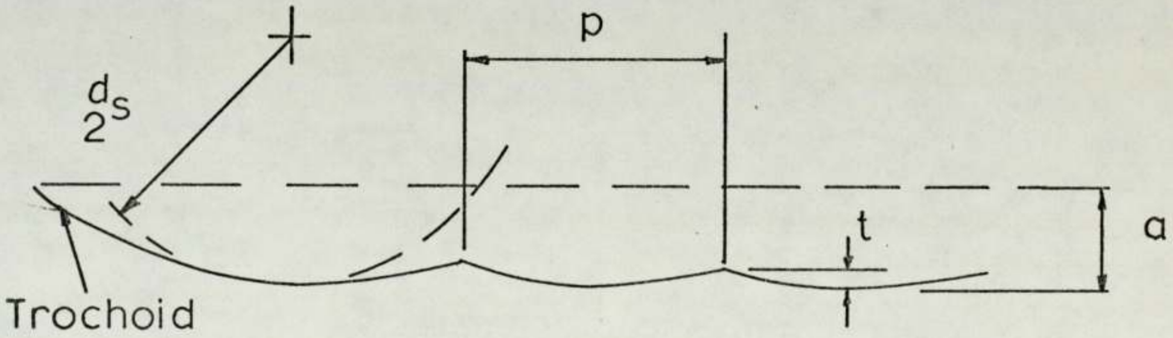

O
O1
θ
(a)
$\frac{d_s}{2}$
H
E
G
a
B
A
V_w
O
$\frac{d_s}{2}$
θ
$\frac{d_s}{2}-a$
a
l
(b)
H
E
F
(i) Chip form
B
(c)
E
h
θ
H
F
B
(ii) Approx chip form
α
Grit
V_s
h
(d)
F_t
F_g
F_n

FIG 3

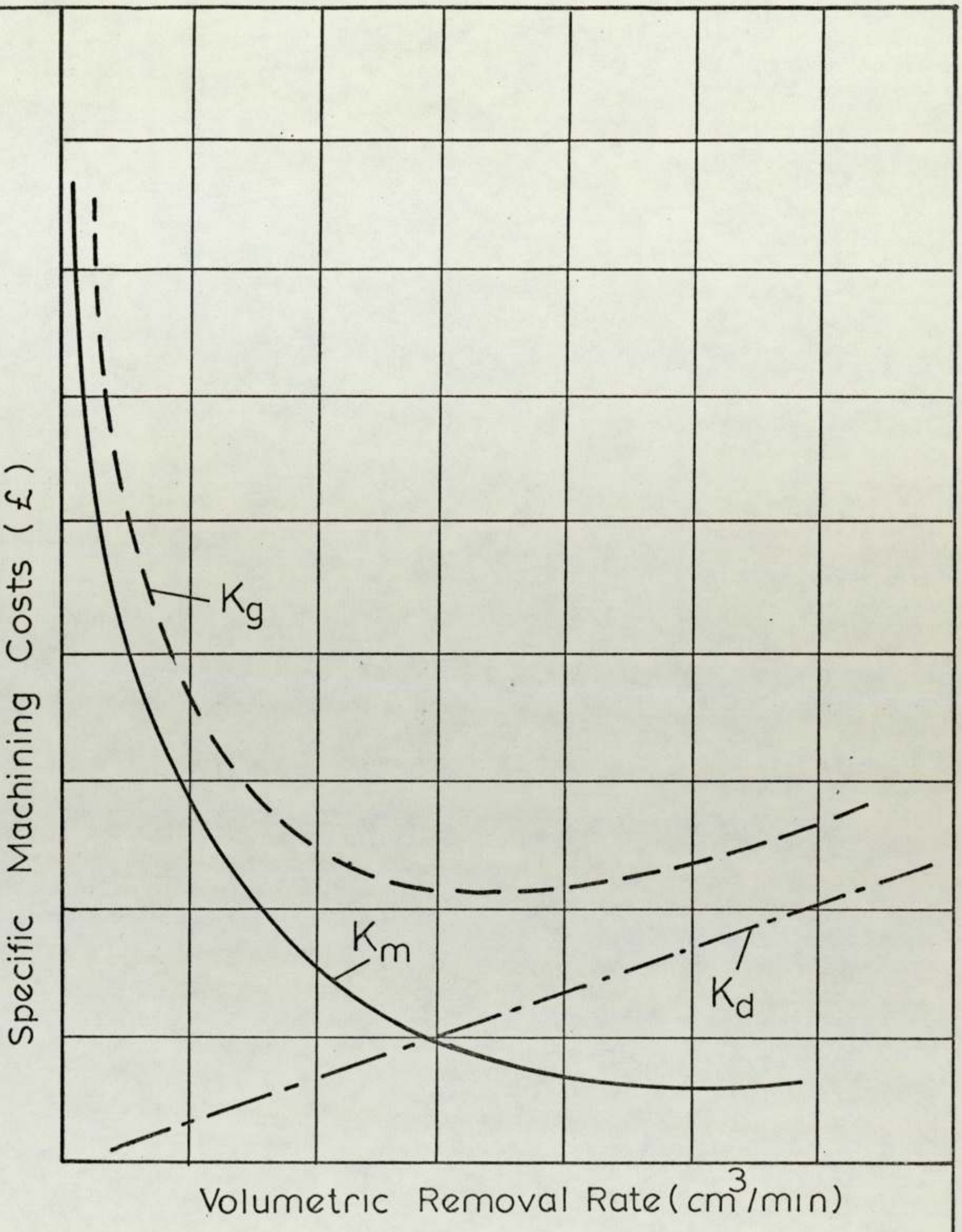


(a) Depth of Grit vs Cutting Pressure
(from ref.24)



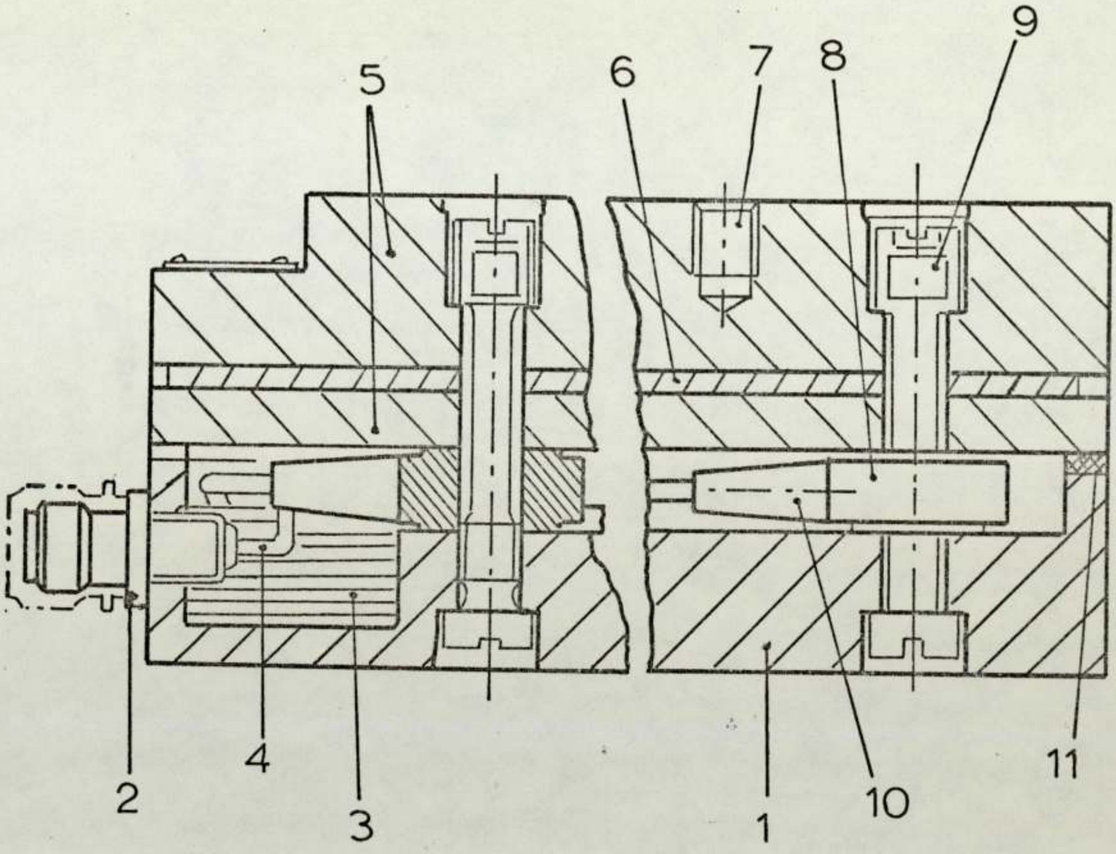
(b) Surface Texture Configuration
(from ref 21)

FIG 4



Typical Cost Curve
(from ref 41)

FIG 5



1 BASEPLATE
2 CHASSIS CHANNELS
3 & 4 CONNECTING LAYERS
5 TOP PLATES
6 MICAVER LAYER
7 MOUNTING HOLES
8 FORCE ELEMENTS
9 STRAIN SCREWS
10 CONNECTORS
11 SEAL

MOUNTING PLATFORM
(from ref 46)

FIG 6

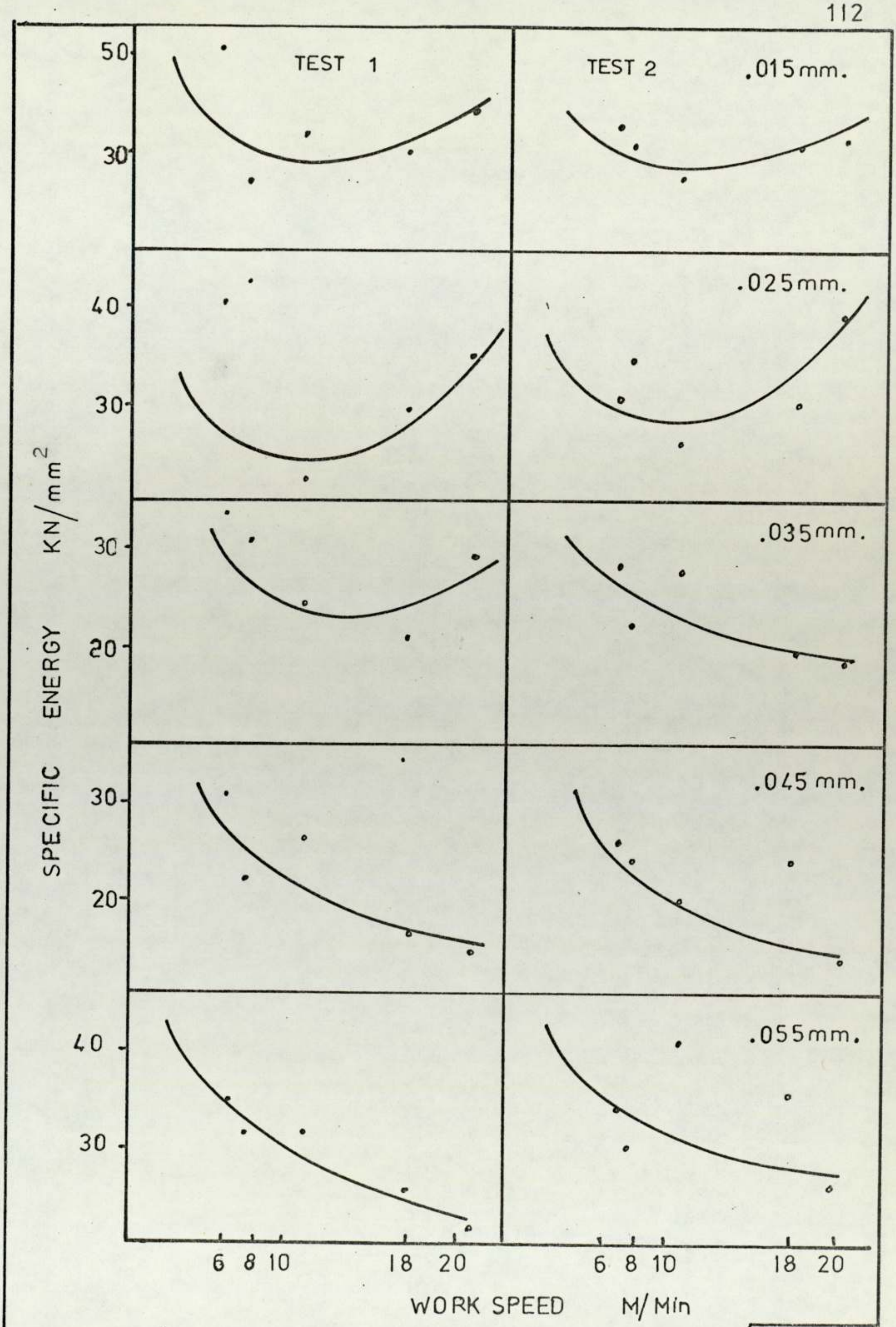

TEST 1
TEST 2
.015mm.
.025mm.
.035mm.
.045 mm.
.055mm.
SPECIFIC ENERGY KN/mm^2
50
30
40
30
30
20
30
20
40
30
6
8
10
18
20
6
8
10
18
20
WORK SPEED M/Min

FIG 7

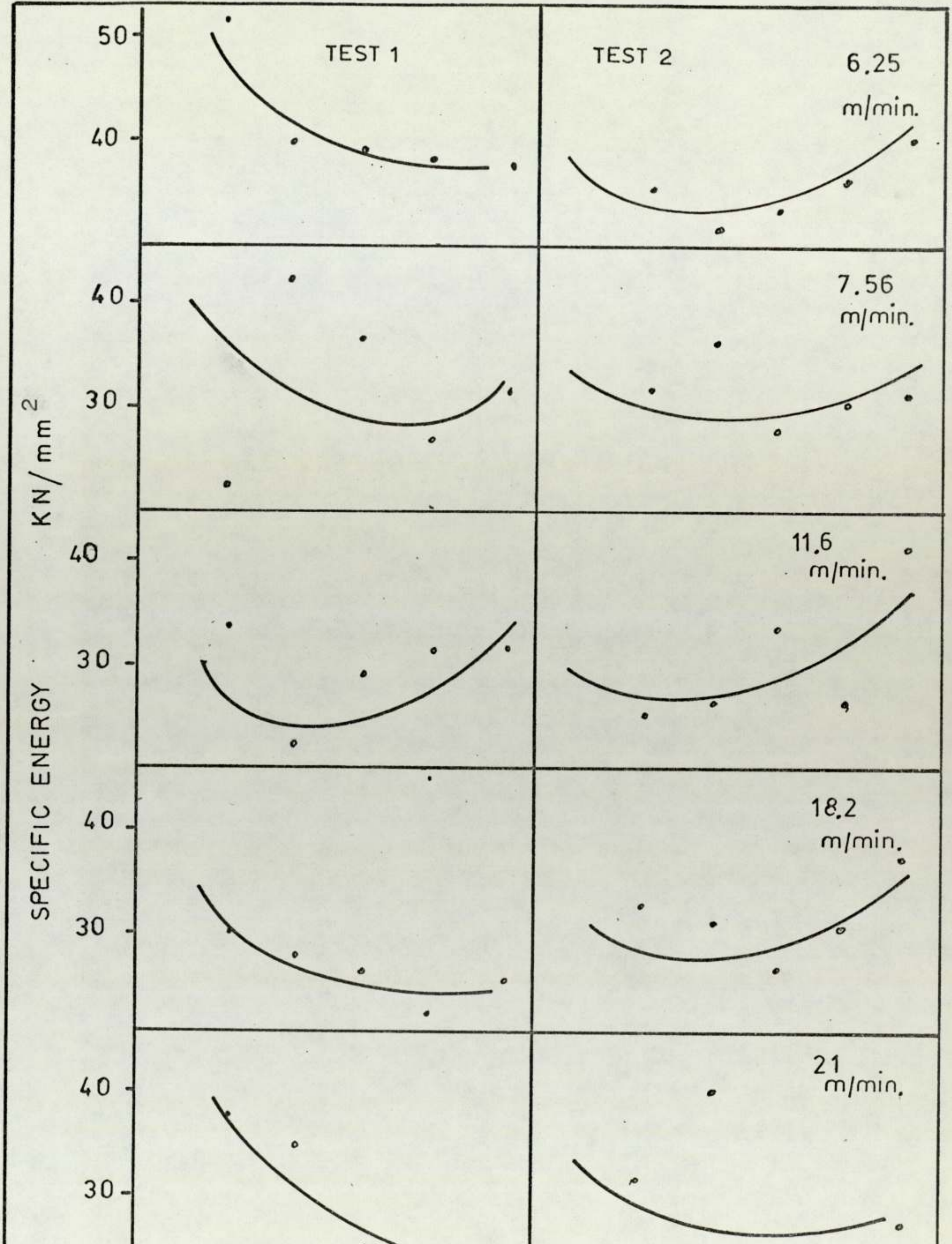
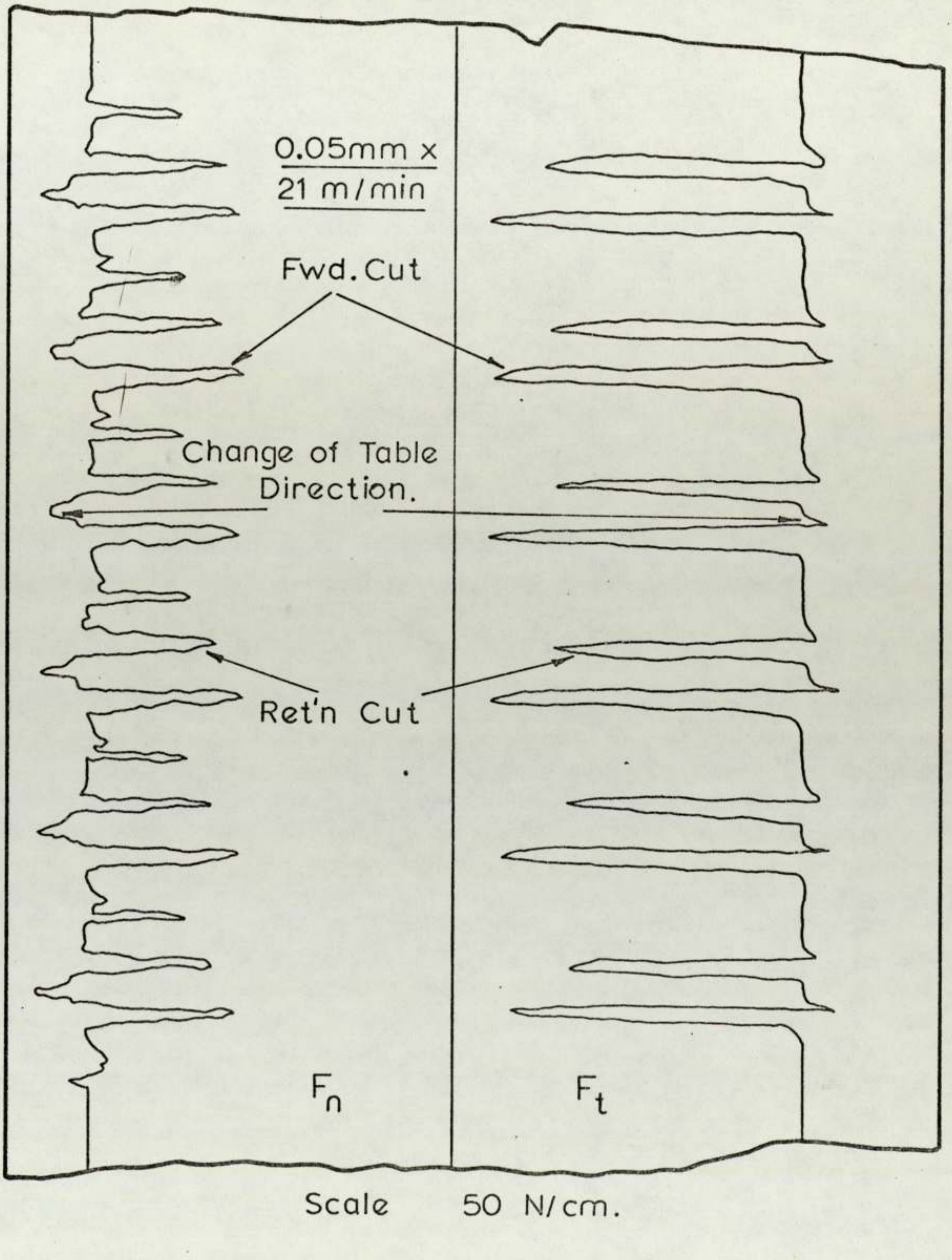
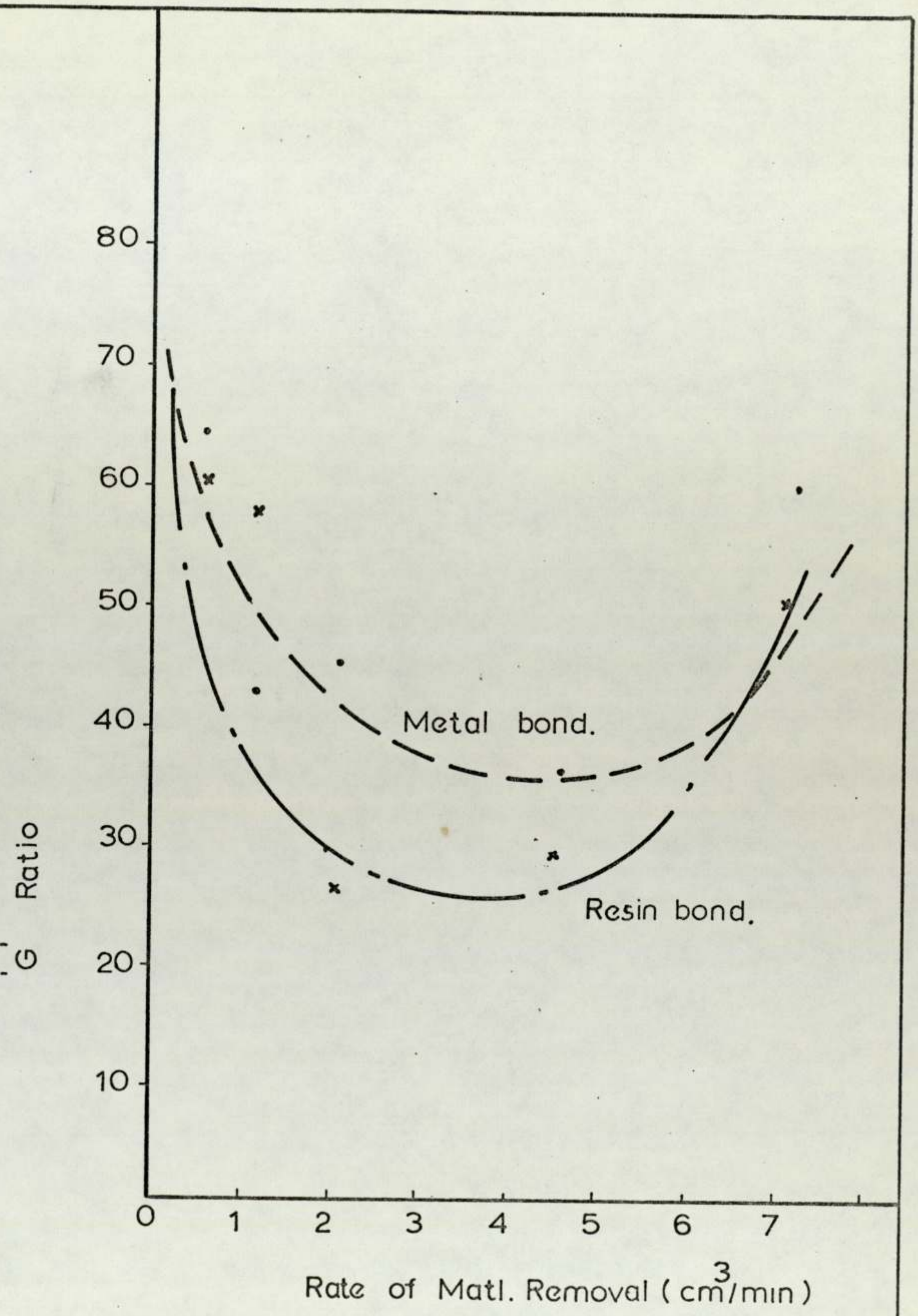

TEST 1
TEST 2
6.25 m/min.
7.56 m/min.
11.6 m/min.
18.2 m/min.
21 m/min.
SPECIFIC ENERGY KN/mm^2
50
40
30
1.5
25
35
45
55
15
DEPTH OF CUT 1/1000 mm

FIG 8



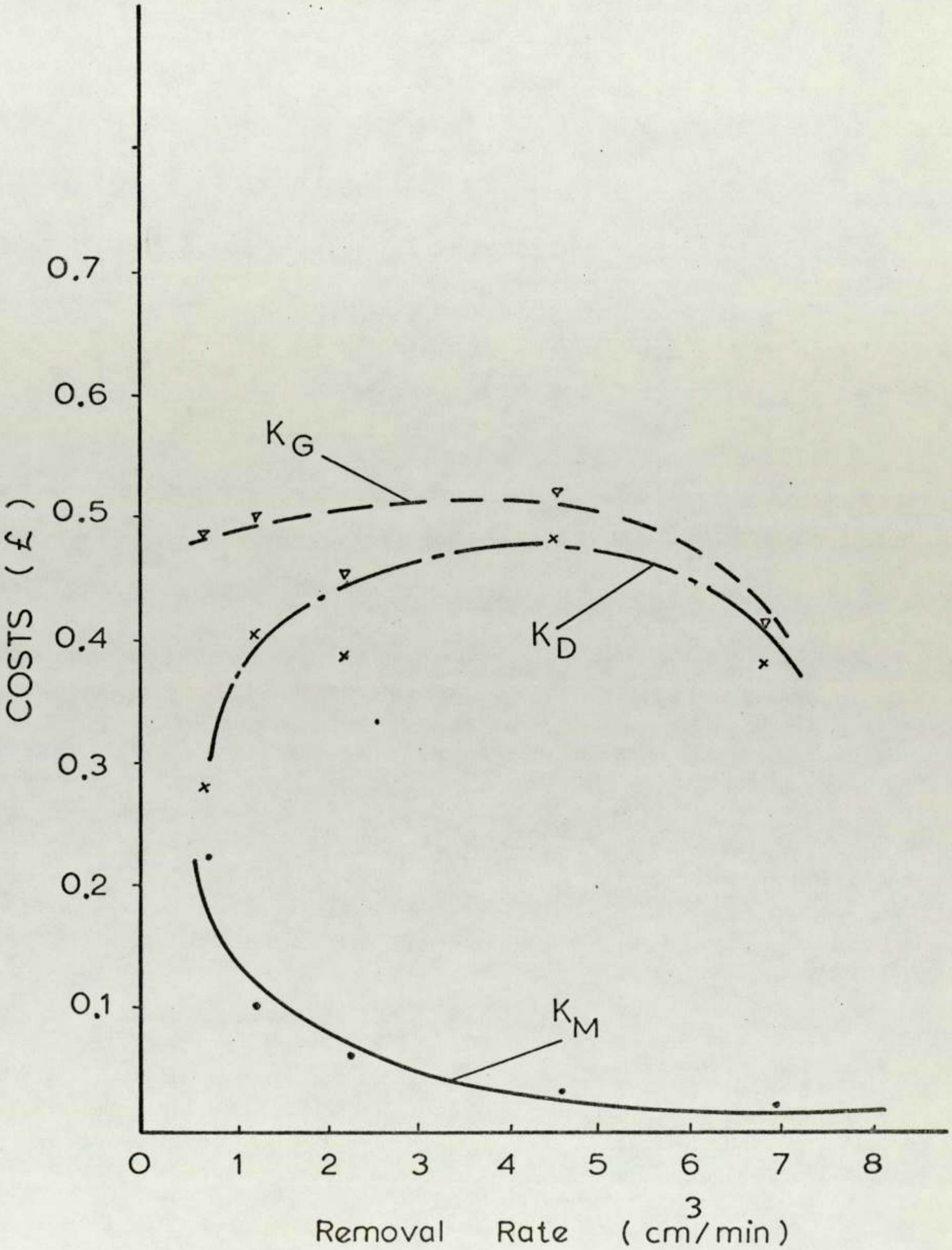
TYPICAL TRACE FROM U.V. RECORDER

FIG 9



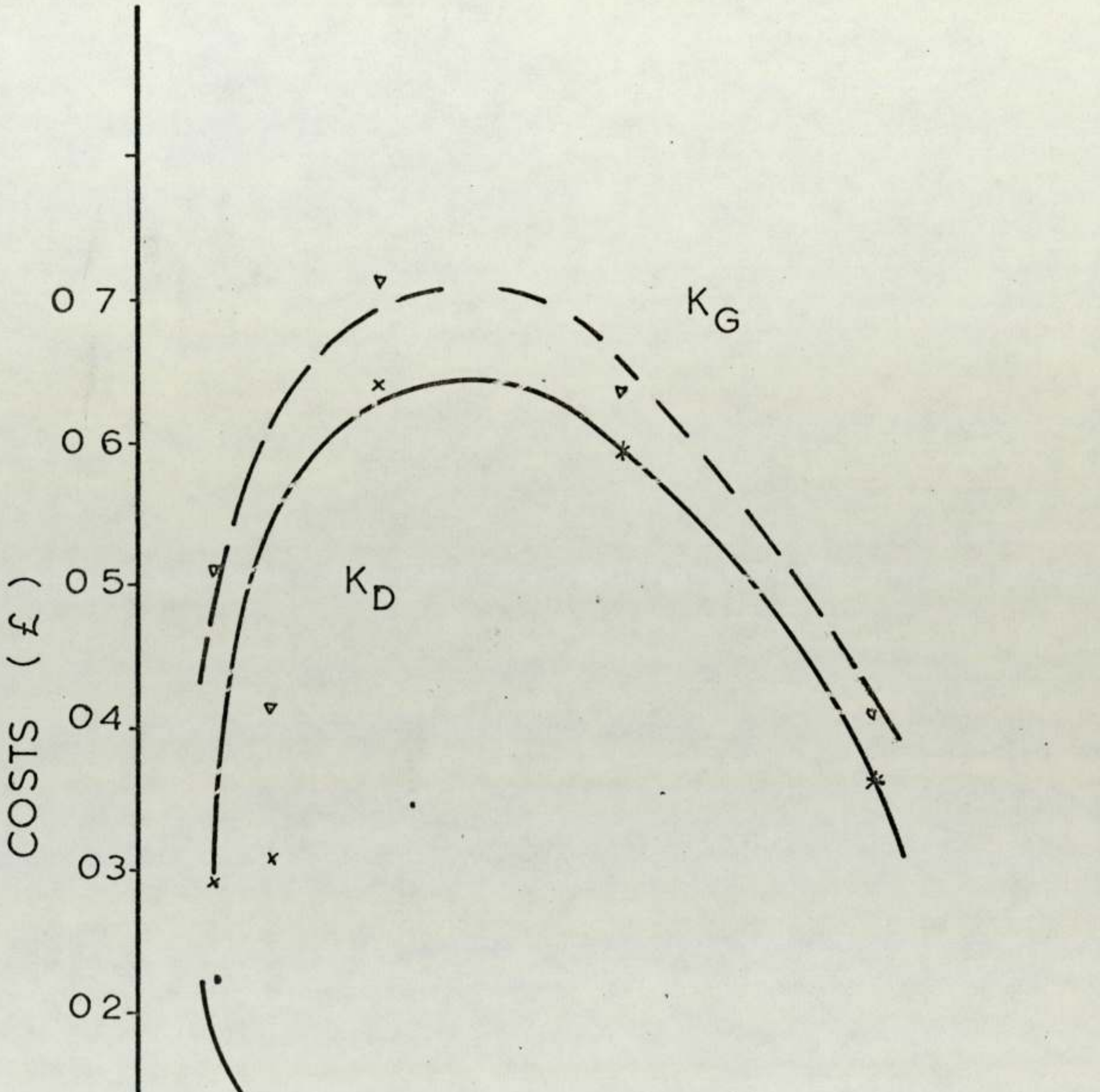
'G' RATIO vs. REMOVAL RATE

FIG10



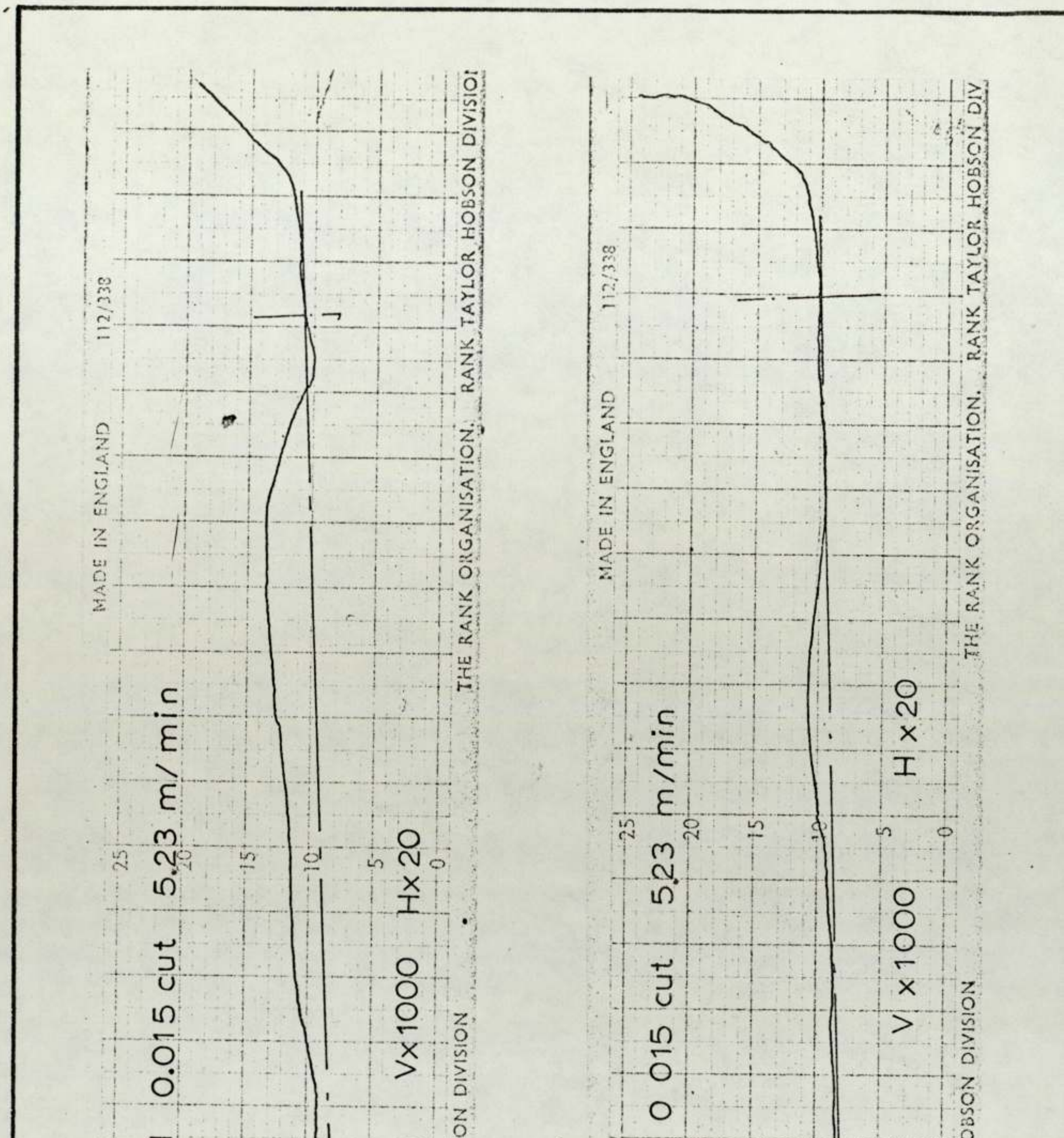
COSTS vs. REMOVAL RATE (Metal bond)

FIG 11



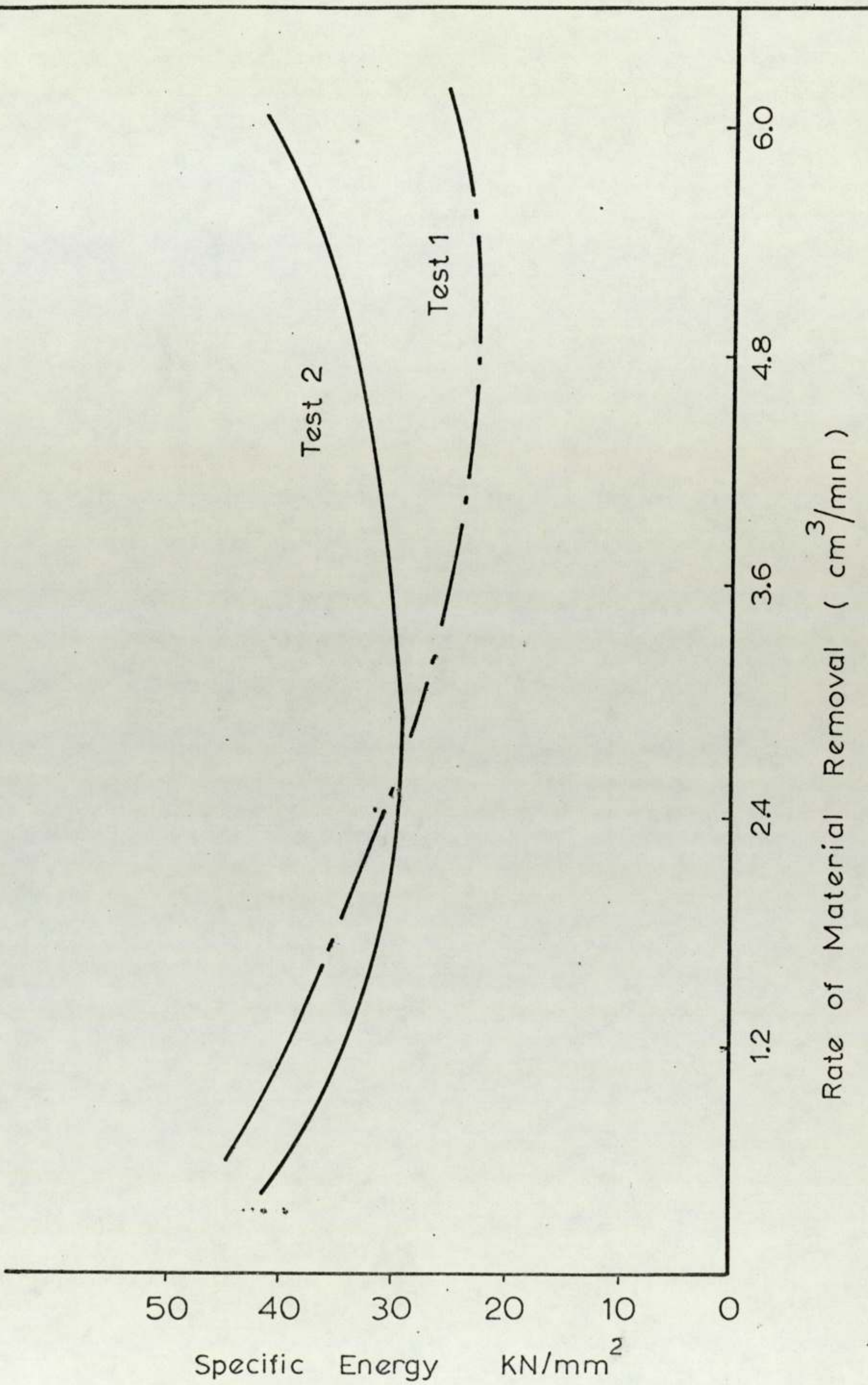
COSTS vs. REMOVAL RATE (Resin bond)

FIG 12



TYPICAL TRACE from TALYSURF

FIG 13

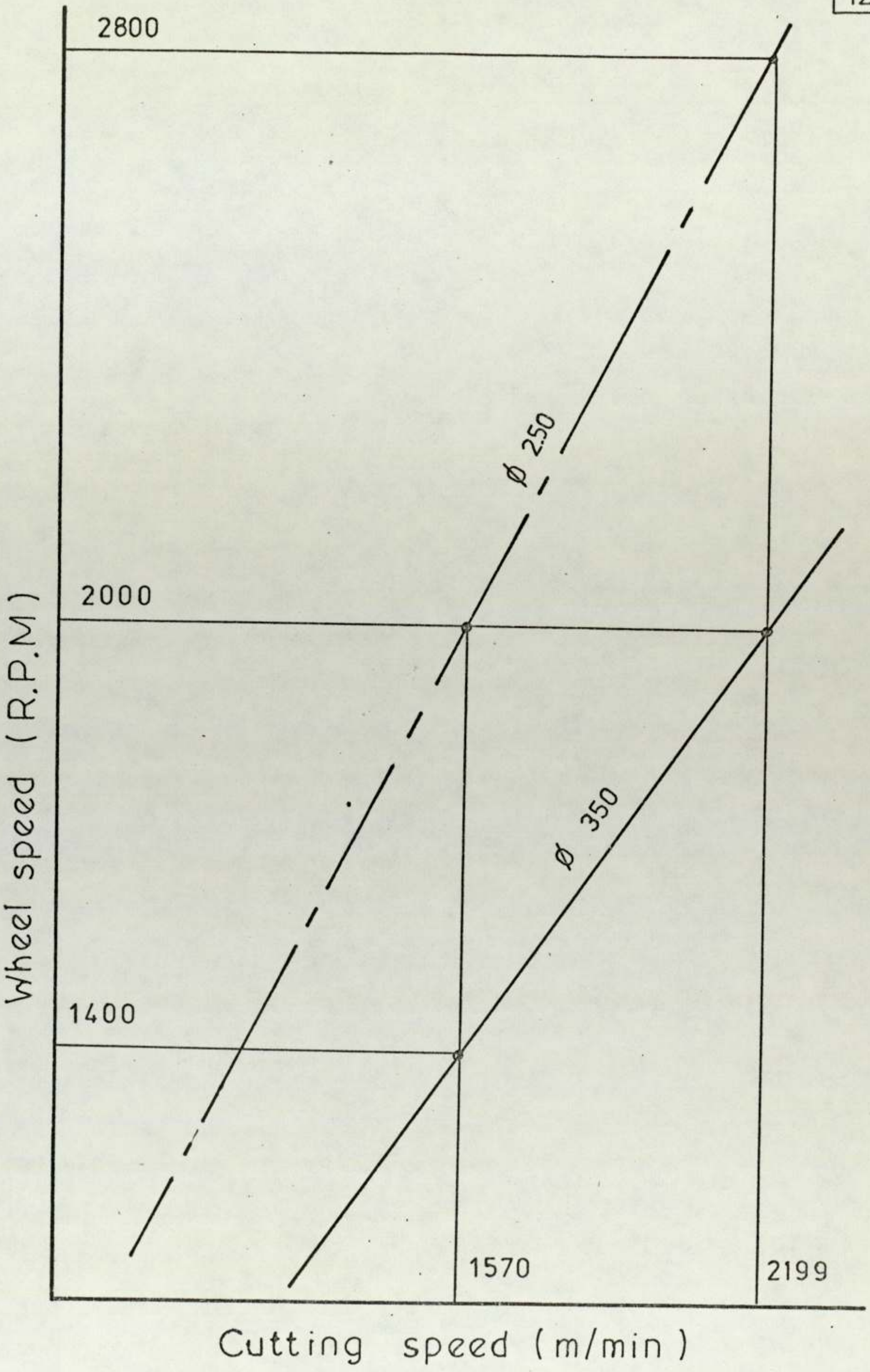


SPECIFIC ENERGY vs REMOVAL RATE

FIG 14

```
JOB FIVEFAC,  : MISTEELE
WPCSTATCR
  TACZLP
OBSERVATION MATRIX          RATIO
COL NAMES                   RATIO
  COLUMICOLUM2COLUM3COLUM4COLUM5COLUM6COLUM7COLUM8
MATRIX                      RATIO
  ROW001
  ROW002
  ROW003
  ROW004
END OF DATA
ANALYSIS OF VARIANCE        RATIO       F TEST
MODEL     Y=A(I)+B(J)+C(K)+D(L)+F(M)+AB(IJ)+AC(IK)
          +AD(IL)+AF(IM)+BC(JK)+BD(JL)+BF(JM)
          +CD(KL)+CF(KM)+DF(LM)+E(IJKLM)
LIMITS    I (Z), J (Z), K (Z), L (Z), M (Z)
GET OFF
****
```

APPENDIX 1   STANDARD   COMPUTER   PROGRAMME   FOR 'F" TEST


2800
2000
1400
Wheel speed (R.P.M)
Ø 250
Ø 350
1570
2199
Cutting speed (m/min)

Appendix II