SEMI-PERMANENT GRINDING WHEELS
FOR INTERNAL GRINDING OPERATIONS

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SUMMARY

The thesis deals with the role of semi-permanent abrasives in internal grinding. The abrasives dealt with are diamond and cubic boron nitride. To determine this role the application of conventional abrasives are explored together with the specification for finished parts. The performance of conventional abrasives determines the minimum objectives that must be attained for the acceptance of semi-permanent abrasives by industry. The type and form of semi-permanent wheels and their method of preparation for grinding are dealt with and found to be very important for the successful application of semi-permanent abrasives.

The factors influencing selection of semi-permanent abrasives are explored in Chapter 3 together with details of performance, wear characteristics, and applications currently in use.

Chapter 4 of the thesis details the equipment selected to carry out the test programme and the manner in which testing is carried out.

Consideration is given to the economic viability of the abrasives by means of two techniques in Chapter 6. The first technique aims to establish the optimum metal removal rate by means of a differentiation method. Results obtained in this manner are confirmed by direct plots of cost vs. metal removal rate. Comparison is made with conventional abrasive costs obtained by reference to standard time data for the same operation.

Grinding tests using semi-permanent abrasives are used to assess the effects of the process variables, wheelspeed, traverse rate and infeed on the grinding performance of the wheels and the results obtained for surface finish, taper and bore profile.

DECLARATION

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

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CHAPTER 1

INTRODUCTION

The majority of abrasives can easily be classified under the headings of conventional and semi-permanent.

Conventional abrasives consist mainly of aluminium oxide and silicon carbide, while the semi-permanent abrasives are diamond and cubic boron nitride.

Until the late 1960's diamond was in a class by itself as an abrasive. At that time it was twice as hard as any other known substance and was therefore used for operations which no other abrasive could handle. Initially it was used for the polishing of diamonds but with the introduction of materials such as hard carbides and oxide ceramics the importance of diamond as an abrasive was realised.

In the mid 1960's the position of diamond was challenged by the successful synthesis of cubic boron nitride, a substance much harder than either silicon carbide or aluminium oxide, but not as hard as diamond. However, it has a greater thermal stability than diamond being able to withstand temperatures up to 2,500°C before detiorating, whereas diamond starts to convert back to carbon at 1500°C.

Prior to the introduction of metal coated diamond, it was rarely used and generally not even considered for the grinding of steels. However, since 1966 there have been many reports and evaluations concerning the use of metal coated diamond. Latterly, reports and evaluations of the use of cubic boron nitride have been available showing that this abrasive can successfully be used for steel grinding applications.

The selection of the internal grinding process is made when either the nature of the workpiece, or the degree of surface finish and bore geometry specified demands the use of this process.

A major application for the internal grinding process is the manufacture of bearings. In this case the material is hardened, the surface finish required is between 9 and 10 μin and a total tolerance of 0.0002" is allowed for concentricity and bore taper. For finishes and tolerances better than this a Honing operation is usually specified. Bearings are generally produced in large quantities and competition between the manufacturers is very keen. Therefore to gain acceptance semi permanent abrasives will have to demonstrate convincingly their economic and operational advantages before they will be substituted for the conventional abrasives currently in general use.

To date semi-permanent abrasives have not gained wide acceptance for a number of reasons, one of which was over promotion by the producers before they were fully developed. This has created resistance to their use, due to previous unsatisfactory performance. There have been many cases where wheels have been discarded after only a short trial and an investigation of these cases has shown that in the majority of instances that incorrect machining parameters have been selected leading to an early failure of the wheels, in addition it has not always been realised that a unique system of wheel trueing and dressing has to be utilised to ensure satisfactory performance.

It will be seen that the use of these wheels in no way alters the fact that grinding is still an 'art' in which the operator plays a far greater role than he does in other metal cutting processes. In consequence the use of semi-permanent wheels for internal grinding has been limited to smaller size operations where correctly used they operate successfully.

It is envisaged that this thesis will regenerate interest in the application of semi-permanent abrasive wheels for internal grinding and demonstrate that they can successfully compete with conventional abrasives in this field.

CHAPTER 2

DEFINITION OF THE PROBLEM

2.1 PRODUCTION RATE AND PRODUCT SPECIFICATIONS

The production of bearings is very competitive and information regarding production rates achieved is not generally advertised. However, it is accepted that metal removal rates of the order of 0.1 - 0.15 in^3/min are achieved by conventional abrasive wheels (MA 60 JV for roughing and MA 100 IV for finishing are typical of wheels in use) when grinding EN31.

The cycle of operations is to rough grind, back off and dress the wheel in a single pass and then finish grind. The amount of stock removed during the operation is usually 0.010"- 0.015" with a cycle time of approximately 15 secs.

Surface finish can be specified as low as between 8 and 10 μin CLA with a general allowance of 0.0002" for the combined errors of taper and concentricity.

Manufacturers of semi-permanent wheels and abrasive suppliers suggest that metal removal rates of 0.1 in^3/min are feas~~b~~ible for their internal grinding wheels, Lindsay (1)* reports a metal removal rate of 0.072 in^3/min in trial production runs when grinding bearing cups.

Semi-permanent abrasives have not yet found acceptance for high production work, however, it has been reported that some manufacturers are using wheels in other spheres of their operations. A growing market has been noted for the use of points which vary in size from $\frac{1}{32}$" to 3" diameter. Their use is restricted, however, to specialised fields.

2.2 Workpiece Materials

The most common material in use in the bearing industry is probably EN31, this material in its hardened condition also approximates to some of the case hardened steels used in other industries. Hardness values of up to R_c 62 can be obtained. In the fully hard condition grinding ratios of 10 are usually attained using conventional abrasives. Some of the 'quality' steels prove extremely difficult to grind using conventional abrasives, as even under optimum grinding conditions the wheel will wear as fast or even faster than the workpiece. Thus the maintenance of tolerances proves a time consuming exercise.

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

To combat these problems it was essential that a more ~~pure~~ wear resistant abrasive be developed. Initially natural ~~material~~ diamond was utilised but with the successful synthesis of diamond and later cubic boron nitride natural diamond tended to be replaced by these new abrasives.

The materials quoted most frequently in grinding literature are EN9 and EN31, certain of the die steels (usually D2, D3 and D6) tool steels include M2 and T15 while sometimes nimonics, carbides and ceramics are featured. All these materials are considered suitable subjects for semi-permanent abrasives as they present problems of varying degree when ground using conventional abrasives.

The work in this survey has been restricted to tests using EN31, with various wheel combinations.

2.3 The Grinding Wheel

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

The main types of abrasive particle are aluminium oxide, silicon carbide, diamond (natural and synthetic) and cubic boron nitride. Generally the application for each abrasive is as follows:

Aluminium oxide : ferrous materials

Silicon carbide : glass, ceramic and non-ferrous alloys

Natural diamond : has been used for some time to grind very hard alloys.

Synthetic diamond and cubic boron nitride are now being applied to relatively ductile materials as well as the materials traditionally ground using natural diamond. Semi-permanent abrasives are many times more expensive than conventional abrasives but their wear characteristics are such that a reduction in overall costs may be obtained by their use in certain instances. In addition their performance characteristics can promote surfaces suffering less damage in terms of loss of hardness or induce a lower or more favourable residual stress.

In this investigation cubic boron nitride and synthetic diamond abrasives have been used with aluminium oxide ~~used only~~ for comparative purposes only.

2.3.1 Wheel Bonding

Wheels using semi-permanent abrasives can be bonded in a number of ways. The types of bond are resinoid, vitreous, metallic and plated.

The plated wheel consists of a precise amount of grit being deposited onto the wheel form either electrolitically or chemically, this results in a single layer of super hard abrasive. This wheel requires precise mounting on the spindle as there are no trueing and conditioning operations prior to use. When the grit wears away the wheel is discarded.

The metal bonded wheel has the grit impregnated throughout a layer of sintered metal. As the grit and bond wear, new cutting edges are continually exposed.

The resin bonded wheel is similar in construction to the metal bonded wheel except that a resin material is used as a bonding agent. The resin can be varied to suit the grinding requirements between a 'hard' and 'soft' bond.

The tests conducted in this programme of research are using resin bonded wheels.

2.3.2 Grit type, size and concentration

The majority of the diamond grit supplied is synthetic though there is still a large market for the natural product. All cubic boron nitride is in synthetic form as this material does not occur naturally. Grit sizes are determined by grading according to sieves or meshes so that for example a 100 grit wheel would contain grits which have been graded in a sieve with 100 spaces per linear inch, the average particle size is 0.0059". Grits are further graded by their shape into needle shaped or blocky. This classification is generally only made on diamond grit. The shape of the grit determines the wear characteristics, those of needle shape tend to 'flake' and are more suitable for grinding carbides, while those of blocky form tend to fracture and so produce new cutting edges, this type is more suitable for grinding ductile materials. The shape of cubic boron nitride is blocky.

A more recent development has been the coating of diamond and cubic boron nitride grits with either copper or nickel. This has helped the adhesion of grits in the resinoid bond, the coating also acts as a heat ~~sink~~ barrier thereby preventing premature degradation of the resin bond due to the heat generated in the grinding process.

Concentration denotes the amount by volume of grit that has been used in the wheel preparation. For example, 100 concentration denotes 4.4 carats/cm^3 and 50 concentration denotes 2.2 carats/cm^3. These are the most common concentrations though other concentrations ranging from 25 to 125 are available and in use. Ideally the grit should be evenly distributed in the bond and wheels of an uneven characterter discarded.

2.4 GRINDING WHEEL PREPARATION

With the exception of crush dressing which can be used to true and condition certain types of HP-HT wheels the technology developed to dress conventional abrasive wheels is inappropriate to the needs of diamond and CBN wheels.

When grinding steel it is essential that there is sufficient chip clearance, i.e. that there is sufficient exposure of the grit. If this exposure of the grit is insufficient and therefore too little chip clearance, loading of the wheel will ensue which leads to a rapid build up of heat and subsequent bond charring. The wheel cannot be used in this condition and if the process has not been arrested quickly the charring can be to a considerable depth.

If the wheel is over conditioned, i.e. the individual grits are exposed too much, the initial grinding forces will remove this layer of grits easily and this could lead to a point where the wheel appears under conditioned.

It is apparent that the process of trueing and conditioning is of utmost importance to the successful outcome of the grinding operation. Various methods have been formulated and because of the nature of the grits not all are compatible for both diamond and cubic boron nitride.

2.4.1 Trueing

The preparation of semi-permanent wheels is a two part operation the first of which is to produce a concentric and parallel form, normally referred to as the trueing operation. The second operation of preparing the wheel for grinding is referred to as conditioning and is covered in Section 2.4.2.

2.4.1.1 Brake Dressing

The brake dresser, using a white aluminium oxide wheel is suitable for trueing both diamond and cubic boron nitride wheels. If, however, a silicon carbide wheel is used it is only suitable for trueing diamond wheels. A reaction occurs between the silicon carbide and cubic boron nitride wheels which leads to hard glaze being deposited on both wheels. A conditioning operation is required to remove this glaze before trueing can proceed.

The brake dresser is mounted on an angle plate preferably at an angle to the direction of traverse, to give a greater contact length. The brake dresser is traversed across the wheel with contact being maintained all the time. Infeed is applied at both ends of the stroke. In this manner a true and parallel form is assured. It is desirable that a coolant flow is maintained at the wheel interface.

The main disadvantage of this method is its slowness both in set up and operation and the rapid wear of the dressing wheel.

Figure 1 shows the set up of the brake dresser on the internal grinding machine.

2.4.1.2 Motorized Dressing Roll

Because of the high wear rates of aluminium oxide wheels the method is suitable only for use with silicon carbide wheels as dressing rolls. Therefore, because of the glazing problems encountered with CBN only diamond wheels can be trued using this method.

The motorized dresser is mounted on an angle plate and the silicon carbide wheel is driven at constant speed. Initially the wheel to be trued is driven at normal speed and the motorized dresser traversed across the wheel and the infeed applied. The dressing wheel quickly assumes a convex shape.

After a time the process is interrupted and the speed of the diamond wheel is changed to a much slower speed ($\approx$50 RPM).This has the effect of changing the speed vector, thus breaking out the bond behind the grit and therebye weakening the hold of the grit in the bond. Figure 2 shows the speed graphs for the process and Figure 3 gives the schematic arrangement of the system.

The speed of the wheel is changed from fast to slow in this manner until a true form is established. This method, providing a fast speed change can be effected, is faster than the brake trueing method of trueing. Figure.4 shows the motorized dresser mounted on the machine table and Figure 5 shows the slow running motor and control gear.

2.4.1.3 Impregnated Diamond Dressing Tools

These are metal bond diamond impregnated tools that can either be in the form of a nib for mounting in the diamond dressing tool post or in the form of a wheel for motorized trueing.

The trueing procedure is somewhat similar to single point diamond dressing. The table is traversed and an infeed is applied at both ends of the traverse. Traverse rates should be slow (3-4 ft/min) and it is essential that a flood coolant be applied. It is evident from the appearance of the wheel when the trueing operation is completed.

Motorized trueing is a similar operation to that described in Section 2.4.1.2 except that the slow running device is not required.

This form of trueing is only suitable for cubic boron nitride grinding wheels. Figure 6 shows the impregnated diamond nib used for trueing in this series of tests.

2.4.2 Conditioning the Wheel

After trueing the wheel has a smooth glazed appearance and in this mode cannot successfully grind steel, as there is no clearance for the grinding debris to be flushed away. To achieve this the bond has to be eroded to leave the grit standing proud, this is known as the conditioning process.

The most common method of conditioning and that recommended by the grit manufacturers is to apply by hand a stick of white aluminium oxide abrasive. The size of grit in the stick is dependant on the wheel grit size. A guide to the selection of abrasive sticks is given in Table 1.

The hand held stick is applied to the grinding wheel running at normal speed, a trickle of coolant is required at the stick/wheel interface. The stick is forced into the wheel and when a slurry is seen to build up above the stick the conditioning can be regarded as complete. A visual check should be made to verify the state of the wheel. This part of the preparation is the most critical and the method relies heavily on the operator's experience. At the present time there is not a generally accepted alternative method of ~~trueing~~ preparation to that described and a certain number of wheel failures during acceptance trials by users are probably attributable to incorrect wheel preparation.

Following the wheel preparation it should be noted that the wheel requires a certain amount of time to 'run in'. During this time it will be seen that performance improves both in terms of wheel loss and surface finish achieved.

2.5 BORE GEOMETRY

2.5.1 Taper

The degree of taper in commercial applications is normally easy to maintain within set limits by adjustment of the workhead, and providing no other parameters are changed the maintenance of this feature will cause few problems.

There is some evidence to suggest that the degree of taper is affected by both the amount of infeed applied and the traverse rate and this point is covered in the later stages of this thesis.

2.5.2 Out of Roundness and Concentricity

These two parameters are closely linked to the state of the machine tool in use and the type of work holding fixture.

No measurements of concentricity have been made during this series of tests.

Values of out of roundness can be severely affected by the type of work holding fixture. Otherwise results can be expected to approximate to a normal or gaussian type of distribution.

2.5.3 Profile

Profile is most affected by the length of traverse. In general when carrying out traverse grinding it is thought best that the wheel should not leave the bore at either end of the stroke and should ideally only leave the bore by no more than half the length of the wheel. The most common defects in a bore profile are bell mouthed and barrel shaped bores. The first of these faults is generally caused by too great a traverse and the second by too short a stroke length. A further factor affecting the profile is the stiffness of the wheel mounting system. Too flexible a system will tend to amplify the defects already mentioned.

CHAPTER 3

A review of previous work and factors governing the use of semi-permanent abrasives.

3.1 NATURAL DIAMOND

3.1.1 General Review

Diamonds occur naturally in a large variety of sizes, from the size of a grain of salt to the size of a man's fist, the smaller the size, the more plentiful. Natural diamond is classified according to shape, colour and degree of transparency into three main categories: gemstones, industrials and boart. The first grade is self-explanatory. Industrials cover a wide variety of types depending on the eventual use to which it is put. Boart generally is all diamond suitable only for crushing to abrasive grain or powder. Modifications in the methods of crushing the boart can be used to manufacture various shapes of grit; crushing between rollers tends to produce weak splintery shapes, while crushing by impact gives a blockier product. Alternatively the shapes can be sorted after crushing. Both methods of production are used.

3.1.2 Physical Properties

The physical properties of diamond are that it is the hardest substance known to man with a value of 8200-8500 on the Knoop scale, other abrasive hardness figures are cubic boron nitride 4700, silicon carbide 2480 and aluminium oxide 2100. (Fig. 7). It is the least compressible material known having the highest value of elastic modulii of any material. With regard to thermal conductivity diamond occurs in two forms, one type possesses thermal conductivity twice that of copper, the next best material in terms of thermal conductivity. The second type exceeds the value of copper by six to one.

Diamond is not a stable form of carbon. At temperatures between 1400 and 1800°F it can revert to graphite in a normal atmosphere. In an oxygen free atmosphere this will happen at about 2900°F.

Diamond is not affected by acids with the exception of those chemicals that cause it to oxidise at high temperatures.

Some metals will also attack the diamond surface, at high temperatures tungsten, tantulum, titanium and zirconium will react chemically with diamond to form carbides.

3.2. SYNTHETIC DIAMOND

Claims for the successful synthesis of diamond have been made since 1880 but in the light of present day knowledge it is felt that the claims made were fraudulent.

Rossini and Jessop using values for heats of combustion, specific heat, compressibility and thermal expansion data, calculated the pressure, at temperatures up to 1200°K at which diamond and graphite have the same energy. From this stability diagram (Fig. 8), research workers at the General Electric Co. decided that a temperature pressure combination of 2000°K and 50-100 kilobars would be necessary for the conversion of graphite to diamond.

An apparatus known as the 'belt' was developed capable of maintaining pressures of 70 kilobars at 3000°C for several hours. With this apparatus it was found that diamond could be synthesized using a suitable catalyst. Effective catalysts were Cr, Mn, Fe, Co, Ni, Ru, Rh, Pd, Os, In, Pt and Ta.

The method of synthesis is to operate at a temperature equal to or higher than the melting point of the metal, or its carbide and to maintain a pressure such as to retain the reaction mixture in the diamond stable region.

In the reaction the graphite in contact with the metal catalyst quickly transforms into diamond when the temperature reaches the melting point of the metal. The boundary moves through the whole charge at a rate which increases with the applied pressure. When the synthesis is complete the diamond crystals are contained in a metal matrix which is dissolved by acid treatment leaving individual diamond crystals.

The crystal type, colour and purity of the synthetic diamond are controlled by the temperature and pressure conditions. High temperatures and pressures produce colourless crystals of an octohedral habit, while low temperatures and pressures produce coloured crystals which tend towards a cubic structure with a high content of metal impurity.

3.3. CUBIC BORON NITRIDE (CBN)

3.3.1 Nature of material

Hexagonal boron nitride has been known for some time and been mainly in use as a refractory material. It is made by the pyrolosis of boron chloride ammonia:

$$BCl_3\ NH_3 \longrightarrow BN + 3HCl$$

The product is a soft white platy powder which in appearance, texture and other properties resembles graphite to the extend that it is known as white graphite.

3.3.2 Manufacture

Hexagonal boron nitride has the same crystal structure as graphite and following the successful synthesis of diamond it was suspected that a boron nitride phase having the same structure as diamond should exist. Attempts to obtain catalysts as used for the production of diamonds resulted in the recrystallisation of boron nitride in the hexagonal form.

Cubic boron nitride was successfully synthesized in 1957 using pressures of between 50,000-90,000 atmospheres and temperatures of between 1500-2000°C and using alkali metals antimony, tin and lead as catalysts. Lithium was found to be a good catalyst but a black opaque product was obtained which had an excess of boron in the crystal. To eliminate this the nitrides of lithium, magnesium and cadmium were used as catalysts and with these catalysts it was possible to produce CBN at 45,000 atmospheres.

3.3.3 Physical Properties

The synthetic CBN crystals when pure are colourless, the crystals when made with lithium nitride as a catalyst are yellow in colour while those containing excess boron are black. CBN is stable in air at atmospheric pressure. to a temperature of 2000°C which is much higher than the temperature at which diamond oxidises and graphitizes. At 2500°C CBN converts to hexagonal boron nitride.

3.4. WHEEL MANUFACTURE

3.4.1 Diamond and CBN Wheel Shapes

Diamond and CBN wheels are manufactured in a wide variety of shapes and sizes to suit various grinding operations. A standardised nomenclature exists to classify wheels according to three main parameters, a number to indicate core or hub shape, a letter designating the shape of abrasive cross section and a further letter to indicate the position of the abrasive section on the hub. A fourth letter can be used to indicate special modification. In this system compiled by the US Standards Bureau (2) ten basic hub shapes, twenty five abrasive cross sections and fourteen different abrasive locations are listed.

The comparable British Standard (3) only lists wheels by shape and application.

3.4.2. Constituents of the wheel

Any wheel can be considered in terms of its three basic components, the abrasive itself, the matrix or bond holding the abrasive and finally the hub. The properties of each of these components contribute to the overall performance of the wheel.

3.4.2.1 The abrasive

Diamond and CBN abrasives can be classified into eight different categories (4) (5,6) depending on their shape, coatings, and the use to which they are put:

(a) Conventional natural - mostly needle shaped

Is normally used in a resin or vitrified bond and recommended for fine finishing because of its ability to impart lustre to a carbide or ceramic body. This type of diamond is monocrystalline and tends to smooth over during the grinding process. It is this wear characteristic that produces a good microfinish and lustre. Recommended for use wet, but can be used dry. Primary sizes 320 grit and finer.

(b) Manufactured diamond - rough sided - needle shaped - friable

Used for general purpose carbide grinding wet or dry in a resinoid or vitrified bond matrix. In comparison with natural diamond is more versatile on similar application and will deliver 25-100% greater wheel efficiency.

(c) Manufactured diamond - rough sided needle shaped - super friable

Due to the very high friability it is used for the dry grinding of solid tungsten carbide. This type of abrasive is used when rapid stock removal is more important than wheel life. It has the ability to plunge grind up to $\frac{1}{16}$" without wheel loading or without the wheel or work overheating.

(d) Natural diamond - slivery shapes super friable

Used for the same applications as outlined in (c) and displays the same characteristics. The fine slivery shapes give this natural diamond the same characteristics as the manufactured diamond, i.e. somewhat of a poly-crystalline structure. Only small segments of the diamond fracture during grinding exposing new sharp cutting edges. Diamond types c and d are somewhat interchangeable and neither has a real advantage, although the natural grit is more heat resistant than the manufactured counterpart.

(e) Same diamond as (b) except nickel coated

The application of nickel coating to each diamond particle gives better adhesion between grit and resinoid bond. Normally the irregular diamond surface will provide good adhesion in the bond and although the crystal is relatively weak in tension or shear it will not tend to flatten, rather it will tend to fracture along weak crystal lattice planes. This will result in wheel wear, but sharp cutting points are maintained and a free cutting action sustained.

One of the drawbacks to the use of friable diamond is that it is difficult to control the nature of the fracture and gross fracture along a major axis can occur leading to premature loss of the abrasive grit.

A partial solution to this problem is provided by coating the diamond with a high modulus tough material to reinforce the crystal, thus partially controlling the nature of the fracture. Evidence of this is presented by analysis of the diamond swarf for natural and manufactured diamond wheels (Fig. 9).

The nickel also acts as a heat ~~sink~~ barrier by conducting and dispersing the heat generated. The diamond particle is retained in the bond longer and thus the wheel tends to act harder and workpiece burn can result unless a flood coolant is used. This type of wheel is very good on carbide-steel combinations. It is more efficient than the uncoated product, when grinding tungsten carbide wheel efficiency can improve by 200-300%.

(f) Same diamond as (b) except copper coated

Because nickel coated diamonds are generally limited to wet flood coolant grinding conditions it is desirable to have a product that is suitable for dry grinding operations. The coating acts as a, heat sink to conduct heat around the particle. The copper coated particle is generally used on carbide only under dry conditions, contact with steel leads to premature pull out due to the reaction between the steel and copper.

(g) Manufactured diamond - semi-friable - blocky somewhat rough sides - nickel coated

This diamond is specifically designed for steel or ductile metal grinding. It is not very efficient on carbide grinding. Advantages of this type of diamond in a resinoid bonded wheel when applied to steel grinding are as follows:

(i) easier size control;
(ii) lower labour costs;
(iii) faster stock removal;
(iv) superior finishes;
(v) many tough materials cannot be adequately machined any other way.

(h) Cubic boron nitride - nickel coated

The full range of applications has yet to be defined. It used for the most part, in wet flood coolant grinding of the harder high speed steels particularly in the 60-62 R_c range.

3.4.2.2 The Bond

Bonding agents that have been used include magnesium oxychloride, alkali silicate, rubber, metal, vitreous, graphite and resinoid. Of these the last four are the most commonly used though rubber bonded wheels are still in use, particularly in polishing operations.

(a) Metal bonds

This category includes the conventional sintered bronze, iron and steel bonds, single layer electroplated and sintered wheels.

In the sintering process the grit, often pre-wet with a wetting agend is mixed with the metal constituents in a powdered form. The mixture can then be either pre-heated to sintering temperature and then pressed or heated to sintering temperature while under full load.

In the infiltration process a pre-pressed relatively porous skeleton of grit and metal powder is covered with a low melting point metal binder and then heated to melt the binder which when molten infiltrates the porous skeleton by capilliary action. The infiltration action can be accellerated by the use of pressure.

For the softer bronze matrices sintering temperatures range from 650-800^{o}C. For the harder matrices particularly those incorporating carbides the temperatures used invariably exceed 1000^{o}C and oxidation of the bond under these conditions can be a problem. However, oxidation can be overcome by sintering in a vacuum or hydrogen atmosphere.

(b) Single layer electro-plated and single layer sintered wheels

This type of wheel is used in a variety of operations particularly in slitting and form grinding operations. Two techniques are used for form grinding :-

(i) single layer diamond roll dresser is used to impart the required form to a conventional abrasive wheel which does the actual grinding; or

(ii) the single layer wheel having the required shape imparts the desired form directly.

(c) Vitreous bond

In general vitreous bond wheels should be capable of high stock removal rates with wheel wear at considerably lower rates than resinoid bonded wheels. Due to difficulties in manufacture, vitreous diamond wheels are considerably more expensive than resinoid counterparts. The vitreous bond to all appearances has the greatest potential, but at the present time is the least developed of the bond types.

(d) Graphite bond

This type of bond has made a relatively recent appearance in the field of abrasive machining and excellent results are claimed particularly for grinding high speed steels. It also can be used for electrolytic grinding which has so far been confined to the electrolytic metal bond.

(e) Resin bond

Resin is the most common bond in use. The resinoid matrix has been based almost entirely on the use of phenolic resin as a binding medium.

A hetrogeneous mixture of abrasive grit, binder resin and usually a number of fillers is compression moulded under the application of heat to the wheel hub. During the heating process, the resin first melts and then polymerizes, binding the grits and fillers into a solid matrix. The temperatures used are lower than those attained for other bond types and diamond oxidation is therefore not a problem.

Development of the phenolic resin bonds has been limited by the physical and chemical characteristics of the resin. Consequently, further development of the resin bond has been with new types of resin.

With advances of the aerospace industry a new resin was required giving a high heat resistance. Du Pont played a large part in the conception and application of new materials based on the polyimides.

The initial application (7) was production of polyimide electrical insulation lacquer that was capable of withstanding temperatures up to 340°C. Further applications followed, including rigid components made from polyimide powders at temperatures of 800°C and very high pressures. In 1967 Du Pont introduced polyimide bonds for diamond grinding wheels.

The high temperature resistance of aromatic polyimide bonds as opposed to phenolic resin may be shown by means of thermogravimetric analysis. Figure 10 shows that the point of 10% weight loss occurs for the phenolic bond at 400°C while this same point for the polyimide bond is 525°C. The polyimide resin tends to suffer from much more rapid loss at temperatures above 550°C.

Apart from their greater heat resistance polyimide resins are felt to have greater strength and particularly greater flexibility than the phenolic resins presently in use. The thermal and mechanical superiority promises improved grinding performance.

3.4.2.3 The Hub

It has been shown (8) that though the effect of wheel hub characteristics depends to some extent on the machine being used, given suitable conditions there is a relationship between wheel hub flexibilities and the grinding ratio as shown in Figure 11.

Grinding ratios increase with increasing hub flexibility though at extreme cases where G ratios are high the volumetric removal rates are too low to be feasible for production processes. At the other end of the scale the rate of decrease of G ratios with increasing regidity is very slight ~~rapid~~.

3.4.2.4 Wheel Grade

The grade is often referred to as 'hardness' but it is not a mechanical or indentation hardness. It is a measure of behaviour of the wheel during grinding. Vitreous bond grade is closely linked to structure but it is difficult to link this concept to resin bonded wheels which are generally compact with little or no porosity. Some manufacturers do grade their bonds according to physical hardness which is varied by the use of fillers.

A second system is that the grade of the bond can be defined by the degree of polymerisation of the resin. This will alter the 'holding power' of the bond without altering the density. In this system a 'soft' bond would only be partially polymerised. There is as yet no standardisation of wheel grading.

3.5. WHEEL DRESSING

3.5.1 Cubic Boron Nitride (CBN)

Trueing and dressing are two distinct operations. (9) The trueing operation is designed to ensure a minimum of runout on the wheel and the conditioning operation should abrade the bond to expose the cutting points to the required depth.

3.5.1.1 Trueing

Before trueing the wheel should be checked and adjusted for minimum runout (0.0001" TIR or better if possible). Failure to do this and centre the wheel on the run may result in wheel damage and chatter marks on the ground surface.

A good trueing device must ideally abrade the wheel's high spots without itself being subject to significant wear. The impregnated diamond trueing nibs mounted in the diamond dressing holder offer one solution which is gaining increasing acceptance. An impregnated nib resembles the more common single point tool except that the tip contains numerous diamond grains with a random distribution. The grain size is usually 80 grit or finer (to 150 grit).

An alternative to the use of an impregnated nib is the use of an impregnated diamond roll which is motor driven. This is reported to give excellent results but the size of the unit and mounting difficulties sometimes preclude.its use. More general use of the concept will not take place until machine tools are purpose built for the use of semi-permanent abrasives with this type of fixture as standard.

Brake trueing devices may also be used for trueing CBN wheels in conjunction with 60-80 grit J-M hardness silicon carbide wheels. This, however, should not be used for wheel sizes over 10" in diameter as the trueing wheel wear becomes excessive. The use of silicon carbide wheels is not however universally accepted, and difficulties are experienced due to excessive glazing of both wheel surfaces when using a motorized dresser. The alternative wheel suggested is an A60 KV aluminium oxide wheel.

3.5.1.2 Trueing Procedure

It is advisable that prior to trueing the wheel periphery be marked with a wax crayon in order that it can be ascertained when the whole surface of the wheel has been touched by the trueing device. Using an impregnated tool initial feeds should not be greater than 0.0002" with a traverse rate of 1-2 FPM. Heavier feeds of 0.0005" can be used but the finish pass(es) should be at 0.0002". Flood coolant must be used at this stage as otherwise severe bond charring will result. Removal of all crayon marking indicates that the entire surface has been abraded. It should also be possible to visually determine that the periphery has been trued. The wheel should now be rechecked for running truth.

At this stage the surface of the wheel will be completely flat and unsuitable for grinding and it is essential that the wheel be dressed or conditioned before use.

3.5.1.3 Conditioning

The conditioning is accomplished using an aluminium dressing stick in accordance with table 1 (10).

When conditioning the wheel the appropriate dressing stick should be forced into the wheel, together with a trickle flow of coolant to promote the formation of a slurry just above the stick. The stick will initially act hard. When the wheel 'cuts' the dressing stick the bond will begin to be eroded from between the grits. Dressing is complete when by visual determination a satisfactory chip clearance is obtained.

The wheel should then be rechecked for true running and balance.

Further conditioning during the wheel's life may be required, but unless the wheel is removed from its' mounting the wheel need not be trued again.

3.5.2.Diamond Wheels

As with CBN wheels the correct pre-grinding preparation of diamond wheels is essential if the optimum performance is to be achieved. Unlike conventional wheels semi-permanent wheels if not correctly prepared will fail at an early stage, involving the user in much time and cost in returning the wheel to a us~~e~~able condition.

As with the CBN wheel the preparation of the wheel falls into three parts.

(1) The setting up including balancing.
(2) The trueing.
(3) The conditioning of the wheel.

3.5.2.1 The Set-up

The wheel is mounted in the appropriate manner and using a dial indicator made to run as true as possible. Following this the wheel should be balanced. The balance of the wheel should be rechecked and adjusted if necessary after trueing.

3.5.2.2 Trueing

There are a number of methods currently in use for trueing diamond wheels (11).

(a) Brake Trueing Device

The brake truer is generally used in this application with an 80 grit K grade silicon carbide wheel, though similar grade aluminium oxide wheels may be used. The operation is generally performed dry as in this manner it is readily determined as to what stage the trueing has progressed. The heat generated by trueing is not excessive. Feeds of 0.0005" should be made at each reversal once the wheels are in contact.

(b) Rotary Diamond Dresser

This trueing device is used on cylindrical grinding machines and is driven by the workpiece spindle motor. The rotary diamond dresser embodies the same principles as the diamond trueing block (3.5.2.2(d)) except that it is used in a rotating mode.

(c) Silicon Carbide Block

A 60/80 grit silicon carbide block (mounted on a steel plate) is mounted to the machine table of surface grinding machines with magnetic chucks. Use of the silicon carbide block is generally restricted to resin bonded wheels up to 5" diameter.

Operations are carried out as in plunge cut or surface grinding. Initial heavy cuts are carried out using coolant while the latter cuts at shallow feed are made dry.

(d) Diamond Trueing Block

The diamond trueing block has been developed by De Beers Diamond Research Laboratory. The block is a 2" x 1" alloyed bronze block containing 60/80 mesh MDA-S (metal bond diamond abrasive) at 200 concentration mounted on a gauge plate to enable its use with a magnetic chuck. Typical operating conditions when using a diamond trueing block are:

Wheelspeed : 5,300 SFPM
Traverse Rate : 13 FPM
Crossfeed : Q.060 IN/PASS
Infeed : 0.0004 IN/CROSSFEED REVERSAL

Flood coolant must be used.
Following trueing the wheel presents a highly polished surface that is unsuitable for grinding.

(e) Electrolytic dressing of metal bond wheels is based on the anodic decomposition of metals. This method is preferably used in electrolytic grinding by changing the polarity of the grinding wheel for a short period.

(f) Electrosparking

In electrosparking of metal bonded wheels the gap between the grinding wheels (anode) and the cathode is filled with a dielectric medium. A high voltage is applied to generate sparking.

(g) Motor Driven Trueing Device

The motorized truer utilises a silicon carbide wheel as the dressing roll. Initially the diamond wheel is rotated at its normal operating speed and the trueing action is much as that used when brake trueing. The second stage of the operation is the reduction of the wheel speed to a very small ~~amount~~ value and the continuation of the trueing process. By this process it is claimed (12) that the bond behind the grit is eroded leading to a faster removal of the abrasive grit and consequently faster trueing than can be achieved by any of the systems previously discussed. Figure 3 shows schematically the arrangement of the trueing device while Figure 2 shows the speed graphs for the dressing process.

3.5.2.3 Conditioning

For the majority of the applications it is claimed that no wheel conditioning is required other than grinding of the workpiece. The exception is the grinding of steels when it is essential that the wheel is conditioned prior to use.

The original practice with these wheels was that the conditioning was carried out by grinding the material to be used with the trued wheel, the performance of the wheel being found to improve until the optimum condition of correct grit exposure is achieved.

It is now more general procedure to condition the wheels in the same manner as that used for CBN wheels, i.e. using a hand held stick of aluminium oxide abrasive.

It must be emphasised that under no circumstances should a single point diamond tool be used to dress either a diamond or CBN grinding wheel.

3.6 THE WEAR MECHANISMS OF DIAMOND AND CUBIC BORON NITRIDE

3.6.1 Diamond Wheels

There is no known abrasive that does not wear to some extent during the grinding process. Investigations when scratching and grinding various steel materials with single point diamonds and grinding wheels have shown the following types of wear mechanisms (13):

(a) adhesion wear;
(b) abrasion wear;
(c) diffusion wear;
(d) combinations of a,b, & c;
(e) built up edges; leading to (f)
(f) grit pull out.

These wear systems occur in all known abrasive systems to some extent depending on the workpiece material being ground and the grinding parameters.

3.6.1.1 Adhesion wear

When adhesion wear occurs the diamond particles show an uneven, pitted surface structure and micro chipping and breakouts of the diamond can be observed.

This type of wear is predominant when grinding tungsten carbides and semi-conductor materials. The intensity of wear is very small in comparison with other abrasives to the extent that diamond is the accepted abrasive for these materials.

3.6.1.2 Abrasion wear

The wear caused by abrasion is characterised by grooves running in the same direction as the cutting action. Under certain conditions these grooves can be caused by the hard carbides in tungsten carbide.

3.6.1.3 Diffusion wear

Diffusion wear occurs when grinding steels with a low concentration of carbon and steel whose components tend to form carbides. In these circumstances the diamond tends to show a chemical affinity for the workpiece material and the carbon of the diamond diffuses into the workpiece.

When diffusion wear takes place the diamond surface shows a smooth, polished wear flat. Diffusion wear is generally a slow process, but high temperatures combined with the continuous generation of new workpiece surfaces can cause this wear mechanism to predominate.

3.6.1.4 Combination of wear types

Wear can occur as a result of combinations of the wear mechanisms so far discussed. As a result of this it would not be possible to predict the optimum grinding conditions and these have to be determined by practical testing.

3.6.1.5 Built up edges

This type of wear affects the cutting ability of the diamond. It is a clogging of the wheel by steel particles (swarf) removed by the grinding process. The process is more apparent with metal bond wheels than with resin bonded wheels. The use of coolant will tend to minimize the creation of built up edges. The adherance of built up edges has been shown to be due to physical and chemical effects. Physical adherence can be due to the shape and surface roughness of the grit, while chemical affects are due to diffusion mechanisms.

3.6.1.6 Grit pull out

Grit pull out occurs if the grinding stresses on one particle are so high that the particle is dislodged from the bond, which in turn may lead to the loss of one or more particles. Analysis of sludge in certain instances has shown that up to 60% of the abrasive grit recovered has the same original grit size. The reason for this is the poor encasement of the grit in the bond and is particularly true of the phenolic resin bond where the grit is not 'wet' at the flow stage of the resin. The incidence of grit pull out can be reduced by the use of:

(a) irregular shaped grits; and
(b) the use of metal clad grits.

3.6.1.7 Bond wear

Bond wear is due to two causes; either mechanical wear or thermal degradation.

Thermal degradation is the largest single contributor to rapid resinoid wheel wear. Most phenolic resins undergo considerable thermal decomposition in the 350-400^{o}C temperature range (see Fig. 10). Because diamond is an extremely good conductor of heat, (about 30-40 times better than the average resin bond formation), the heat generated at the cutting edge is quickly conducted to the resin immediately surrounding the grit. The temperatures generated are usually well in excess of 400^{o}C during a single pass. Thermal decomposition of a thin layer of resin occurs and the grit is lost within the next few passes.

Metal cladding of the grits alleviates this situation in that the metal cladding being a poorer conductor of heat than diamond or CBN acts as a heat barrier ~~sink~~. Conduction of localized heat across this metal layer is much slower and is accompanied by a greater heat loss than is the case with diamond.

By the time any effective heat can reach the bond the particle has completed its' cutting cycle and will be undergoing rapid cooling either by coolant or air-flow. Thus thermal degradation will be considerably reduced, leading to a decrease of grit loss and wheel wear.

Mechanical wear of the bond is the result of friction between the bond and the swarf generated and also the bond and the workpiece. If the bond is too hard no fresh cutting edges are presented to the workpiece after the initial particles have been blunted or lost. As a consequence the wheel glazes and requires continual redressing.

Conversely if the bond is too soft it is abraded rapidly and particles are lost before they have made a significant contribution in terms of metal removal.

The abrasion resistance of the bond is the most easily controlled and modified property of the bond. Hardness of the bond can be altered by the addition of suitable fillers or an alteration in the density in the case of resinoid bonds. The control of the amount of tungsten carbide in the bronze matrix is used to vary the abrasion resistance of metal bond wheels.

Grit pull out and wear, and bond wear are inter dependent and in ideal circumstances should both occur at the same rate.

3.6.1.8. Wheel efficiency

Investigations (13) to find the efficiency of a single grit and of the same grit in a wheel bond have shown that the single grit tests were often very much more efficient. The potential efficiency for the single grit is very much reduced once it is in the bond. In comparison with conventional abrasives diamond grits were not as well utilized in the corresponding bond. The ratio of $\frac{GWH}{GSG}$ for conventional abrasives was 0.1-0.2 while for diamond wheels the ratio was 0.07 [GWH: grinding ratio of wheel, GSG = grinding ratio of single grit] the attainment of a unity ratio would not be practicable but it is thought that ratios of 20-40% should be possible by means of further bond development.

3.6.2 Cubic Boron Nitride

Triemel (14) differentiates between macrogeometric and microgeometric wear of the grinding wheel in his development of models of wheel wear.

During initial stages of grinding the formation of the grinding section takes place. At the end of this phase the wheel wear is constant without affecting the shape of the grinding section. This phase is macrogeometric wear. Apart from this the grit and bond the subjected to wear and damage and it is the wear of grit and bond that are known as microgeometric wear.

Assuming an initial plane surface, during the first pass of the grinding wheel only the ~~utmost~~ leading edge of the ~~section~~ wheel ~~contacts~~ removes the workpiece while the rest of the wheel contacts the already ground surface. The length of the cutting edge equals the set up depth of grinding. The abrasive particles at the edge of the grinding section are subjected to a heavy load during the initial stages of the first cut due to the fact that the number of grits available to remove the required volume of workpiece material is very small. The wear at this stage is very high as the grits which lie at the leading edge of the section have an unstable seating due to the one sided support of the bond. Wear then begins at the edge of the wheel and the worn surface makes an angle α to the face of the grinding section. The back passes cause a similar removal of grits from the small diameter of the grinding section towards its middle (see Figure 12). As the grinding process continues the effective grinding edge l_a increases and a greater number of grits are available for cutting, correspondingly the length l_b is reduced. At the end of this process the grinding section reaches its ultimate shape and is an equilateral triangle with

$$\alpha = \arctan \frac{2Z_T}{B} \tag{1}$$

Each circumferential element of the wear flats can be related to an equal and minimum amount of material to be removed. These elements have a number of grits to do the task. The grinding section reduces gradually at a constant rate. The reduction per number of passes or time interval is

$$A_s = h_m \sqrt{Z_T^2 + \left(\frac{B}{2}\right)^2} \tag{2}$$

The shape of the grinding section after each pass and the number of passes Z_E required to reach the ultimate profile can be calculated based on the model in Fig. 12.

The wear volume V_S^* is seen to be

$$V_S^* = \pi D_m \left(\frac{B-l_b}{2}\right) Z_T \text{ for } 1 \leq Z \leq Z_\epsilon \tag{3}$$

where D_M is the average diameter of the grinding section.

During the actual formation of the profile the wear/pass V_{SH} depends on the actual number of passes being considered and on the basis of experimental results was found to be of the form:

$$V_{SH} = f(Z) = aZ^b \tag{4}$$

The wear volume V_S^* after a definite number of passes can be calculated through the integration of V_{SH} from 1 to Z_E

$$V_S^* = F(Z) = \int_1^{Z_E} aZ^b \, dZ = \pi D_M \frac{B-l_b}{2} Z_T \tag{5}$$

equating 3 and 5 l_b can be determined.

$$l_b = B - \frac{2a(Z^{b+1}-1)}{(b+1)\pi D_M Z_T} \quad (1 \leq Z \leq Z_E) \tag{6}$$

Knowing l_b values of α and Z_E are derived

$$\alpha = \arc\tan \frac{(b+1)\pi D_M Z_T^{\;2}}{a(Z^{b+1}-1)} \tag{7}$$

$$Z_E = \left|\frac{1}{2a}\,(b+1)\,\pi\,D_M\,BZ_T + 1\right|^{\frac{1}{b+1}} \tag{8}$$

Practical testing using M2 gave the following coefficients

$$V_{SH} = 368\ Z^{-0.506}$$

The number of passes required to attain the ultimate profile was 1458 during which 105 Cm^3 of material were removed.

The wear mechanism during the formation of the profile can also be observed in the microscopic region. The grits on the active wear flats which take part in the actual machining split off and fall out of the bond.

Cubic boron nitride has sharp edges and smooth crystal surfaces and therefore receives a metal coating when used with a resin bond to achieve better holding properties. The adhesion between grit and coating is not entirely satisfactory and it has been observed that grits have fallen out of the coating before completing their useful life (see Figure 13).

The middle section of the profile, being a remainder of the original dressed profile plays only a subordinate role in the grinding process and is distinctly visible as a dark circumferential element. The darkness caused by small particles which are either accumulated in the chip channels or adhering to the bond. The only work done by the grits in the middle section is to smooth the work.surface. Hence they are only subject to small forces leading to the grits blunting very quickly. The increased flank area leads to the generation of heat and observations have been made of chips and grits being welded in the middle zone.

3.7 SURFACE INTEGRITY AND RESIDUAL STRESSES

3.7.1 Surface Integrity

Navarro (15) used aluminium oxide and CBN wheels to determine the extent of sub surfaces damage on M2, M42 and T15 workpieces. After grinding the surface appearance of each specimen was noted before the side perpendicular to grinding was polished and nital etched. Following examination the ground surface was etched for 20 minutes in a hot solution of hydrochloric acid and an examination made for cracks.

On the basis of visual examinations it was concluded that sub surface damage was caused by aluminium oxide wheels on M42 and T15 while the CBN wheels had caused similar damage to the M2 test pieces.

The microscopic examination following etching, however, revealed that the aluminium oxide wheels had caused sub surface damage even on the test pieces that showed only a light straw discolouration as well as those that showed significant discolouration.

However, in the case of CBN wheels the burning of the surface would appear to be of a superficial nature as no change in the microstructure was observed.

Examination of the etched specimens gave results for the extent of damage caused by the rehardening of the surface, in addition to the rehardened layers a transition zone of overtempered material was evident which was verified by hardness testing. The T15 test pieces as well as showing the same characteristics of a rehardened layer had also been subject to considerable grain growth signifying that the metal had been plastic when being ground with aluminium oxide. T15 was the only material on which any degree of change could be found after grinding with CBN.

Hardness tests of the specimens indicate the extent of the damage. It is noted in the case of grinding with CBN that in most cases there had been a loss of hardness to a depth of 0.001", consistent with a temperature of 200°C being reached. This should not significantly affect tool life. Details are given in Table 2.

The specimens ground with aluminium oxide all showed signs of surface cracking while those ground with CBN wheels were free of this defect.

Dyer (16) notes a substantial pearlite content increase with the lamallae having some preferred orientation to the direction of grinding in tests, using a diamond wheel. However, neither the material nor the mode of testing was specified and, as it was concluded that temperatures in excess of 800°C were required for the transformation from BCC to FCC iron, it must be concluded that this was a dry-grinding test. The need for the use of coolant and metal clad grits were stressed to ensure grinding temperatures below 800°C.

3.7.2 Residual Stresses

The problems of induced stress are often encountered in the aerospace industry, where strength to weight ratios are of considerably importance. In order to reduce the possibility of damaging the workpiece low stress grinding conditions using conventional abrasives are frequently specified. A typical low stress grinding operation would involve making a minimum of 24 passes to remove 0.010". The advantages to be obtained by this mode of grinding are better fatigue strength, bending strength, impact strength, micro hardness, wear and corrosion resistance.

It can be demonstrated (17, 18) that the material can be removed using infeeds of 0.002" but that the desirable qualities can be improved by a significant margin, (see Figures 14, 15 and 16) using semi-permanent abrasives.

The presence of either tensile or compressive residual stresses can be attributed to three causes

(a) the forces between workpiece and tool;
(b) the result of thermal expansion; and
(c) the result of structural transformation.

(a) Forces between workpiece and tool

The forces in a cutting process cause elastic and plastic deformation. Elastic deformation, by its definition subsides as soon as the cutting process terminates. The plastic deformation remains and results in compressive residual stresses in the workpiece surface.

(b) Thermal expansion

The material expands locally owing to the heat generated during the cutting process. If the heat generated is too high the inhomogeneous expansion will exceed the limits of elastic deformation and will lead to tensile residual stresses after cooling. In extreme cases cracks can appear in the workpiece surface.

(c) Structural transformations

The extent of structural transformation is dependant on the material and its crystal structure.

The following cases illustrate the mechanisms:

1. A hardened steel whose structure is wholly martensitic is ground at a temperature not exceeding the transformation temperature. During the consequent tempering the tetragonal strained body centred lattice of martensite with lattice constants of 2.84 Å and 3.04 Å is transformed to a cubic body centred lattice of α iron with a lattice constant of 2.86 Å. The volume decrease causes tensile residual stresses in the workpiece surfaces.

2. If, however, the hardening temperature is exceeded during grinding the temperature gradient will be such that tempering will occur in certain layers below the surface while the surface itself will be re-hardened by the action of the coolant.

The tempered layers have a smaller volume than originally while the surface reverts to its original volume. Tensile residual stresses are created which can lead to cracks within the tempered layers which, under loading, can reach the surface.

3. When a hardenable steel is ground in the annealed condition and the surface temperature exceeds the hardening temperature a transformation of α iron

to γ iron results. Through the action of the coolant the critical cooling rate is exceeded thus causing the transformation of γ iron to martensite. The 1% increase in volume counteracts the normal cooling contraction. However, in the sub surface layers these transformations will not take place and relatively different contractions or volume expansions take place within the workpiece. In this case the transformations which lead to surface hardening result in compressive residual stresses.

It is advantageous to obtain compressive residual stresses in a workpiece, in that they can be interpreted as increasing the density of the material at the surface leading to increased wear and corrosion resistance and an increase in micro hardness. Tensile stresses on the other hand can lead to cracks in the surface which will seriously impair corrosion resistance. When bending stress is applied the residual stress is added to the bending stress. It is seen from Figure 17 that the case of compressive residual stress results in the most favourable condition.

3.8 APPLICATION OF SEMI-PERMANENT ABRASIVES

In assessing the abrasive to use the following points must be considered:

(1) economic factors which can be sub divided into wheel cost and time costs;
(2) volumetric output: this is measured by the capital installation required for a grinding job;
(3) workpiece quality: surface finish, surface integrity, thermal damage and dimensional accuracy are the parameters to be considered in evaluating the abrasive to be used.

The materials to be assessed for use with semi-permanent abrasives may be roughly sub divided into four groups:

(1) steel includes tool steels, alloy steels, low alloy steels and stainless steels;
(2) carbides and steel/carbide combinations;
(3) non-ferrous alloys e.g. nimonics and waspalloy;
(4) ceramics;

of these only the materials in Group 1 are regularly internally ground though there is a small amount of work in the other groups.

3.8.1 Effect of Grit Size

As grit size increases the number of grits in a wheel bond decreases. This results in a larger chip cross section per grit and therefore an increased grit load. However, due to the larger size of the grit it is held more securely in the bond. The space between the particle is also increased allowing a faster more efficient removal of the swarf and a decrease in the wear of the bond material. A balance can be found from these counteracting affects where the optimum grinding ratio is achieved. Figure 18 shows the effect of grit size on Grinding ratio when using DXDA-MC to surface grind a tool steel at varying infeeds.

With regard to surface finish, decreasing the grit size improves the quality of surface finish. The increasing number of particles of smaller size and the removal of smaller chips due to the shallower penetration results in improved finish.

3.8.2 Effect of Concentration

Concentration refers to the number of carats of grit contained in a unit volume of bond material; 72 carats/in^3 eing defined as 100 concentration.

It follows, therefore, that the number of particles in the bond increases with the concentration for the same grit size. Therefore, a higher grinding ratio could be expected with a higher concentration. This has been shown to be the case with light infeeds ($\lesssim$ 0.001"). However, the increasing number of grits results in a decrease in the amount of bond at the wheel rim and at heavier infeeds the grit pull out is intensified with increasing concentration. Figure 19 shows the effect of concentration on the consumption of diamond carat/in^3 of material removed.

3.8.3 Grinding Ferrous Metals

Ferrous metals can be divided into six categories:

tool and die steels;
standard carbon and alloy steels;
ultra high strength alloy steels;
stainless steels;
cast steels;
cast iron.

Tool and die steels include those which are capable of being hardened and tempered. Included are the water hardening, shock resisting steels, the hot and cold work grades, and high speed steels.

Standard carbon and alloy steels comprise the low carbon (0.05 - 0.3%) structural steels, rods and plates, medium carbon (0.3-0.7%) used in crank shafts, gears and machine parts; and high carbon grades (0.7-1.3%) used in hand tools, drills etc. the last group of steels is normally heat treated. Overall, this group of steels accounts for approximately 90% of steel production.

Ultra high strength alloy steels are those steels specially developed from standard steels, with strengths between 200,000 and 300,000 lbf/in^2.

Stainless steels are comprised of martensitic, which can be readily hardened, austenitic which has a high nickel content; ferritic which is normally used soft and precipitation which is characterised by good hardenability.

Cast steels is a term applied to those metals which are cast to the desired shape rather than wrought the carbon content is normally 0.2-0.5% and the alloy content as high as 30%. Typical components are valve bodies, turbine shells and machine structures.

Cast irons include grey and malleable iron castings and other less common groups.

Tarasov (20) in one of the first articles to be published on the subject stated that high Vanadium, high speed steels and die steels, difficult to grind conventionally, can be ground more rapidly and profitably with diamond wheels. These also generate far less heat than aluminium oxide wheels when high carbon, high chromium die steels are ground. Man made diamonds are superior in these applications.

Five steps have characterised the chain of events that provided industry with semi-permanent grinding tools for machining ductile materials (21):

(1) production of manufactured diamonds;
(2) development of superior resin bonds;
(3) introduction of metal clad diamonds;
(4) development of chemically inert bonds;
(5) introduction of metal clad CBN abrasive.

Figure 20 relates the progress of development to a time scale and shows how under similar conditions, the ease of grinding M-2 and T-15 has increased over the past two decades as a result of the innovations and improvements listed above.

Table 3 (17) shows that CBN, except for the generally higher grinding ratios, behaves somewhat like aluminium oxide in that it is sensitive to workpiece chemistry. This is especially so on materials with a high chrome content which tend to affect CBN adversely. The relatively high grindability of D3 classes it as much easier on wheel wear than the molybdenum and tungsten type high speed steels.

Diamond, except for the notable exceptions of the die steels and cast irons achieves relatively consistent ratios regardless of the workpiece chemistry leading to the conclusion that factors other than diamond strength and shape influence its performance on these metals.

The following summarizes the position: (22)

High speed tool steels: are not only hard but tough; their high shear strength results in the forces exerted on individual chips being high thus taxing bond retention. At the same time tough discrete chips are formed which are highly erosive to the bond, thereby, giving the abrasive even more protusion.

Generally with these tool steels the choice of abrasive lies between diamond and CBN. In the case of T15 the most attractive of the diamond abrasives is the friable type of diamond, though Dyer (16) reports that the performance of DXDA-MC (blocky-diamond) is improved from 38 to 180 by the substitution of an improved resin bond for the standard bond.

Standard carbon and alloy steels: generally speaking are easily ground with conventional abrasives and it would be extremely hard to justify the use of semi-permanent abrasives. However, it is the type of steel most often encountered in steel/carbide combinations and the choice of diamond (usually) wheel is decided on the basis of percentage carbide to be ground.

Ultra high strength alloy steels: materials in this range are in general easier to grind with semi-permanent abrasives than with conventional abrasives and there is not too much difficulty in achieving reasonable costs.

Stainless steels and non-ferrous alloys: a broad category embracing a range of metals which are often difficult to grind using conventional abrasives. In general they are not unduly hard but tough and are often susceptible to work hardening. Very little data has so far been published but the use of diamond has been investigated by Dyer (16) for the nimonics, titanium and waspalloy. The priliminary results are encouraging for the application of semi-permanent abrasives in this field.

Cast iron: using semi-permanent abrasives spectacular grinding ratios can be obtained for this material.

However, this is a field where conventional abrasives also have few problems and so the decision on which abrasive to use has to be made on the other advantages to be obtained, e.g. dimensional accuracy. Cost can be reduced if in the case of large wheels the use of single layer electro plated wheels are considered.

The influence of various parameters on the efficiency of the grinding wheel can be very marked. However, it must be stressed that to achieve the best results the machine tool must be in a good state of repair. The substitution of semi-permanent abrasives for conventional abrasives on a poorly maintained machine will in a lot of cases produce a poorer quality of work as these abrasives are in some degree less tolerant of these conditions.

3.8.3.1 The influence of wheel speed

Increasing the peripheral speed of the grinding wheel gives the following results (23)

(a) the increase of the peripheral speed (V) causes a degressive reduction of the cutting power P_s.

This phenomena is according to the formula

$$N_s = \frac{P_s\ V}{102}\ \text{kW} \qquad (1)$$

where P_s = cutting power in k_p

V = peripheral speed in m/s

(b) A reduction in the feed per revolution of the grinding wheel and thereby a reduction of the feed per diamond grain s_d given by:

$$S_d = \frac{S\, k_s}{D_s \pi} \qquad (2)$$

where S_d = feed per diamond grain

S = feed rate/revolution

D_s = diameter of wheel

k_s = characteristic value of diamond layer (constant).

(c) A degressive increase of the power consumption N_s, beginning at a certain value of peripheral speed the increase in power consumption will become lower.

The results of the increase in peripheral speed are shown in Figure 21.

The reduction of cutting power caused by the increase in wheel speed leads to a reduction of the stress acting on individual grains. In view of the wear rate of the bond this must be considered as a positive reaction. The advantage of having small cutting powers is also that machines designed for heavier metal removal rates do not need increased stiffness. The increased peripheral speeds do, however, have the disadvantage that increased temperatures in the cutting area will lead to problems of diffusion wear in diamonds and a loss of surface integrity of the workpiece unless the action of coolant can be guaranteed at the higher speeds.

Practical test results (24) show that at 5,500 SFPM DXDA-MC performed best on titanium and waspalloy ($< 50\ R_c$) while CBN yielded excellent results when grinding M2 and T15 tool steels ($> 50\ R_c$). Downfeed did not significantly affect grinding ratios and an increase of downfeed sometimes eliminated surface burns and increased productivity.

At 9000 SFPM both friable and blocky diamond grit showed 200% improvements in G ratios when grinding titanium and waspalloy, Performance dropped off however when grinding M2 and T-15. CBN wheel life increased when grinding tool steels especially so in the case of T-15.

At 12,500 SFPM friable diamond performance was equal to that of blocky diamonds when grinding titanium and waspalloy which represented a significant improvement in performance. The performance of CBN wheels on these materials improved but still did not match diamond results. Friable diamond charred when grinding T15 but the blocky diamond ground the T-15 with only traces of surface burn. Peak performance was obtained at this speed for CBN wheels grinding T-15 with grinding ratios of between 300 and 400 and a metal removal rate of 3 in^3/hr. On M2 CBN achieved very high grinding ratios but these were not significantly higher than those obtained at 5,500 SFPM.

At 16,000 SFPM the friable diamonds gave remarkable efficiencies when grinding titanium and waspalloy especially at a heavier downfeed of 0.002". Grinding ratios improved from 11 at 5,500 SFPM to 356 at 16,000 SFPM.

In a similar manner CBN broke away from the flat pattern at this speed and grinding ratios of 3670 were recorded when grinding M2 with a downfeed of 0.002" (at 5,500 SFPM G ratio = 500-1000).

CBN was less efficient grinding T-15 at this speed than 12,500 SFPM.

This series of tests was designed to investigate the effect of wheelspeeds on grinding ratios and no attempts were made to eliminate the surface burn a measure residual stresses and on some materials.the surface finish was unacceptable. Blocky diamonds, however, yielded very good surface finish characteristics at all stages and at no stage was there any evidence of surface cracking when grinding titanium with these diamonds.

3.8.3.2 The effect of coolant

The choice of a suitable coolant is of great importance in grinding steel materials. The advantages sought by the use of coolants are

(a) to cool the wheel;
(b) to lower the friction between the wheel and workpiece;
(c) to reduce chemical reactions between abrasive and workpiece material which cause increase grit wear;
(d) facilitate chip removal and cool the chips that are removed.

Water containing rust inhibitor is the most effective coolant, being able to absorb twice as much heat as the same amount of oil. However, water will not lubricate the surfaces, because of its high surface tension and consequent low wettability of the workpiece surface and grinding wheel surface.

Surface active solutions may be added to the water to reduce the factor of low wettability and lubricants may be added to these solutions.

Extreme pressure additives in coolants have the ability to react chemically with the workpiece to form layers of chlorides, phosphates and sulphides which lower the coefficient of friction between workpiece and wheel. These reactions, however, depend on temperature and pressure and if too low a pressure temperature level occurs the use of E.P additives will be inefficient.

The fourth alternative is the use of neat oil. The heat dissipation characteristics of neat oil are not as good as water based coolants and there are environmental objections to its use.

Table 4 (1) gives the results of surface grinding of various materials using 80/100 mesh CBN wheel with various coolants at varying concentrations.

Results published by De Beers give grinding ratios of 300 when using plain water, 450 when using surfactants and between 600 and 650 for E-P additives when surface grinding D2.

3.8.4 Grinding carbides and steel/carbide combinations

It is generally agreed that the most efficient abrasive for the grinding of carbide is diamond. However, the majority of users it is felt are not achieving the best results possible because of a number of factors.

The grinding of carbides can be broken down into three major areas:

1 wet grinding;
2 dry grinding;
3 grinding of steel carbide combinations.

3.8.4.1 Factors that influence the grindability of carbides

Hughes (25) reports that when using 100/120 grit RDA-MC under identical conditions to grind ten different grades of carbide that grinding ratios varied between 212 and 332. It was also noted that wide variations were obtained when grinding the same grade of carbide supplied by different manufacturers, (variations of up to 22% reported).

Factors that influence the grindability of carbides are listed as:

the amount of cobalt binder;
the amount of tungsten carbide;
the amount of titanium and tantulum carbides;
the manner in which the carbides associate
  during the sintering process;
the sintering techniques used;
the grain size of the various carbides;
the hardness;
the toughness;
the thermal conductivity;
the coercivity;
the magnetic saturation.

Claims that the hardest carbides are more easily ground are not substantiated by Hughes results though the hardest carbide tested, K05, did yield the highest efficiency. Otherwise no correlation could be found between hardness and grinding ratio.

3.8.4.2 The wet grinding of carbide

(a) The effect of wheel speed

In wet grinding the supply of coolant results in a dissipation of the heat allowing an increase in wheelspeed from that used for dry grinding (see Figure 22) without causing thermal damage to the bond. The average underformed chip cross section decreases simultaneously with an increase in wheelspeed leading to a decrease in the mechanical load per diamond particle and the maximum grinding ratio is displaced to a higher speed.

The size of the average undeformed chip cross section (Aa) is given by (26):

$$A_a = \frac{Z_T x V_T}{N_D x V_S x B_H}$$

where Z_T = downfeed;

V_T = tablespeed;

N_D = number of diamonds per unit of surface;

V_S = wheelspeed;

B_H = width of major wear flank.

However, it will be noticed that there is a decrease in the grinding ratio to that achieved when dry grinding. Studies of the wheels used after wet and dry grinding show that the wheel used dry is covered with a grey layer of tungsten carbide swarf from which the cutting points protrude. In contrast the wheel surface following wet grinding is completely free of swarf leaving the abrasive grits, pores and cavities clearly visible. The coolant therefore is performing a cleaning action in addition to cooling the wheel.

The swarf in dry grinding when it fills the bond pores and cavities provides additional support for the diamond grit. This supposition was confirmed by a count of the number of active particles on the wheel surface when it was found that the number was greater when dry grinding.

Tests by Lindenbeck have shown that when the coolant flow is positioned so as not to impinge directly onto the wheel surface that improved efficiencies will result.

It is also to be noticed that the selection of wheelspeed is far less critical when wet grinding than in dry grinding.

(b) The effect of downfeed

Figure 23a shows the affect of increasing the downfeed when surface grinding P20 carbide. As can be seen the grinding ratio drops off very quickly but when total costs are considered the most economical downfeed is 0.002". (Figure 23B)

The figures for time cost used are \$12 per hour. and wheel costs have been computed at \$410 per in^3. If cheaper labour rates prevail the most economical downfeed can be displaced to a slightly lower rate.

(c) The effect of crossfeed

Figure 24 AB give the relationship between G ratio and downfeed and total cost and downfeed. The normal operating practice is that crossfeed should be a quarter of the wheel width. The graph shows that the optimum setting would be at this figure i.e. 0.060" for the conditions used.

(d) The effect of table speed

Figure 25 shows the effect of table speed on grinding ratio and total cost. Optimum table speed is in the 50-60 ft/min range and this is in accordance with normal operating speeds.

The total cost curves for all four parameters are shown together in Figure 26. From this it will be apparent that the greatest economies are to be obtained when heavier downfeeds are used.

(e) The effects of metal cladding

Figure 27 shows a range of G ratios obtained when grinding G6 tungsten carbide for various grit sizes using a 0.001" downfeed and also a 0.0004" downfeed for smaller grit sizes. As can be seen the clad grit is more efficient than the unclad grit. However, the wheel using the clad grit requires more power than the unclad grit (33% more for 60/80 grits down to 4% more for 325/400 grits) and this could be a disadvantage when the machine is low powered.

Allied to the improved efficiencies of the clad grit there is a considerable saving in total cost. Generally speaking there is also an improvement in surface finish.

(f) The effect of concentration

There is no problem in the manufacture of wheels using unclad grits with concentrations of up to 200. Using the clad grits due to the cladding increasing the diamond volume percentage 140 concentration is a reasonable upper limit for manufacture.

The efficiency of the unclad grit reaches its peak at 175 concentration while the efficiency of the clad grit continues to rise right up to 140 concentration. (Figure 28).

Consideration of costs, however, reveals that the optimum cost points for the unclad grit is 125 concentration and for the clad grit at 100 concentration (Figure 29). It is noted as previously stated that lower costs will be obtained using metal clad grits.

3.8.4.3 The dry grinding of carbide

The effect of wheelspeed

The selection of the optimum wheelspeed is very critical in dry grinding and various researchers (19, 26, 27) have shown that a speed of 2,500 SFPM will yield the greatest efficiencies. (Figure 22).

Referring to the expression for average undeformed chip cross section given in section 3.8.4.2 at decreasing wheelspeed the value of A_a increases as does the value for the mechanical load per diamond particle. If this load exceeds the ability of the bond to hold the particle, the resulting particle loss will mean that there are fewer particles with consequent increases in the mechanical load per particle. This situation leads to heavy wheel wear.

At a certain wheel speed a state of equilibrium between particle loss and increase in undeformed chip cross section will occur.

The drop in grinding ratio above this speed is attributed to thermal degradation of the resin bond leading to accelerated grit pull out. The effect is confirmed by Busch and Grassmann (26) when it was shown that by a reduction in workpiece height, leading to reduced contact time, that optimum grinding speeds could be increased to a higher value due to a lessening of the thermal degradation at lower speeds.

The dry grinding of carbides is limited to fairly small areas and generally does not exceed ½" ~~and~~ x ½", nevertheless temperatures even on these small areas still rise very rapidly and this has to be offset by the idling period during which the wheel does not touch the workpiece. This is relatively long in tool and cutter grinding as opposed to surface grinding when the temperature increases over a long period.

A further limitation of dry grinding is that accurate control of wheel speed is required. Any deviation from this speed will lead to a rapid decline in the grinding ratio.

Ratterman (19) also reported that at speeds of greater than 2800 SFPM that the wheel was found to leave 'peen' marks on the surface of the workpiece at each revolution. It was reported that this phenomena occurred using different wheels though no mention is made of using other machines to check the findings.

3.8.4.4 Grinding carbide/steel combinations

The simultaneous grinding of two materials as dissimilar as tungsten carbide and steel poses technical difficulties because it is fairly difficult to fully satisfy the abrasive requirements of both materials. With the range of metal coated diamond grits now available, however, this operation can be termed economically feasible.

However, the positive effects obtained when dry grinding tungsten carbide alone in terms of bond support by the carbide swarf no longer obtain due to the abrasive nature of the steel swarf leading to high bond wear rates and therebye precluding the deposits of carbide swarf in the pores and cavities.

This does not preclude carrying out the operation dry, though this is now not the most economic way of carrying out the work.

Optimum conditions for dry grinding (28) are much the same as when grinding carbide alone, the optimum wheelspeed is about 2,300 SFPM. At speeds above 3700 SFPM severe workpiece burn was found to result. The influence of wheelspeed was found to diminish as the percentage of carbide decreased. The optimum concentration was found to be 100 concentration for downfeeds of 0.001" and 75 concentration for 0.002" downfeeds.

When carrying out the operation using flood coolant test results (26) show that optimum conditions are very similar to those obtained when grinding carbide alone except that reactions are more drastic. Figure 30 shows the composite cost curves in respect of the machine parameters of downfeed, crossfeed and tablespeed. Once again it is apparent that downfeed is the parameter that should be increased if the metal removal rate is to be increased.

The type of grit to be used can be shown (29) to depend on the proportion of carbide present. When steel is the dominant component DXDA-MC grits should be used and when carbide is dominant a friable grit such as RDA-MC is preferred.

CHAPTER 4

EXPERIMENTAL EQUIPMENT AND TEST PROCEDURE

4.1 GRINDING MACHINE

The grinding machine is a pre production prototype of the Cincinnati 071B plain internal grinding machine. The machine is semi-automatic in operation and the basis of the design was for one-off and small batch production.

The workhead, table oscillation and wheelhead cross slide feed are semi-automatic, wheel dressing operations are manual. A manual facility is also provided for the cross slide feed.

The drives for the workhead spindle, wheelhead and table oscillating mechanisms are electric motors. A hydro-pneumatic system provides the power and control for table positioning and traverse. Operation and control of the cross slide feed is by a pneumatic system utilising air pressure for both the control signal and operating media. Figure 31 gives the specification of the grinding machine.

4.1.1 Grinding Cycle of Operations

When grinding with conventional abrasives the following sequence of operations is performed:

(a) rough grind;

(b) dress;

(c) finish grind.

The machine is equipped with a semi-automatic feed mechanism which divides the total infeed of 1 mm into two intervals of 0.8 mm of feed for rough grinding after which the wheel backs off to allow for the dressing operation followed by 0. 2 mm feed at finish grinding rates. Two periods of spark out are allowed during the finish grinding, these occur 0.05 mm before the end of the feed and at the end of the cycle before the wheel finally backs off.

When using semi-permanent abrasives the intermediate back off position is not required and when carrying out a rough grind followed by a finish grind this feature was suppressed by a substitution of a plain feed cam. Table 5 gives details of the range of feeds that may be selected.

4.1.2 Wheelheads

The wheelhead is belt driven by a 4 H.P. a.c. motor running at 3,000 R.P.M. The wheelheads used for this series of tests were:

(a) type 5-2-U500 Cincinnatti Redhead with a maximum operating speed of 17500 RPM;

(b) type 1-2A-U500 Cincinnatti Redhead with maximum operating speed of 38,000 RPM. Pulleys were selected to give the following operating speeds; 16,500 RPM, 25,400 RPM, 31200 RPM and 35,000 RPM.

Initial testing was carried out at 17500 RPM the standard speed for the machine as supplied. As a result of the survey of literature and discussions with wheel manufacturers and users it was apparent that the full potential of the semi-permanent abrasive wheels would not be realised unless wheel speeds were increased. The majority of results reported are with the wheelhead with the higher operating speed.

Standard wheel holding quills were used with both wheelheads but it was found that with the wheelhead capable of attaining higher speeds the forces encountered both in trueing and grinding a quill of stiffer construction was required. Details of the quill are given in Figure 32. The design of the wheelhead is not entirely suitable for this size of quill, and undesirable features are apparent in the bore profile.

4.2 WHEEL DRESSING AND CONDITIONING

The techniques available for the trueing and conditioning of semi-permanent abrasive wheels are dealt with in Section 2.4.

The survey of literature revealed that there is a common concept in the trueing and conditioning of diamond and cubic boron nitride wheels. Both types of wheel can be adequately trued using a brake trueing device employing either aluminium oxide or silicon carbide wheels.

Lindenbeck (12) reported that employing a motorized silicon carbide dressing roll the operation of trueing diamond wheels could be carried out significantly faster if variable speeds were employed for the diamond wheelspeed. This technique was tested and adopted as the mode of practice when preparing diamond wheels.

When this technique was used for trueing CBN wheels both the CBN wheel and the silicon carbide wheel developed hard glazed surfaces. These then had to be cleaned to allow trueing to proceed. The substitution of white aluminium oxide wheels was not practicable due to the high rate of sacrificial wear.

The use of diamond impregnated dressing tools was investigated for trueing CBN wheels and the use of the trueing nib proved satisfactory and faster than the brake truer in operation. The alternative of using a motorized roll was not pursued at this stage due to lack of equipment. The use of the trueing nib was thus used for the preparation of CBN wheels.

The conditioning process is almost universally carried out using hand held sticks of white aluminium oxide. This method relies heavily on operator experience to produce a wheel with the right exposure of grit. Attempts by other investigators to develop alternative methods of conditioning have been unsuccessful in regard to internal grinding wheels and this method is used throughout to condition the grinding wheels.

4.3 MODIFICATIONS TO MONITOR WHEEL AND WORKHEAD SPEED

The monitoring of the wheelhead and workhead speed is carried out using Tachometers which obtain their input signals from Texas Instruments SDA20/2 Fork Assembly Optically Coupled Counter Modules. The modules consist of a light emitting diode and a photo transistor mounted on opposite sides of the fork. A circular drilled plate is mounted on the spindle and rotates between the two elements of the counter module. The plate is drilled with 60 holes, the spacing of the holes is such that the alternating spaces are equal to the hole size. In this manner a square waveform signal is transmitted. The signal is further modified by the inclusion of a Schmidt Trigger to ensure the waveform changes are 'sharp'. The Tachometer counts the number of pulses over a predetermined time interval and the output is displayed in revs per minute. Figure 33 shows the arrangement of the perforated disc and counter module mounted on the workhead spindle.

4.4 MEASURING EQUIPMENT

4.4.1 Surface Measurement

The Talysurf 3 (see Figure 34) was used for all measurements of surface finish of the ground bores. The Talysurf 3 is a Triple Cut Off Average Meter with three cut off values:

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

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

(c) 0.1" cut off is used for rougher surfaces and surfaces with chatter marks up to 0.1" apart.

There are six standard ranges of magnifications available and details of the chart scales and C.L.A. Index Scales are given in Table 6.

The majority of readings were taken using the average meter, surface finish traces were not taken for record purposes. The average meter is designed so that pointer fluctuations are avoided by the use of an integrating meter. The integrating meter is connected to the output from the amplifier for a predetermined time of operation, which is controlled by contacts in the gear box. These contacts operate after the start of the stroke and just before completion of the stoke. The meter sums the fluctuations of current which the instrument receives as the stylus traverses the work and shows the average directly on the scale. This reading is maintained until the pick up is moved forward to the start position.

In order that a representative reading is obtained the operative length of the traverse is several times longer than the meter cut offs. Details of the traverse lengths for the various cut offs are given in Table 7. On this instrument the stroke length and meter cut off are changed in pairs and cut outs prevent mismatching.

4.4.1.1 Selection of cut off

The manufacturers recommend that generally the 0.03" cut off is suitable for surfaces produced by the grinding and honing process, with the 0.01" cut off being used for short parts like piston rings.

When roughness (primary texture) is repetitive as in Figures 35A and B, typical of a single point process, the requirement is that the cut off be greater than the crest spacing, which will generally be equal to the traverse feed.

In the case of Figure 35C which is representative of tool marks combined with chatter marks of greater crest spacing two sample lengths could be considered, the short value will give an average of tool marks only and the longer an average of both tool and chatter marks.

The requirement for the surface shown in Figure 35D, an irregular abraded surface is not so clear and often not easy to determine from inspection of the surface or even a profile graph.

In this series of tests the surface finish readings have been made using the 0.03" cut off.

4.4.2 Bore Profile Measurements

Three pieces of equipment are used to measure the amount of taper in the bore and trace the bore profile, the Talysurf 4, the Talytron S, a traversing table and the reversing stylus accessory for the Talysurf 4.

4.4.2.1 Talysurf 4

The talysurf 4 is similar in most respects to the Talysurf 3 already described with the exception of the additional magnifications of 500 X and 100,000X.

4.4.2.2 Air Traversing Table

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

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

The components from the grinding test are supported in a Vee Block which is adjustable in three directions, swivelling about the vertical axis (± 3 mm), tilting about the horizontal axis (± 1 mm) and adjustment crosswise to the measuring direction (15 mm). Initially these controls are manipulated to give a horizontal trace of the bottom of the bore, the stylus traversing the bottom of the bore over its full travel. The top of the bore is traced as the second operation after the stylus pressure is reversed using the reversible stylus.

4.4.2.3 Reversing stylus

With the aid of a bias unit the direction of the stylus force can be reversed, enabling, when a double tipped stylus is used that is near in length to the bore diameter, traces to be made of the crest and bottom of the bore without alteration being made to the pick up height.

The stylus arm used throughout the tests has a magnification of 0.7, this was checked using gauge blocks of 0.0001" difference at 20,000X magnification. The height measured on the graph (Figure 36) being 1.4" which corresponds to 0.00007" at the indicated magnification.

Figure 37 shows the combined set up of the Talysurf 4, a Traversing Table and Reversing Stylus.

4.4.3 Out of Roundness Measurements

Out of roundness measurements were made using the Talyrond. The Talyrond (Figure 38) is an instrument for measuring the roundness of parts such as balls and rollers, ball and roller races, pistons and cylinders. External diameters from $\frac{1}{16}$" to 12" and internal diameters from $\frac{1}{8}$" - 12" can be checked.

The maximum height of the specimen is 18".

An electric displacement indicator carried on an optically worked precision spindle of extreme accuracy is rotated round the inside or outside of the part to be examined, the part remaining stationary on the work table. The signal from the indicator is amplified and applied to a polar co-ordinate recorder, the rotation of the chart is synchronised with that of the spindle.

The graph obtained shows the amount by which the periphery of the work being tested departs from a truly circular form. The residual error of the spindle does not exceed 3 μ in.

Facilities are available to filter out closely spaced irregularities to assess the general form of the test piece or to filter out the general shape of the component to observe the more closely spaced irregularities. The filter details are given in Table 8. The results reported in this series of tests have all been recorded at 3 RPM with the A Filter. Figure 39 shows the affect of the various filters when measuring a single workpiece.

A reference computer is linked to the Talyrond enabling a reference circle to be plotted on the polar co-ordinate chart based on the principle of least squares.

The plot is orientated such that metal is represented where ever it is found i.e. inside the trace on a shaft or outside the trace in the case of a bore.

The range of magnifications available using the 2½" arm are between 200 and 10,000X.

4.4.4 Determination of grinding ratio

The grinding ratio is a comparison between the amount of metal removed and the grinding wheel wear which is given by:

$$\text{Grinding ratio} = \frac{\text{Metal removed}}{\text{Wheel wear}}$$

Measurements of wheel wear and metal removed were taken using micrometers. If the wheel wear at the end of the test were insufficient to be accurately measured, testing was extended to give a significant amount of wear.

Ideally the grinding wheel wear should exceed the depth of a single layer of grit during the duration of a single test. Due to limitations of material and time testing to this extent could not be carried out.

4.4.5 Details of Workpieces

The material used for all the tests reported was EN31 hardened and tempered to 60 R_c. All test pieces were manufactured from the same bar. EN31 is widely used in the bearing industry and is a 1% C/ 1% Cr steel.

The initial size of the test peices was 3.5" O.D x 1.4375" ID x 1.5" long. The final bore size was 1.875" I.D. Grinding beyond this size was precluded by the size of the chuck. Due to the increasing bore size the wheelspeed was adjusted to keep the speed in surface feet per minute constant.

The test pieces were held by means of a 3 jaw self centering chuck.

4.4.6 Test procedure

Grinding tests were carried out by removing between 0.015" and 0.020" on diameter from each test piece at a selected infeed. The infeed was applied at each end of the traverse stroke. At the conclusion of the infeed three 'spark-out' passes were allowed before the wheel back off was actuated.

A normal test series consisted of between 12 and 16 such test grinds, though if wheel wear was slight this was extended to obtain sufficient wheel wear.

CHAPTER 5

TEST RESULTS AND DISCUSSION

Results of the grinding tests are presented in tabular form and graphically as listed below:

Wheel	Infeed	Table of Results	Graphical Representation		
			Grinding Ratio	Surface Finish	Out off Roundness
85 CBN II R100 BZ10	Various	9	Fig 40	-	-
120/140 CBN II R100 BZ10	0.0001"	10	Fig 41	Fig 42	Fig 49
120/140 CBN II R100 BZ10	0.00025"	11	Fig 43	Fig 44	
170 CBN II R100 BZ10	0.0001"	12	Fig 45	Fig 46	
170 CBN II R100 BZ10	0.00016"	13	Fig 47	Fig 48	
50 DXDA-MC	0.0001"	14	-	-	-
100 DXDA-MC	0.0001"	14	-	-	-

The explanation of the wheel coding is as follows:

The first figure e.g. 85 or 120/140 is the grit size CBN II - cubic boron nitride type II (metal coated)

R - Resin bond
100 - 100 concentration
BZ10 - Bond type (designation of wheel manufacturer).

The two wheels designated 50 and 100 DXDA-MC are:

120/140 - grit size
DXDA-MC-Blocky Type grit - metal coated
50 or 100-grit concentration.

With the exception of the tests made using the 85 grit CBN wheel and the diamond wheels all the tests were conducted using the wheelhead with a maximum operating speed of upto 38,000 RPM.

5.1 GRINDING RATIO

The test results show that the grinding ratio increases if the following action is taken:

(i) the wheelspeed is increased;
(ii) the workspeed is increased;
(iii) the grit size is increased;
(iv) the metal removal rate is decreased.

5.1.1 The Effect of Wheelspeed

In all tests carried out the grinding ratio showed an increase of linear nature as the wheelspeed was increased. This increase does not show any signs of 'tailing off' at the higher speeds and one can only conjecture at the value of wheelspeed to obtain peak efficiency. The rate of increase appears to slacken as the metal removal rate is increased.

A beneficial aspect of increasing wheelspeed is that as the wheelspeed is increased more cutting points are presented to the work per unit of time and therefore the load per grit is decreased. Hence, tests can be conducted at higher speeds that could not be carried out at the lower wheelspeeds without giving excessive wear or charring the bond.

5.1.2 The Effect of Workspeed

From the results obtained the effect of increasing the workspeed is seen to increase the grinding ratio, however, these results are not comprehensive and further testing will be required to confirm the trend noted.

5.1.3 Effect of Grit Size

The results of the tests confirm the trends depicted in Figures 18 and 27 of the peak efficiencies occurring for the larger grit sizes. It must be borne in mind however that the more advantageous results with regard to surface finish will be obtained with the smaller grit sizes. These two factors must be balanced when making the wheel selection.

5.1.4 The Effect of Metal Removal Rate

As may be expected the highest grinding ratios occurred when the infeed and traverse rates were lowest. However, as will be demonstrated these low metal removal rates do not in fact coincide with the economical operating point.

As the metal removal rate is increased the incidence of bond charring increases. If this condition is not halted quickly damage can occur to a considerable depth, which entails costly delays while the wheel is retrued and conditioned. It was noted when grinding using the 85 grit wheel that 'loading' of the wheel occurred at the higher metal removal rates. Samples of this loading were analysed and proved to be 80% nickel with traces of iron, phosperous and magnesium. This is evidently the nickel coating of the grit being extruded in the form of loading.

5.1.5 Diamond Wheels

The results of tests using both the 50 and 100 concentration diamond wheels gave extremely low grinding ratios. In addition the feed rates could not be maintained for the period normally applied when grinding using CBN wheels without a tendency for bond charring to occur. In the circumstances testing was discontinued in favour of the CBN wheels. It is possible that more compatible results would be obtained at higher wheelspeeds.

5.2 SURFACE FINISH

Surface finish was found to improve as:

(i) the wheelspeed increased;
(ii) the metal removal rate decreased;
(iii) the grit size decreased.

5.2.1 The Effect of Wheelspeed

The surface finish is seen to improve as the wheelspeed increased, this is explained by the fact that a greater number of cutting points are presented to the work for the same amount of metal removed and as the cutting forces decrease there is a smaller degree of plastic deformation leaving a smoother bore. A similar effect has been claimed for conventional wheels.

5.2.2 The Effect of Metal Removal Rate

The results due to decreasing the metal removal rate are predictable and no surprise can be occasioned that surface finish will improve as either the infeed or traverse rates are lowered.

5.2.3 The Effect of Grit Size

As the grit size is reduced and if the concentration is maintained constant more cutting edges will be employed in removing metal and consequently a finer finish will result. A consequence of employing finer grit sizes is that the maximum amount of infeed applied must fall due to the limitations of chip clearance.

5.2.4 Comparison with Conventional Abrasives

At no time was a surface finish better than 13 μ in CLA achieved when using semi-permanent abrasives. This compared with the specification of between 8 and 10 μ in CLA achieved with conventional abrasives. The reason for this lies in the number of cutting points per unit area. For an equivalent grit size there are approximately twice as many cutting points on a conventional abrasive wheel as a semi-permanent abrasive wheel of 100 concentration. If then the wheelspeed can be raised further it follows that more cutting points can be presented per unit of time and an improvement in surface finish expected.

5.3 OUT OF ROUNDNESS

Analysis of the data for the 120/140 and 170 grit CBN wheels shows that values for this feature are not affected materially by alteration of the machining parameters. The plot of frequency of occurence against out of roundness, Figure 49, yields similar curves of a Gaussian distribution for both wheels with the median points slightly displaced.

5.4 BORE PROFILE AND TAPER

In the majority of tests there was a tendency for a barrel shaped bore to be produced. This defect appeared more towards the front of the bore with the back half exhibiting a slight tendency to be bell mouthed. A trace of such a bore is given in Figure 50. It was noted that the condition was less pronounced as the wheelspeed increased.

The taper measurements in the tables carry a suffix 'L' or 'S' to denote whether the bore had a large or small mouth. No discernable pattern could be distinguished during the tests reported to account for the variations in the direction of taper due to changing machine parameters. Short trials were made to determine the effect of infeed and traverse rate on the degree of taper. The result of these trials were inconclusive in establishing a definite relationship between these parameters and the amount of taper.

The figures quoted for the degree of taper are the average amount for the test and the variation was of the order of ± 0.00025". This amount of variation is beyond the limits of 0.0002" for the combined error of taper and concentricity.

It is felt that both the bore profile characteristics and the ability of the process to hold the taper limits would be further improved if the wheel holding system were of a stiffer nature.

CHAPTER 6

ECONOMIC EVALUATION OF CUBIC BORON NITRIDE

6.1 INTRODUCTION

The two main factors in the process cost are wheel and labour costs. Included in the labour costs are both direct and indirect labour cost and an allowance for overheads. Generally speaking the labour cost will be the largest part of the cost whether conventional or semi-permanent abrasives are used. The figures used for the calculations of cost in this section are \$410/IN^3 for abrasive and \$12/HR for labour costs. The cost is of course variable for individual plants but it is felt that they are representative of current costs.

The cycle of operations when grinding using conventional abrasives is as follows:

(a) rough grind;
(b) wheel dress;
(c) finish grind.

When using semi-permanent abrasives the necessity to dress at each cycle is removed. It is apparent therefore that if the same or superior metal removal rates can be achieved together with comparable surface finish and bore profile characteristics grinding with semi-permanent abrasives will be economically feasible.

However, semi-permanent abrasive wheels do need to be retrued at fairly regular intervals so that bore geometry is maintained and some allowance needs to be made for this operation. Lindsay (1) demonstrated that only trueing and compensation were required when grinding roller cups and that this was required at intervals of sixty components. The actual allowance will depend on the equipment available for this operation.

A further point in favour of semi-permanent abrasives is that due to their slower wear rate it is much easier to maintain workpiece tolerances especially on materials that are difficult to grind and when grinding ratios of conventional wheels approach unity. Thus when semi-permanent abrasive wheels are selected considerable time can be saved in measurement checks.

6.2 DETERMINATION OF OPTIMUM ECONOMIC GRINDING CONDITIONS

To assess technical and economic parameters of any abrasive completely it is not sufficient to have only a knowledge of the wear behaviour. It is necessary to define the optimum grinding conditions - machine and wheel parameters for each application.

The consideration of maximum grinding ratio alone is insufficient to determine which wheel to use. A survey to determine the lowest total cost point should be made to select the appropriate wheel.

Shaw and Farmer illustrated that the grinding ratios obtained by Tarasov (20) obeyed the Taylor like equation

$dG^N = C$ - (i) where d = spindle feed rate
G = grinding ratio
N = the inverse slope of log/log plot G vs. d
C = constant

Ratterman (19) notes that in plotting the data obtained from his tests, that while there is some scatter which results from the use of a variety of parameters the same straight line relationship holds and is given by:

$$R_M G^N = C \qquad \text{(ii)}$$

where R_M = metal removal rate in in^3/min.

With the relationship between R_M and G it is possible to predict the conditions for least cost stock removal knowing the cost of labour and wheels. The total cost for grinding is given by:

$$T.C. = \frac{X}{R_M} + \frac{Y}{G} \qquad \text{(iii)}$$

where T.C. = total cost per in^3 of material ground
X = labour and overhead costs
Y = specific cost of useable wheel.

The equation ignores wheel wear. The relationship between the true removal rate R_A and the feed rate R_M is given by

$$R_A = \left(\frac{G}{1+G}\right) R_M$$

When G is greater than 10, which is generally the case with semi-permanent abrasive wheels, $\left(\frac{G}{1+G}\right) \rightarrow 1$ and R_A and R_M are essentially equal.

Combining (ii) and (iii) and differentiating T.C. with respect to G or R_M and equating the result to zero yields:

$$G^* = \frac{Y\ R_M^*}{NX} \quad \text{* indicates optimums for G and } R_M$$

Then selecting appropriate values for N, X and Y a graph of G vs. R_M may be plotted and the intercept of the two curves indicates the conditions for minimum cost.

To illustrate the principles outlined in this section, experimental data published by Thompson (30) is used to perform sample calculations. Table 15 gives the recorded data for grinding ratio and metal removal rate, Figure 51 is the log log plot of grinding ratio vs. metal removal rate for the plunge grinding of tungsten carbide using a 230/270 metal coated diamond wheel.

The log log plot of metal removal rate vs. grinding ratio yielded a straight line relationship for the expression $R_M\ G^{-0.835} = 3.1$. The correlation coefficient for the plot was 0.835.

Substituting values of 0.835 for N, 12.0 for X and 410.0 for Y in the formula

$$G^* = \frac{Y\,R_M^*}{NX} \qquad \text{gives } G^* = 2480\ R_M^*$$

When this was superimposed on the plot of grinding ratio vs. metal removal rate, Figure 52, the point of interception denoting optimum metal removal rate occurred at 0.075 in^3/min.

To confirm the results obtained for economic metal removal rate a graph of cost vs. metal removal rate was prepared based on the formula:

$$\text{T.C.} = \frac{X}{R_M} + \frac{Y}{G}$$

where T.C. = total cost per in^3 of material ground

X = labour and overhead costs

Y = specific cost of useable wheel

R_M = metal removal rate

G = grinding ratio

A sample calculation is given below:

metal removal rate = 0.02

grinding ratio = 470

Time to remove 1 in^3 of metal = $\frac{1}{.02}$ = 50 min

Cost to remove 1 in^3 of metal = $\frac{50}{60} \times 12$ = \$10.0

Wheel cost to remove 1 in^3 of metal = $\frac{410}{470}$ = \$0.87

TOTAL COST = \$10.87

The figures $\$410/\text{in}^3$ for the cost of the wheel are obtained from De Beers Publications, the figure for labour rates is thought to be consistent with rates presently charged. Dollars have been used throughout this presentation as much of the material quoted in the survey was either American or South African in origin and that currency was used in their presentations.

Using these figures a graph of total cost vs. metal removal rate was plotted, Figure 53. The resulting curves confirm that a metal removal rate of 0.075 in^3/min is the optimum economic operating point.

These two techniques are used to illustrate the optimum operating conditions for the wheels used during tests at varying machine conditions.

6.3 DETERMINATION OF ECONOMIC OPERATING CONDITIONS

6.3.1 85 CBN II R100 B210 Wheel

Grinding results for this wheel are given in Table 16, the log log plot of metal removal rate vs. G ratio, Figure 54, shows a straight line relationship of $R_M G^{-2.59} = 4.56$. The correlation coefficient for the plot being 0.76.

Substituting values of 2.59 for N, 12.0 for X and 410.0 for Y in the formula

$$G^* = \frac{Y R_M^*}{NX}$$

yields $G^* = 790 R_M^*$

When superimposed on the original plot this suggests an economic operating condition of 0.10 in^3/min metal removal rate.

The plot of cost vs. metal removal rate, Figure 55, suggests a slightly lower optimum operating condition of 0.08 in^3/min metal removal rate.

6.3.2 120/140 CBN II R100 BZ10 Wheel

6.3.2.1 16,500 RPM wheelspeed

Grinding results are given in Table 17, only three sets of data are available and they were thought insufficient to draw the log log plot of grinding ratio vs. metal removal rate. The plot of cost vs. metal removal rate, Figure 56, suggests that the optimum metal removal rate would be of the order of 0.06 in^3/min but it was not possible to obtain data on tests where the metal removal rate exceeded 0.04 in^3/min at this wheelspeed.

6.3.2.2 25,400 RPM Wheelspeed

The data obtained for tests at this wheelspeed is presented in Table 17. This data gave a very poor correlation coefficient for a straight line relationship on the log log plot of grinding ratio vs. metal removal rate and the data is not presented in this form.

The graph of cost vs. metal removal rate, Figure 57, suggests that the optimum operating point is in excess of 0.06 in^3/min though metal removal rates in excess of this were not achieved.

6.3.2.3 35000 RPM Wheelspeed

Data relating to tests at this wheelspeed is given in Table 18. The data gives a straight line relationship with a correlation coefficient of 0.52 when plotted on the log log plot of grinding ratio vs. metal removal rate, Figure 58. The relationship between metal removal rate and grinding ratio is denoted by $R_M\ G^{-1.2} = 3.766$.

Substituting values of 1.2 for N, 12.0 for X and 410.0 for Y in the formula

$$G^* = \frac{Y\ R_M^*}{NX} \text{ yields } G^* = 1708\ R_M$$

When this curve is superimposed on the original plot of grinding ratio vs. metal removal rate the intercept occurred at 0.13 in^3/min indicating the optimum metal removal rate at that point.

The graph of cost vs. metal removal rate, Figure 59, confirms that the optimum metal removal rate was not achieved but it was not found possible to grind at metal removal rates in excess of 0.05 in^3/min.

6.3.3 170 CBN II R100 B210 Wheel

6.3.3.1 25,400 RPM wheelspeed

Data for grinding results at this wheelspeed is given in Table 19. The log log plot of grinding ratio vs. metal removal rate for this data gives a straight line of expression $R_M G^{-1.94} = 3.56$ the correlation coefficient being 0.76.

Substituting the appropriate values for N, X and Y in the expression $G^* = \frac{Y R_M^*}{NX}$ yields $G^* = 1057 R_M^*$.

When this is superimposed on the log log plot of grinding ratio vs. metal removal rate, Figure 60, the intercept denoting the economic metal removal rate occurs at 0.073 in^3/min.

This data, however, when plotted on a graph of cost vs. metal removal rate, Figure 61, suggests that the economic metal removal rate occurs at the lower figure of 0.04 in^3/min.

6.3.3.2 35,000 RPM wheelspeed

Grinding results at this wheelspeed are tabulated in Table 20. The log log of grinding ratio vs. metal removal rate, Figure 62, yields a straight line for the expression $R_M G^{-1.3} = 3.748$. The correlation coefficient for this plot is 0.55.

Substituting appropriate values for N, X and Y in the formula

$G^* = \frac{Y R_M^*}{NX}$ and superimposing the result on the log log plot of grinding ratio vs. metal removal rate gives an intercept denoting economic metal removal rate of 0.13 in^3/min.

The plot of cost vs. metal removal rate, Figure 63, confirms that the economic removal rate was not attained in this series of tests; it was not found possible to grind at metal removal rates higher than 0.06 in^3/min.

6.3.4 Grinding using conventional abrasives

Grinding tests using conventional abrasives carried out on the test machine showed that metal removal rates in excess of 0.05 in^3/min were not feasible for the equipment in use due to unsatisfactory bore characteristics at the higher removal rates. Reference to standard time data for internal grinding (31) shows that metal removal rates of this order are quoted and therefore these costs are used for comparison purposes.

A time data sheet, Figure 64, prepared using this data gives a cycle time of 1.483 mins for removing 0.015 in stock from a component with bore measurement of 1.4375" x 1.5" long.

The items that are relevant only to conventional abrasive grinding were selected for comparison costs as follows:

(1)	allowance for dressing	-	0.093	
(2)	wheel change	-	0.061	
(3)	rough grinding	-	0.575	
(4)	finish grinding	-	0.345	
			1.074	minutes/piece

The following assumptions are made in computing these costs:

(a) stock removal 0.015" on dia

(b) tolerance on finished bore ± 0.00025"

(c) one pass with the dresser

(d) the wheel is changed every 100 components.

The cost, therefore, of removing 1 in^3 of metal would be \$4.30 using previously applied labour rates. The wheel cost is estimated at \$0.10 giving a total cost of \$4.40 per in^3 metal removed.

The computed metal removal rate is 0.054 in^3/min for the cost specified.

6.3.4.1 Cost comparison between conventional and cubic boron nitride abrasives

The lowest costs obtained using CBN are at the highest wheelspeeds and generally at the highest metal removal rates. Under these conditions the total costs are seen to be marginally superior to conventional abrasives with the 120/140 grit wheels though this is not the case with the 170 grit CBN wheel. Figure 65 shows the total costs when using the 120/140 grit CBN wheel at various metal removal rates. The general trend in all cases is improving while at the higher metal removal rates the costs of the operation are lower. It can be conjectured that at higher wheelspeeds greater benefits may acrue.

The figures for the 85 grit CBN wheel were all obtained at low wheelspeeds and it may confidently be assumed that at higher wheelspeeds more advantageous costs will be obtained. The total cost is lower than for conventional abrasive at 0.1 in^3/min metal removal rate and were the lowest costs obtained during this series of tests.

CHAPTER 7

CONCLUSIONS

The predicted economic metal removal rates except in one case were not achieved. There is a considerable doubt that rates in excess of 0.1 in^3/min at wheelspeeds up to 35,000 RPM can be consistently achieved due to the probable breakdown of the wheel caused by bond charring.

In all cases the lowest total costs are attained at the highest wheelspeed, higher metal removal rates are only achieved as the wheelspeed is increased.

Marginally superior costs are achieved using the 85 and 120/140 grit cubic boron nitride wheels over figures computed for the use of conventional abrasive wheels. The figures for the 170 grit cubic boron nitride wheel are slightly inferior in this respect. However, the metal removal rate computed for conventional abrasives is lower than that intimated from industrial sources. If this were the case a much lower labour content would lead to an overall cost of the order of $2.50 per cubic inch of metal removed and hence CBN would be more expensive.

The surface finish achieved during these tests was never better than 14 μ in CLA. This is well outside the range of finishes achieved using conventional abrasives. A point to be noted when using semi-permanent abrasives is that the same even texture cannot be obtained that results from the use of conventional abrasives even though the CLA value might be identical.

No firm conclusions can be drawn with regard to taper or the alteration in direction of the taper. The variation of taper is outside the limits specified of 0.0002" for taper and concentricity, but it was not found possible to maintain these limits using conventional abrasives on this machine. It is concluded that a stiffer wheel mounting system than that employed could produce beneficial results for the bore profile and possibly produce more consistent results with regard to taper.

In all cases the efficiency of the wheels used has been enchanced by increasing wheelspeed. The nature of the increase is generally of a linear nature. There is no apparent tailing off of the trend at the higher wheelspeed and no estimate can be made of the speed at which peak efficiency will occur. At higher speeds difficulty will however be encountered in delivering fluid to the cutting zone and this may well prove to be the limiting factor.

The overall picture with regard to the use of cubic boron nitride for internal grinding would be more promising if higher wheelspeeds together with a stiffer wheel mounting system could be applied to the task. The trend of results obtained indicates that this may well be the case.

CHAPTER 8

FUTURE WORK

The main points to emerge from this work are

that (a) the optimum operating conditions were not generally attained during testing;

(b) that higher efficiencies could possibly be achieved at higher wheelspeeds.

Both these objectives could possibly be achieved by the design of a new spindle that would enable higher wheelspeeds to be attained. The spindle should also be of a more rigid design to minimise deflections under load.

A refinement that should be incorporated in the new spindle is the incorporation of facilities for the measurement of forces. The measurement of forces during internal grinding is particularly difficult and can only realistically be carried out at the spindle. The equipment available is too cumbersome and in the case of strain gauges the noise content from slip rings would drown the signal at the operating speeds in question.

No work was carried out in this series of tests using wheels consisting of the finer grits. Work in this field would determine the lowest limits of surface finish attainable.

The effect of concentration has not been considered at this stage; if a lower concentration of grit is more economic the figures quoted for total cost would be lowered though the effect would only be marginal as wheel costs are generally much lower than labour costs.

The use of diamond was possibly too easily dismissed, it would be advantageous to assess its capabilities at higher wheelspeeds than those employed in the early tests, 17,500 RPM, where it could not compete with cubic boron nitride even under the most gentle conditions.

This work has been concerned wholly with the grinding of EN31 with cubic boron nitride, it would obviously be advantageous to compare performances with other materials generally ground such as M2, T15 and possibly nimonics.

CHAPTER 9

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Grit size	Dressing stick
80/100	WA 150 GV
100/120, 120/140	WA 220 GV
140/170, 170/200	WA 320 GV
230/270	WA 500 GV

TABLE 1

Selection Table for abrasive sticks to condition cubic boron nitride wheels.

Abrasive	Material	Infeed	No. of Passes	Surface Appearance Degree of Burn	Depth of Damage (visual)	Hardness R_C Depth Below Surface					
						0.0005	0.001	0.0015	0.002	0.003	Parent Metal
ALOX	M2	0.003"	5	Light	0.0003"	55	58	61	63	65	66
CBN		0.003"	5	Light	-	63	64	66	66	66	66
ALOX		0.003"	15	Light	0.0017"	55	62	64	63	65	66
CBN		0.003"	15	Medium	-	63	64	65	66	66	66
ALOX		0.003"	35	Light	0.002"	55	60	64	65	65	66
CBN		0.003"	35	Dark	-	64	64	66	66	66	66
ALOX	M42	0.003"	5	Medium	0.002"	62	66	66	64	65	66
CBN		0.003"	5	Light	-	66	66	66	66	66	66
ALOX		0.003"	15	Medium	0.004	56	60	65	66	66	66
CBN		0.003"	15	Light	-	66	67	66	66	66	66
ALOX	T15	0.001"	15	Dark	0.001"	54	64	67	67	67	67
CBN		0.001"	15	Light	-	64	66	67	67	67	67
ALOX		0.002"	5	Dark	0.002"	54	58	62	65	66	67
CBN		0.002"	5	Light	0.0001"	64	66	67	67	67	67

Wheel used for test: ALOX - A60 JV
CBN - 80/100 grit 100 concentration resin bond

Test pieces ¼" x ¾" x 1" M2, M42, T15

Test conditions Wheelspeed 4000 SFPM Tablespeed 6 FT/MIN
Infeed see above Time between grinds - 5 secs.

TABLE 2 Extent of Sub Surface Damage

Material	Hardness	Wheel used		
		Al Oxide	CBN	RVG-W
M-2	R_C 60	4.5	1030	85
M-4	R_C 60	2.0	180	95
M-50	R_C 60		250	150
T-4	R_C 65		360	105
T-15	R_C 64	0.8	120	100
O-1	R_C 62	50	750	135
A-2	R_C 62	20	390	210
D-2	R_C 62	3.0	650	1000
D-3	R_C 60		190	1700
S-5	R_C 57		1140	300
P-20	R_C 49		485	240
L-6	R_C 58	90	295	218
Grey Cast iron	R_A 32		2700*	9600*
Nodular cast iron	R_A 57		870	910

Grinding conditions:	Wheelspeed	5,500 SFPM
	Table speed	50 FPM
	Cross feed	0.050
	Downfeed	0.001"/pass (*0.002)
	Coolant	Sol oil water (1:50) 1 GPM
	Wheel spec	
	Wheel spec	5" x $\frac{3}{16}$" x $1\frac{1}{4}$", $\frac{1}{8}$" RIM 25 VP or 100 C

TABLE 3

Abrasive Performance on Various Workpieces

Material	Soluble oils				Sulpho-Chlorinated Oil
	Light duty		Heavy Duty		
	2%	5%	2%	5%	
410 Stainless Steel	60	130	790	1360	2350
Iconel 718	35	-	130	270	450
AISI 52100 (EN31)	550	1800	3690	3900	5500
M50	110	180	760	950	4000
AISI 4340	200	-	2760	4470	-

TABLE 4

Grinding Ratios obtained with combinations of work materials and grinding fluids using cubic boron nitride wheels.

Setting	Infeed (Ins)	
	Rough Grind	Finish Grind
1	0.0001	0.00002
2	0.00025	0.00004
3	0.0004	0.00008
4	0.0006	0.00012
5	0.0008	0.00016
6	0.0011	0.00018

TABLE 5

Grinding Machine Feeds

Setting	Magnification	Chart full scale		CLA index full scale	
		Imperial μ in	Metric microns	Imperial μ in	Metric microns
1	1000	2000	50	200	5.0
2	2000	1000	25	100	2.5
3	5000	400	10	40	1.0
4	10,000	200	5	20	0.5
5	20,000	100	2.5	10	0.25
6	50,000	40	1	4	0.1

TABLE 6

Talysurf 3 Range of magnifications and Scales

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

TABLE 7

Talysurf 3 Meter cut offs and stroke lengths

Spindle R.P.M	No. of Undulations			
	Normal	Filter		
		A	B	C
3	1-450	1-45	1-15	15-450
9	1-150	1-15	1-5	5-150

TABLE 8

Talyrond filters and No. of Undulations Recorded

Test No.	Wheel	Material	Wheel speed R.P.M. (SFPM)	Work speed R.P.M. (SFPM)	Infeed In.	Traverse Rate Ft./min.	Metal Removal Rate $In^3/min.$	Grinding Ratio	Surface finish μ in CLA	Degree of taper in.	Out of Roundness μ in.
5	85 CBN II R 100 BZ10	EN 31	17,500 (5,600)	170 (70)	0.0001	7.0	0.04	310	30	0.0017"L	145
6					0.00025	7.0	0.10	82	54	0.001"L	213
7					0.0001	4.5	0.024	5880	35	0.0025"L	220
8					0.0001	9.0	0.06	820	37	0.0012"S	260

TABLE NO.

Test No.	Wheel	Material	Wheel speed R.P.M. (SFPM)	Work speed R.P.M. (SFPM)	Infeed In.	Traverse Rate Ft./min.	Metal Removal Rate $In^3/min.$	Grinding Ratio	Surface finish μ in CLA	Degree of taper in.	Out of Roundness μ in.
19	120/140 CBN II R 100 BZ10	EN 31	16,500 (4,800)	170 (63)	0.0001	4.5	0.0183	270	18	0.0013"S	0.00005
20			25,400 (7,300)	170 (64)	0.0001	4.5	0.0186	630	14	0.0016"S	0.000025
22			(9,800) 35,000	170 (68)	0.0001	4.5	0.0194	2630	14	0.0002"L	0.000032
23			16,500 (4700)	170 (70)	0.0001	6.75	0.0294	106	28	0.0003"L	
24			25,400 (7,100)	170 (71)	0.0001	6.75	0.0297	350	15	0.0014"L	0.000023
35			35,000 (10,400)	170 (80)	0.0001	6.75	0.0339	2270	22	0.0003"S	0.000070
38			35,000 (10,300)	350 (137)	0.0001	6.75	0.0284	1180	20	0.0001"L	0.000038

TABLE 10

Test No.	Wheel	Material	Wheel speed R.P.M. (SFPM)	Work speed R.P.M. (SFPM)	Infeed In.	Traverse Rate Ft./min.	Metal Removal Rate In^3/min.	Grinding Ratio	Surface finish µ in CLA	Degree of taper in.	Out of Roundness µ in.
27	120/140 CBN II R100 BZ10	EN 31	16,500 (5170)	170 (73)	0.00025	3.5	0.042	328	32	0.0006 S	0.000076
28			25,400 (8000)	170 (74)	0.00025	3.5	0.042	627	24	0.0003 S	0.000046
32			35,000 (10,850)	170 (79)	0.00025	3.5	0.042	683	23	0.0006 S	0.000075
29			25,400 (7,850)	170 (75)	0.00025	4.5	0.053	599	28	0.0008 S	0.000080
36			35,000 (10,600)	170 (82)	0.00025	4.5	0.058	603	30	0	0.000075
33			35,000 (10,800)	350 (160)	0.00025	3.5	0.042	1200	28	0.0003 L	0.000075
37			35,000 (10,600)	350 (160)	0.00025	4.5	0.047	1167	30	0.0019 L	0.000065

TABLE 11

Test No.	Wheel	Material	Wheel speed R.P.M. (SFPM)	Work speed R.P.M. (SFPM)	Infeed In.	Traverse Rate Ft./min.	Metal Removal Rate In^3/min.	Grinding Ratio	Surface finish μ in CLA	Degree of taper in.	Out of Roundness μ in.
59	170 CBN II R 100 BZ10	EN 31	16,500 (5,000)	170 (69)	0.0001	4.5	0.02	335	25	0.0002 L	0.000061
44			25,400 (8,000)	170 (76)	0.0001	4.5	0.02	731	14	0	0.000045
67			35,000 (10,600)	170 (77)	0.0001	4.5	0.022	1794	16	0.001 L	0.000040
60			16,500 (5,000)	340 (141)	0.0001	4.5	0.02	473	21	0.0002 L	0.000052
74			25,400 (7,650)	315 (151)	0.0001	4.5	0.023	1181	20	0.00065L	0.000055
68			35,000 (10,600)	320 (145)	0.0001	4.5	0.022	1943	14	0.0007 L	0.000027
-											
63			35,000 (10,590)	340 (145)	0.0001	6.75	0.031	1077	15	0.0024 L	0.000040
45			25,400 (8,000)	170 (76)	0.0001	6.75	0.033	518	23	0.0006 S	0.000060
69			35,000 (10,570)	170 (78)	0.0001	6.75	0.033	1826	20	0.0002 L	0.000045
47			25,400 (7,900)	170 (77)	0.0001	9.0	0.049	81	36	0.0002 S	-

TABLE 12a

Test No.	Wheel	Material	Wheel speed R.P.M. (SFPM)	Work speed R.P.M. (SFPM)	Infeed In.	Traverse Rate Ft./min.	Metal Removal Rate $In^3/min.$	Grinding Ratio	Surface finish μ in CLA	Degree of taper in.	Out of Roundness μ in.
72	170 CBN II R 100 BZ10	EN 31	35,000 (10,530)	315 (148)	0.0001	9.0	0.051	418	25	0.0005 L	0.000065

TABLE 12b

Test No.	Wheel	Material	Wheel speed R.P.M. (SFPM)	Work speed R.P.M. (SFPM)	Infeed In.	Traverse Rate Ft./min.	Metal Removal Rate In^3/min.	Grinding Ratio	Surface finish μ in CLA	Degree of taper in.	Out of Roundness μ in.
55	170 CBN II R100 BZ10	EN 31	31,200 (9,630)	350 (137)	0.00016	4.5	0.033	851	17	0	0.000050
64			35,000 (10,590)	330 (143)	0.00016	4.5	0.033	1012	20	0.0015 L	0.000045
70			35,000 (10,560	320 (148)	0.00016	6.75	0.053	451	28	0.0002 S	0.000060
48			31,200 (9,680)	170 (78)	0.00016	3.5	0.029	754	18	0.0001 S	0.000045
66			35,000 (10,580)	170 (76)	0.00016	3.5	0.028	1262	19	0.001 L	0.000040
73			31,200 (9,380)	315 (149)	0.00016	3.5	0.028	638	22	0.0007 L	0.000063
57			(35,000) (10,770)	350 (139)	0.00016	3.5	0.028	1354	18	0.0004 S	0.000043
65			35,000 (10,580)	330 (145)	0.00025	3.5	0.043	2097	19	0.002 L	0.000039

TABLE 13

Test No.	Wheel	Material	Wheel speed R.P.M. (SFPM)	Work speed R.P.M. (SFPM)	Infeed In.	Traverse Rate Ft./min.	Metal Removal Rate $In^3/min.$	Grinding Ratio	Surface finish μ in CLA	Degree of taper in.	Out of Roundness μ in.
	50 DXDA -MC	EN31	17,500 (5,600)	170 (70)	0.0001	4.5	0.02	14	16	-	-
	100 DXDA -MC	EN31	17,500 (5,600)	170 (70)	0.0001	4.5	0.020	25	13	-	-
	100 DXDA -MC	EN31	17,500 (5,600)	170 (70)	0.0001	6.5	0.031	60	20	-	-

TABLE 14

Test No.	Wheel	Material	Wheelspeed R.P.M. (SFPM)	Metal Removal Rate in^3/min	Grinding Ratio	Labour Cost $	Wheel Cost $	Total Cost $
	7" φ 1A1 230/270 Metal coated diamond 75 Concentration	Tungsten carbide		0.02	470	10.00	0.87	10.87
				0.03	389	6.67	1.05	7.72
				0.04	379	5.00	1.08	6.08
				0.04	330	5.00	1.24	6.24
				0.06	353	3.33	1.16	4.49
				0.06	206	3.33	1.99	5.32
				0.08	172	2.50	2.38	4.88
				0.09	154	2.22	2.66	4.88
				0.12	70	1.67	5.86	7.53

TABLE 15

Test No.	Wheel	Material	Wheelspeed R.P.M. (SFPM)	Metal Removal Rate in^3/min	Grinding Ratio	Labour Cost $	Wheel Cost $	Total Cost $
5	85 CBN II - R - 100 - BZ10	EN 31	17,500 (5,600)	0.04	310	5.00	1.32	6.32
6			17,500 (5,600)	0.10	82	2.00	5.00	7.00
7			17,500 (5,600)	0.024	5880	8.40	0.07	8.47
8			17,500 (5,600)	0.06	820	3.33	0.50	3.83

TABLE 16

Test No.	Wheel	Material	Wheelspeed R.P.M. (SFPM)	Metal Removal Rate in^3/min	Grinding Ratio	Labour Cost $	Wheel Cost $	Total Cost $
27	120/140 CBN-II-R - 100 - BZ10	EN 31	16,500 (5,170)	0.042	328	4.76	1.25	6.01
23			16,500 (4,700)	0.0294	106	6.80	3.87	10.67
19			16,500 (4,800)	0.0183	270	11.11	1.52	12.63
20	120/140 CBN II R100 - BZ10	EN 31	25,400	0.0186	630	11.11	0.65	11.76
24			25,400	0.0297	350	6.73	1.17	7.90
28			25,400	0.042	627	4.76	0.65	5.41
29			25,400	0.053	599	3.77	0.68	4.45

TABLE 17

Test No.	Wheel	Material	Wheelspeed R.P.M. (SFPM)	Metal Removal Rate in^3/min	Grinding Ratio	Labour Cost $	Wheel Cost $	Total Cost $
22/34	120/140 CBN II R100 BZ10	EN 31	35,000 (9,800)	0.0194	2630	10.31	0.16	10.47
35			35,000 (10,400)	0.0339	2270	5.90	0.18	6.08
38			35,000 (10,300)	0.0284	1180	7.04	0.35	7.39
32			35,000 (10,850)	0.042	683	4.76	0.60	5.36
33			35,000 (10,800)	0.042	1200	4.76	0.34	5.10
36			35,000 (10,600)	0.058	603	3.45	0.68	4.13
37			35,000 (10,600)	0.047	1167	4.26	0.35	4.61

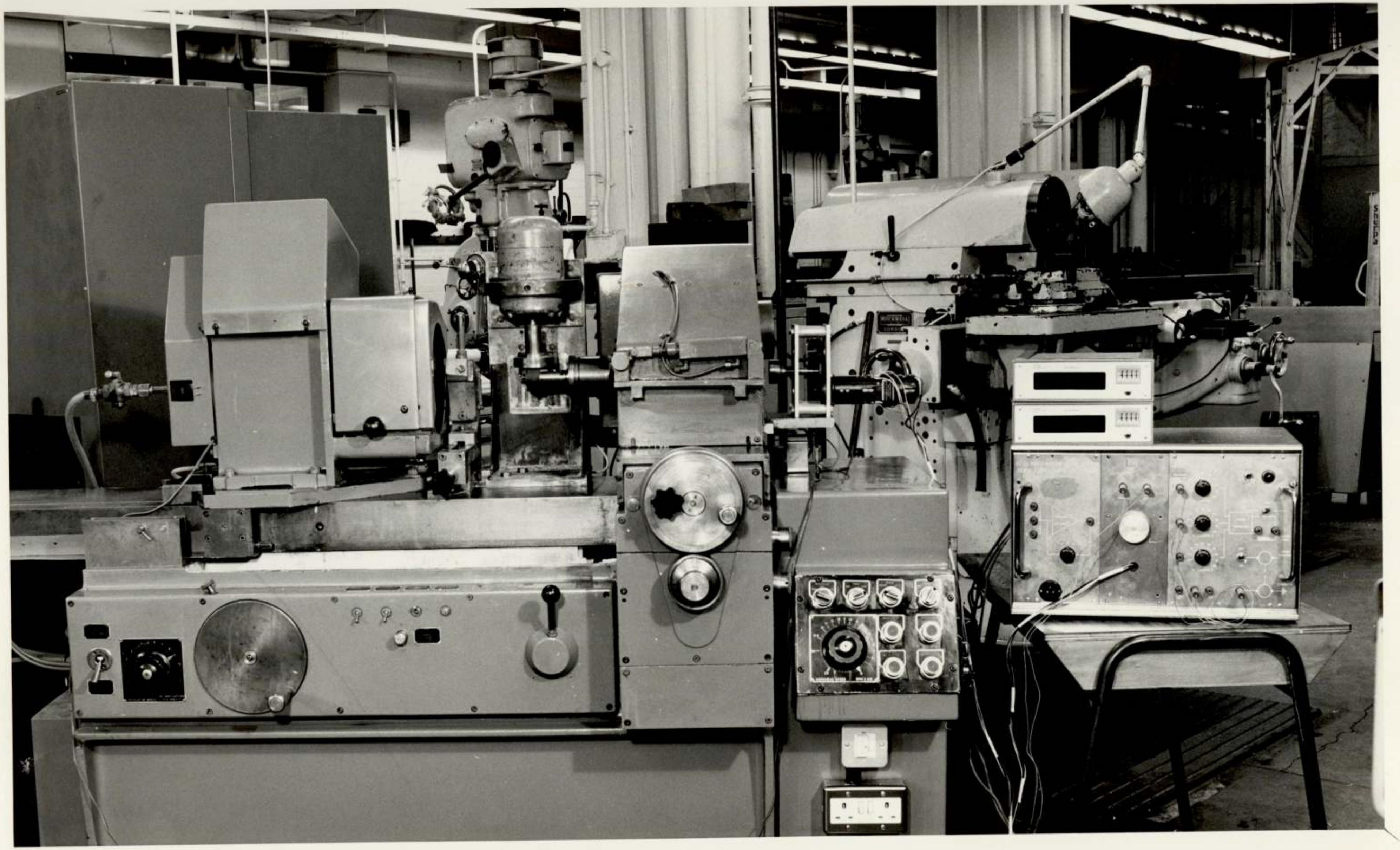
TABLE 18

Test No.	Wheel	Material	Wheelspeed R.P.M. (SFPM)	Metal Removal Rate in^3/min	Grinding Ratio	Labour Cost $	Wheel Cost $	Total Cost $
			25,400 (8,100)	0.018	730	11.11	0.56	11.67
44	170 CBN II R 100 BZ10		25,400 (8,000)	0.020	731	10.0	0.56	10.56
74			25,400 (7,650)	0.023	1181	8.70	0.35	9.05
45		EN 31	25,400 (8,000)	0.033	518	6.06	0.79	6.85
			25,400 (8,100)	0.036	520	5.56	0.79	6.35
47			25,400 (7,900)	0.05	81	4.00	5.06	9.06

TABLE 19

Test No.	Wheel	Material	Wheelspeed R.P.M. (SFPM)	Metal Removal Rate in^3/min	Grinding Ratio	Labour Cost $	Wheel Cost $	Total Cost $
67	170 CBN II R 100 BZ10	EN 31	(10,600)	0.022	1794	9.09	0.23	9.32
68			(10,600)	0.022	1943	9.09	0.21	9.30
66			(10,580)	0.028	1262	7.14	0.33	7.47
57			(10,770)	0.028	1354	7.14	0.30	7.44
63			(10,590)	0.031	1077	6.45	0.38	6.83
69			(10,570)	0.033	1826	6.06	0.23	6.29
64			(10,590)	0.034	1012	5.88	0.41	6.29
65			(10,580)	0.043	2097	4.65	0.20	4.85
70			(10,560)	0.053	451	3.77	0.91	4.68
72			(10,530)	0.057	418	3.51	0.98	4.49

TABLE 20



The Grinding Machine

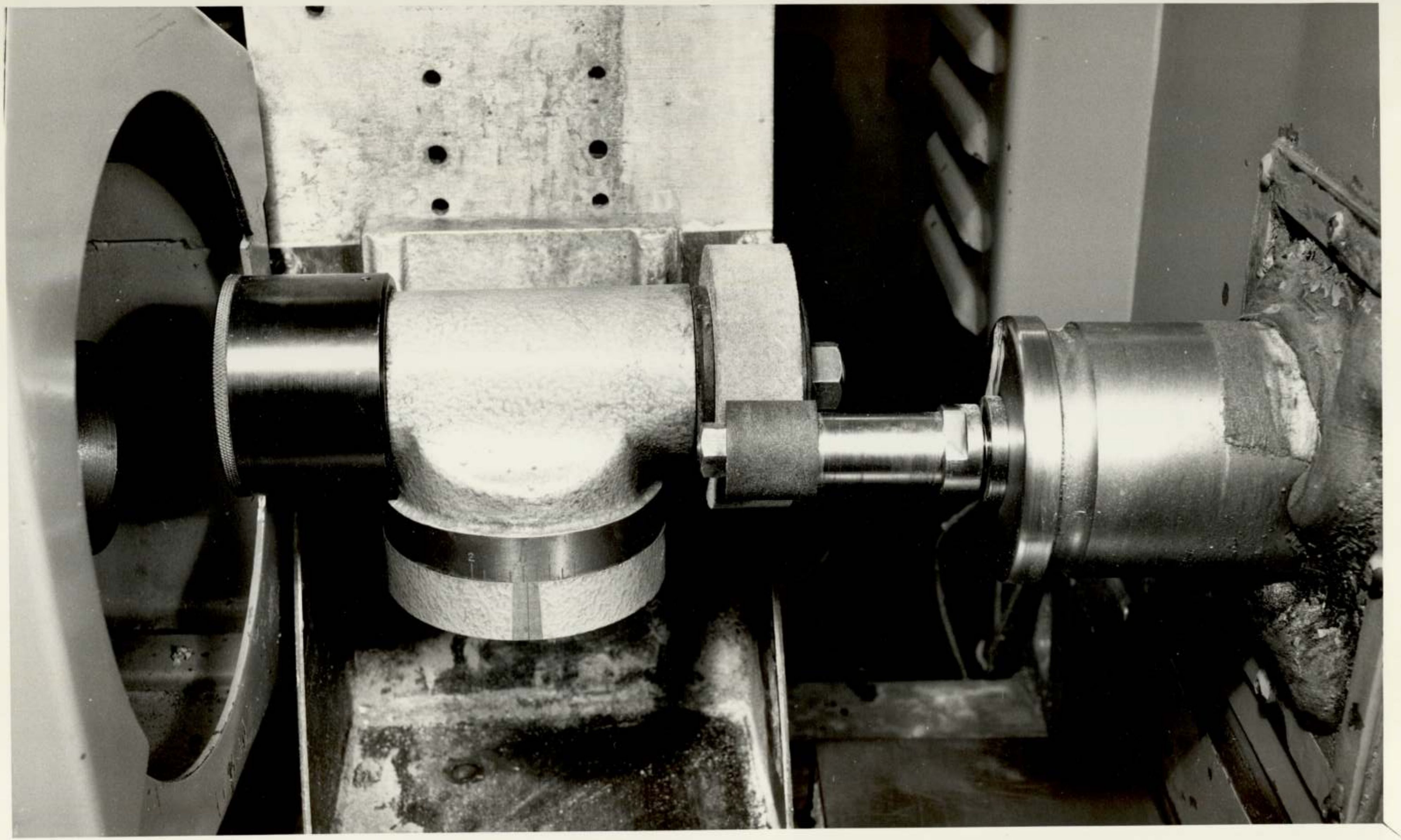
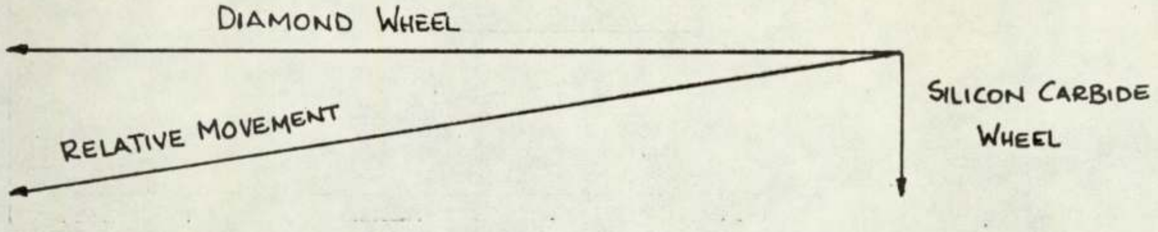
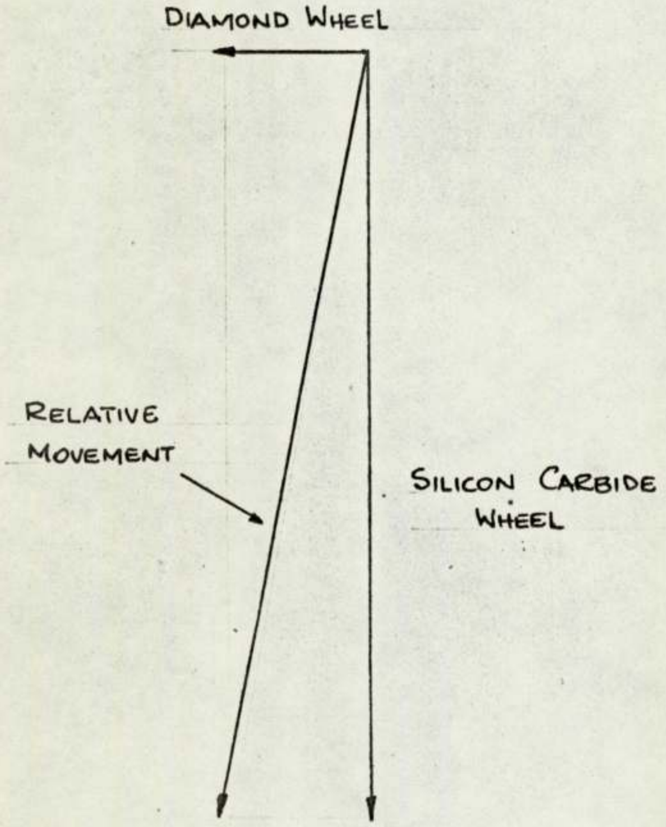


FIG.1



DIAMOND WHEEL RUNNING AT NORMAL SPEED



DIAMOND WHEEL RUNNING AT SLOW SPEED

FIG.2 SPEED GRAPHS FOR DRESSING PROCESS (12)

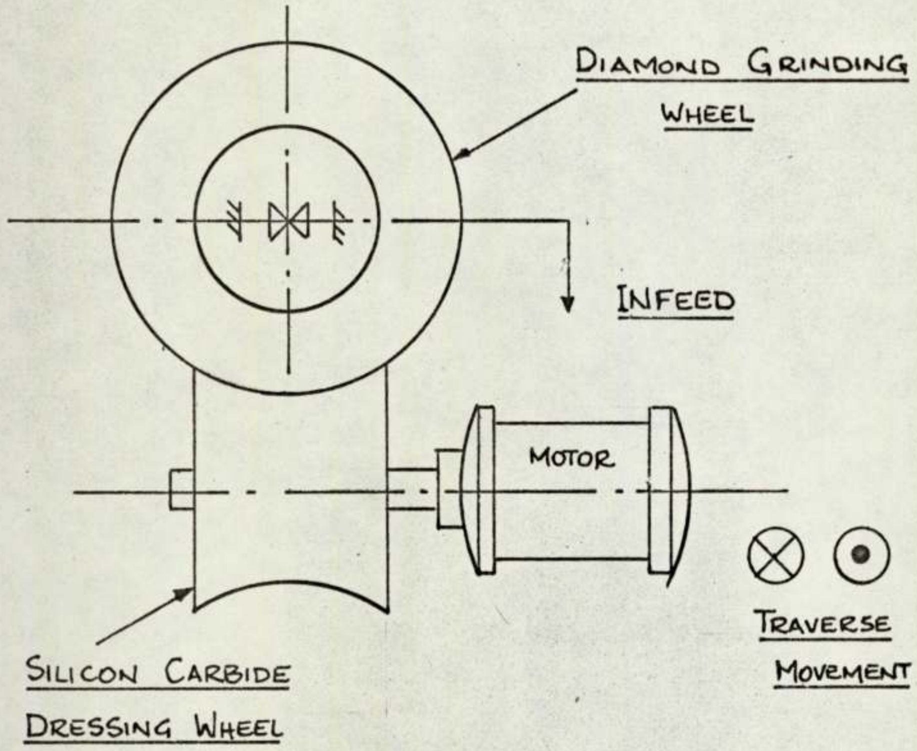


FIG.3 SCHEMATIC ARRANGEMENT OF DRESSING PROCESS (12)

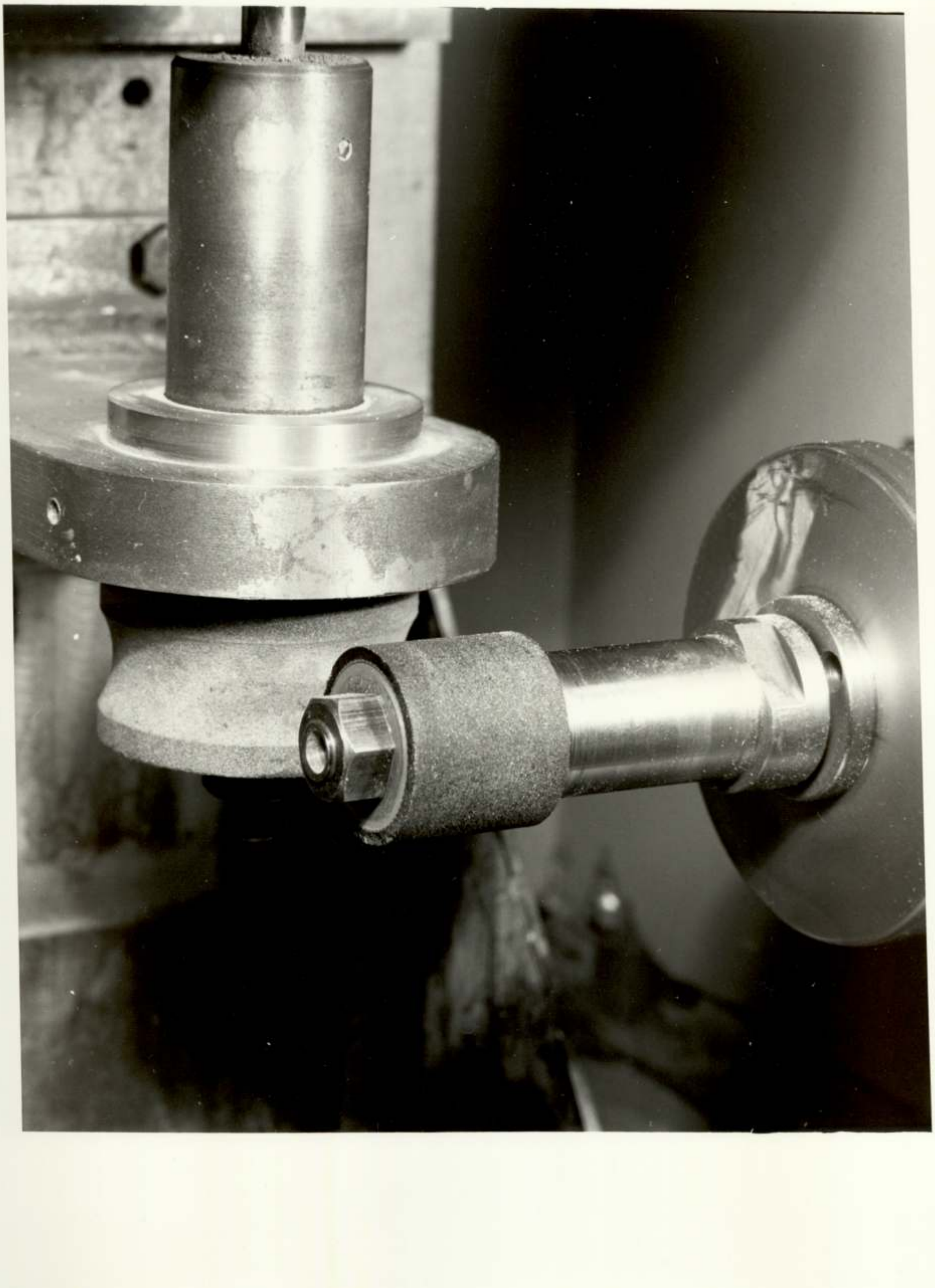


Fig. 4

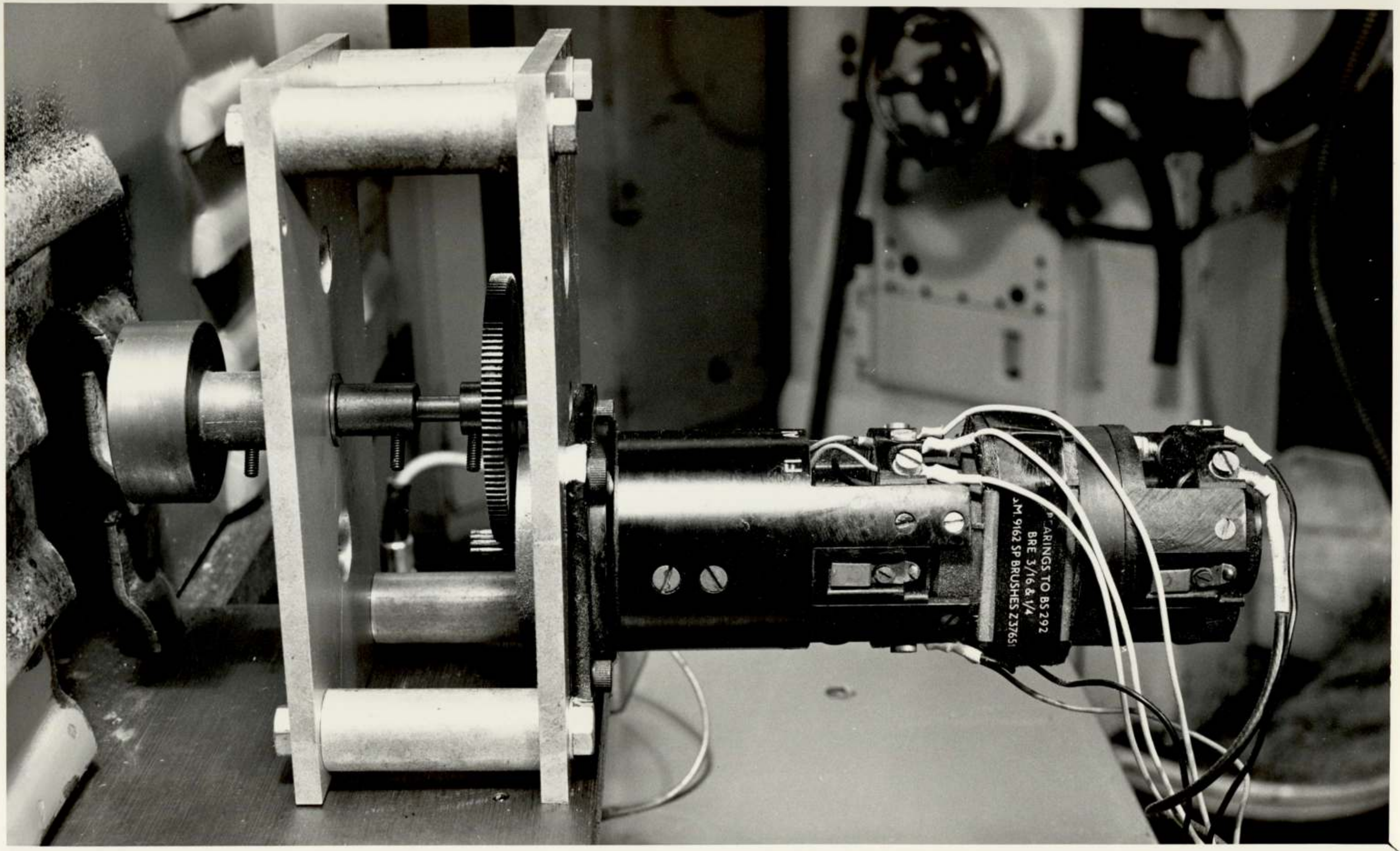


FIG. 5

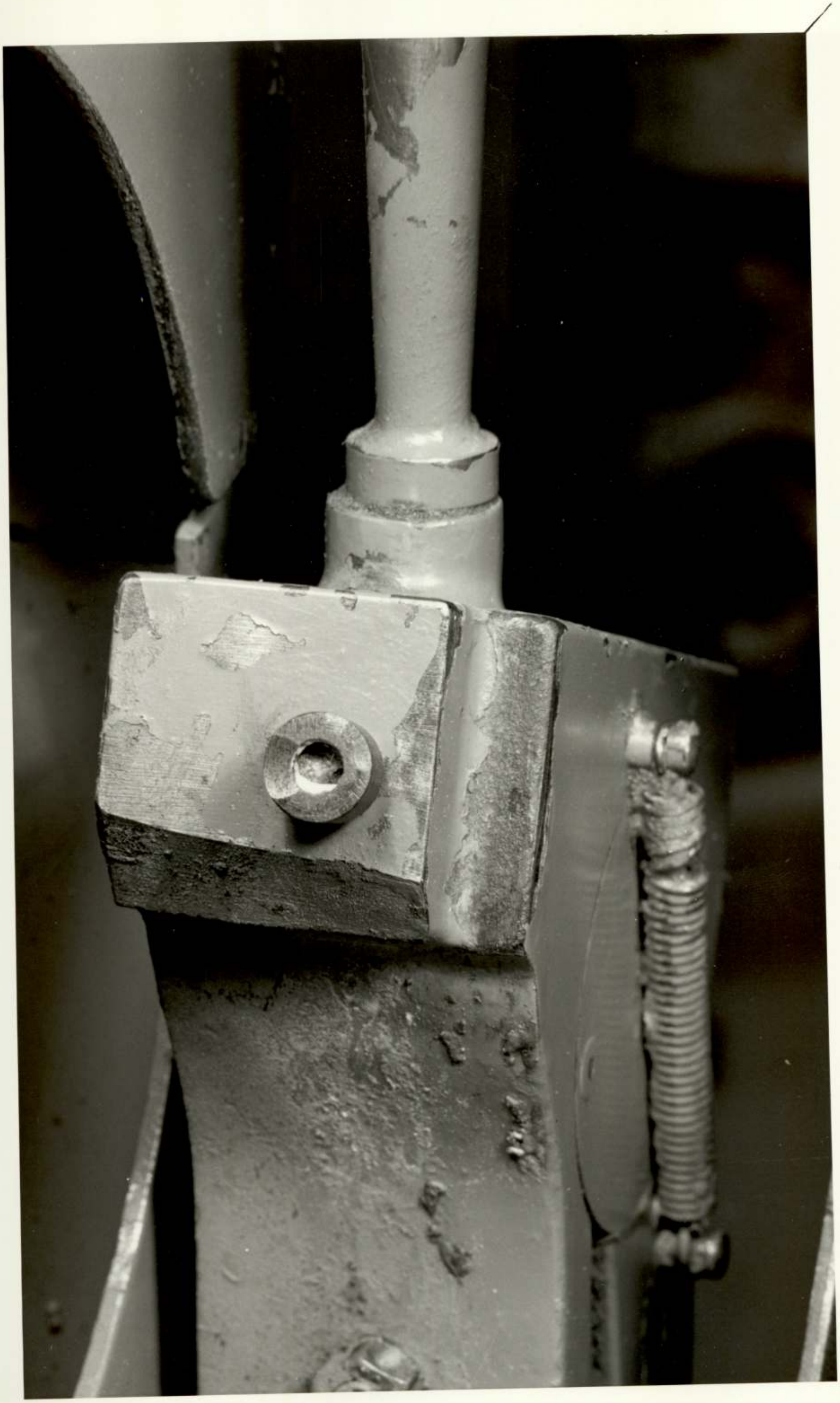


Fig. **6**

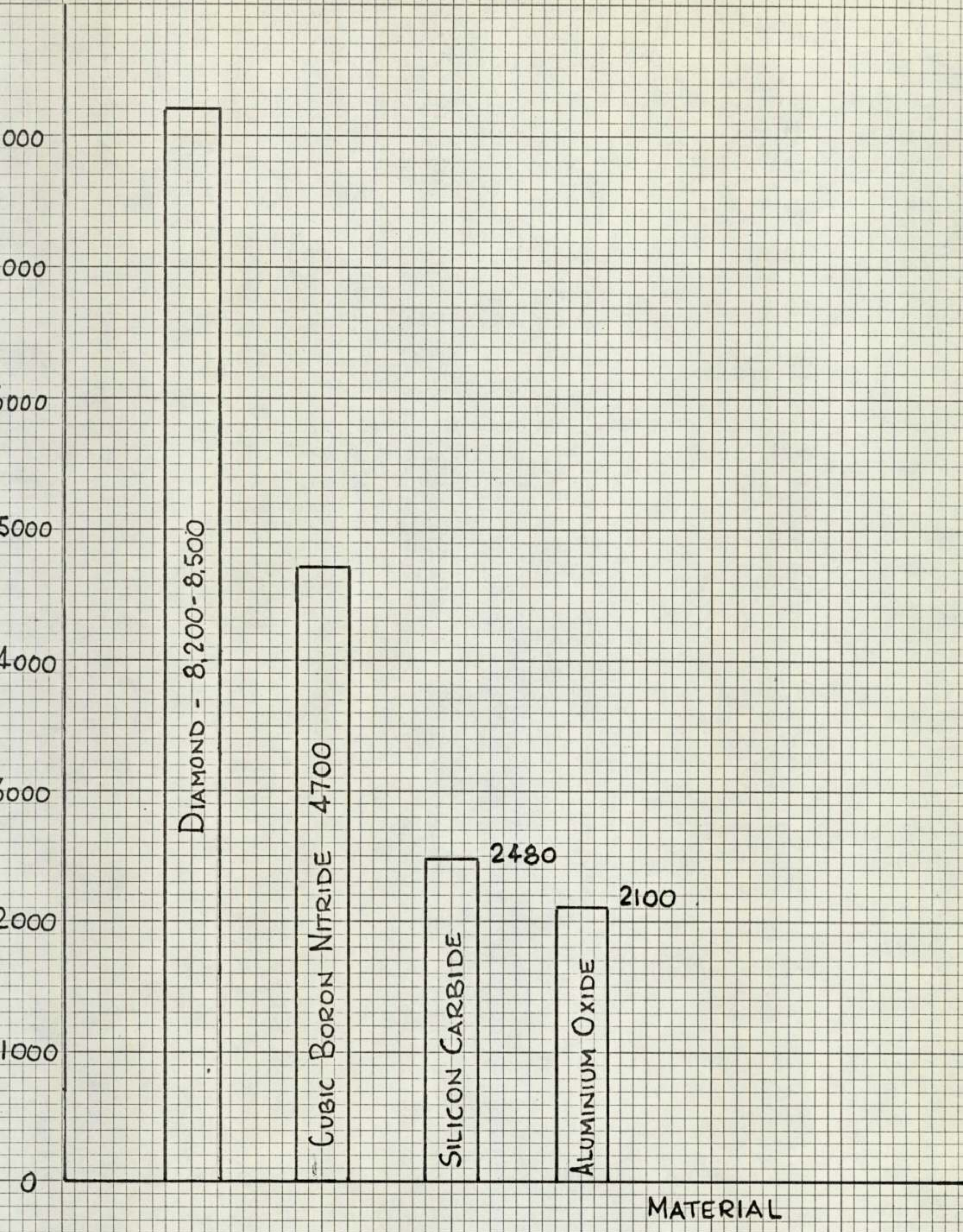


FIG.7 HARDNESS OF ABRASIVE GRAINS

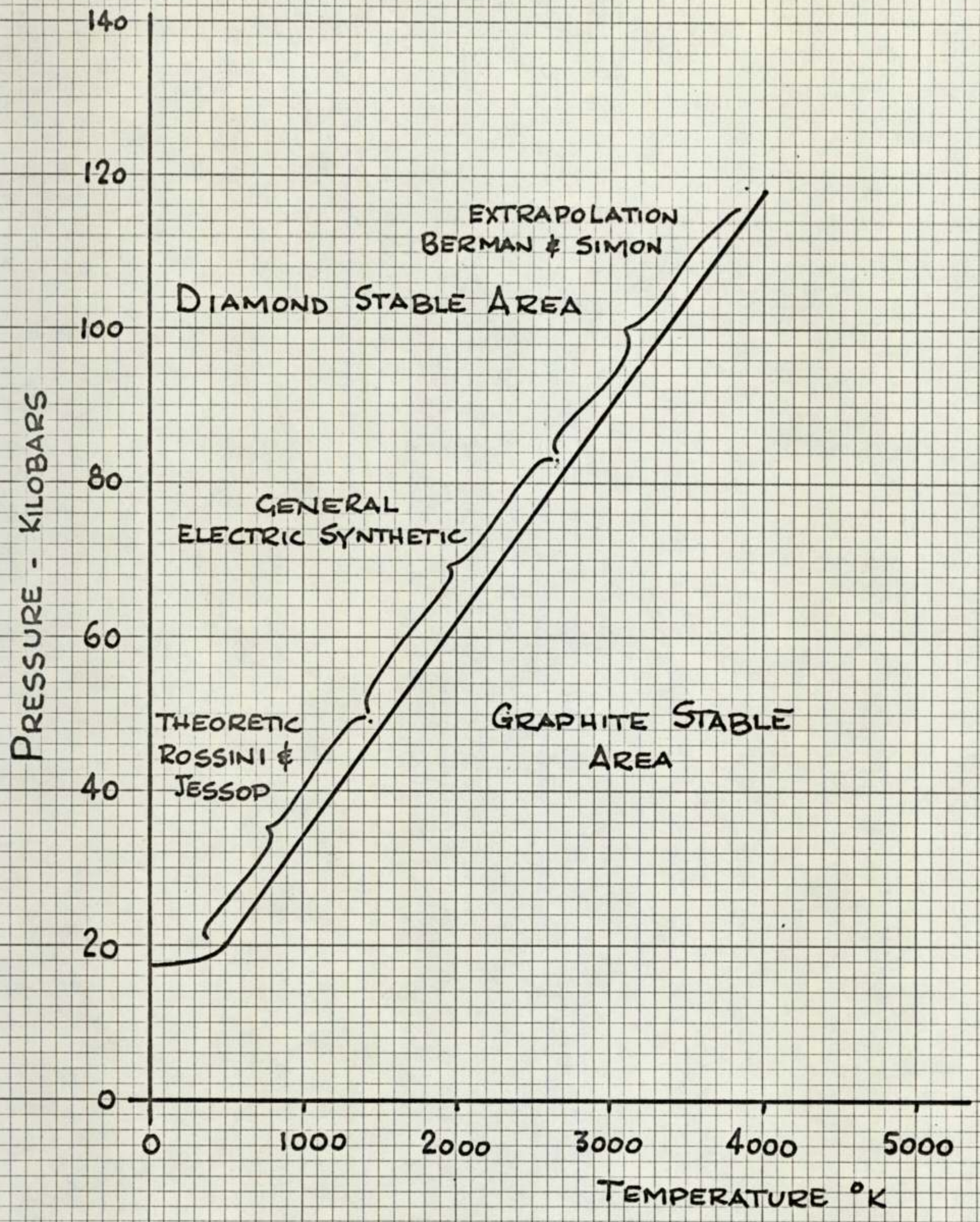


FIG. 8 GRAPHITE/DIAMOND PHASE DIAGRAM

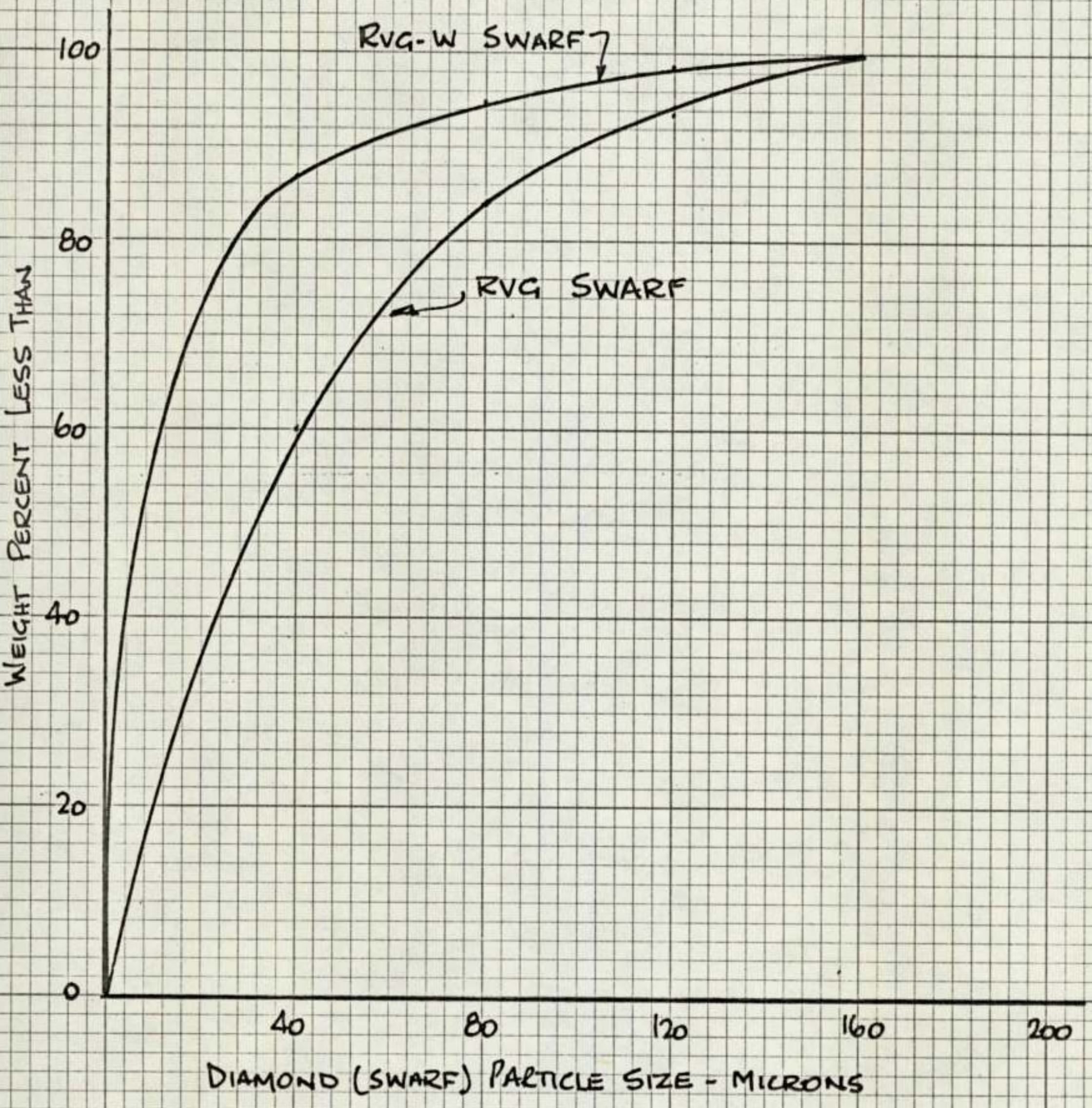


Fig 9 Diamond Swarf Analysis (5)

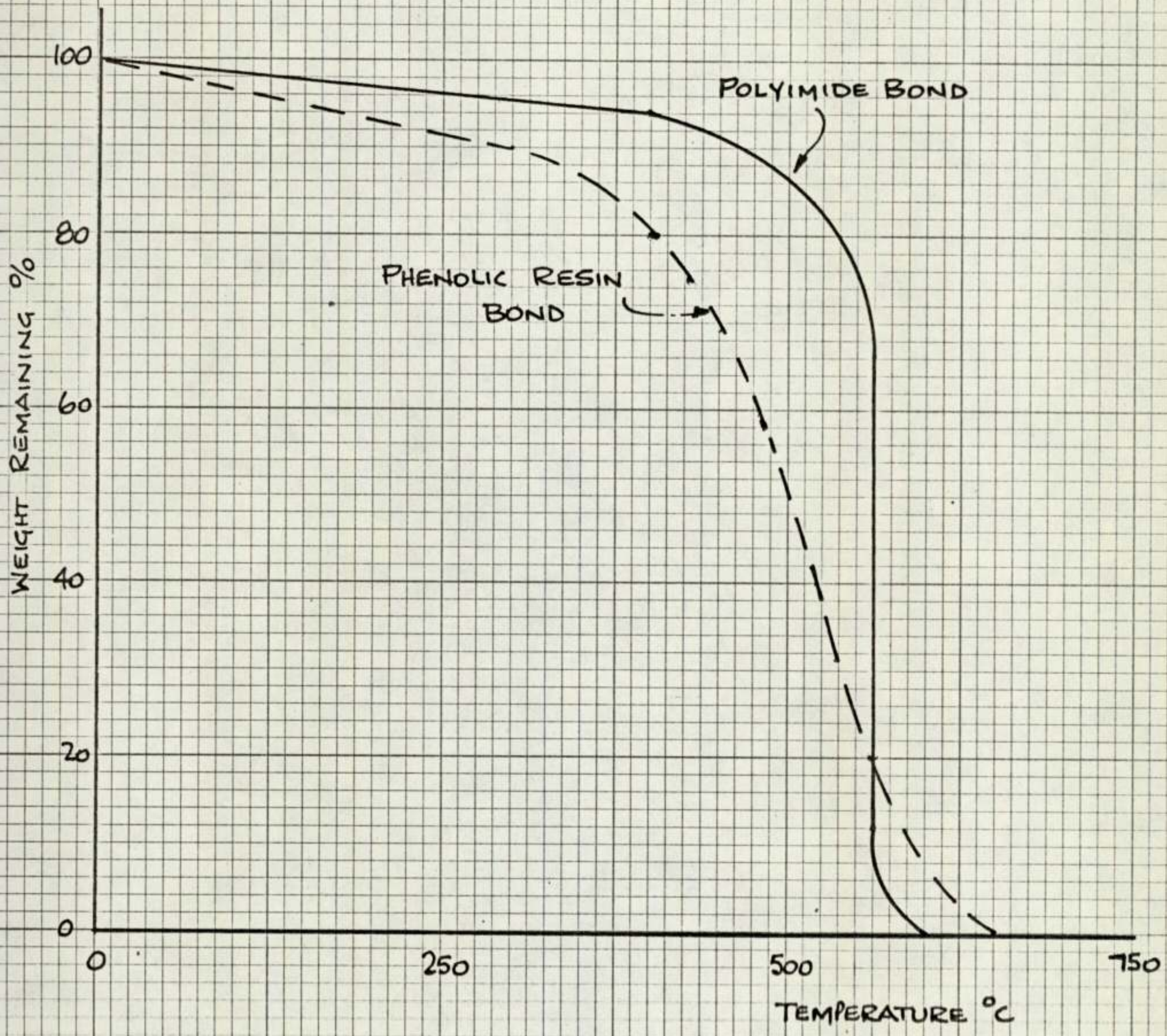


Fig10 Thermograph of Phenolic Resin and Polyimide Bonds (7)

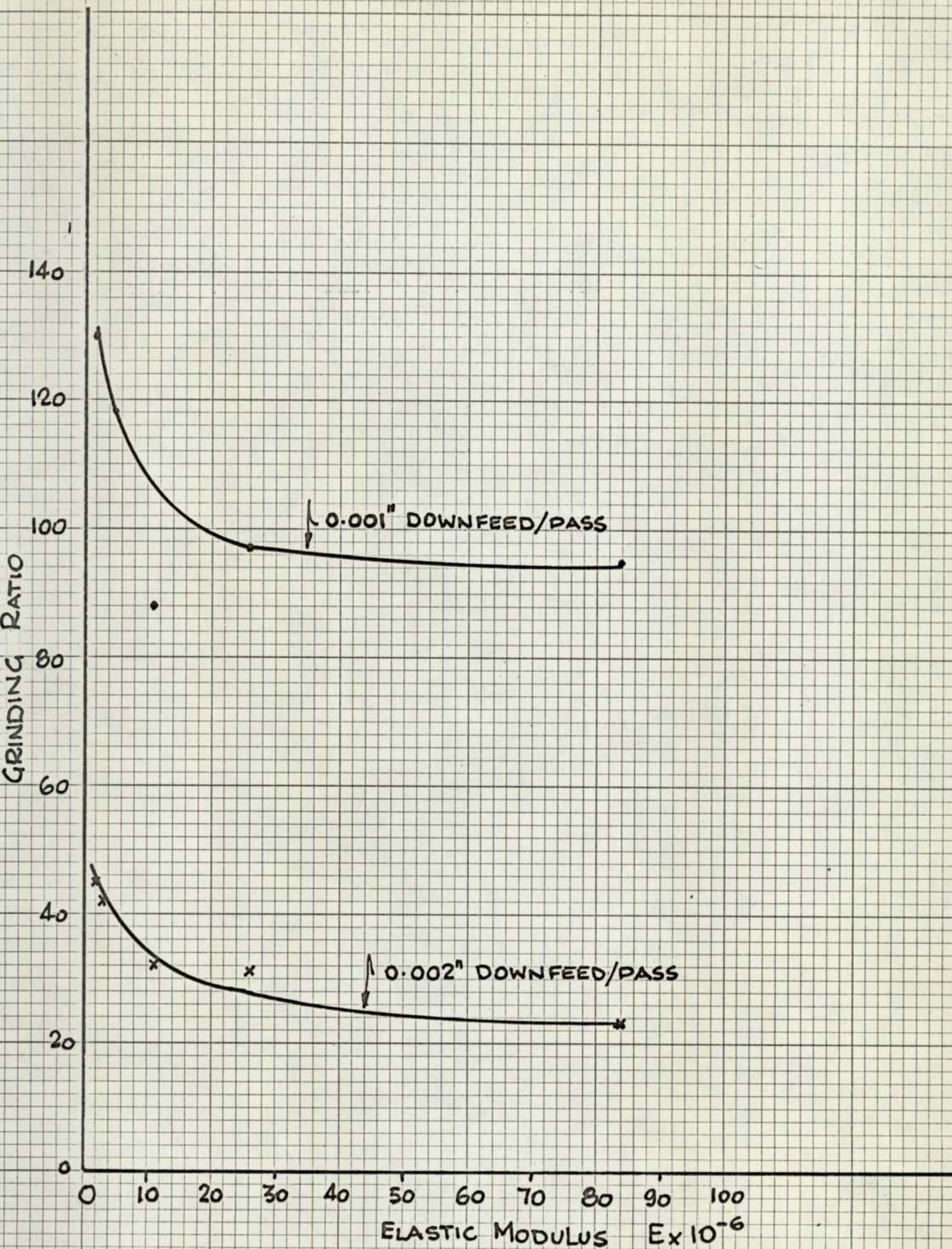
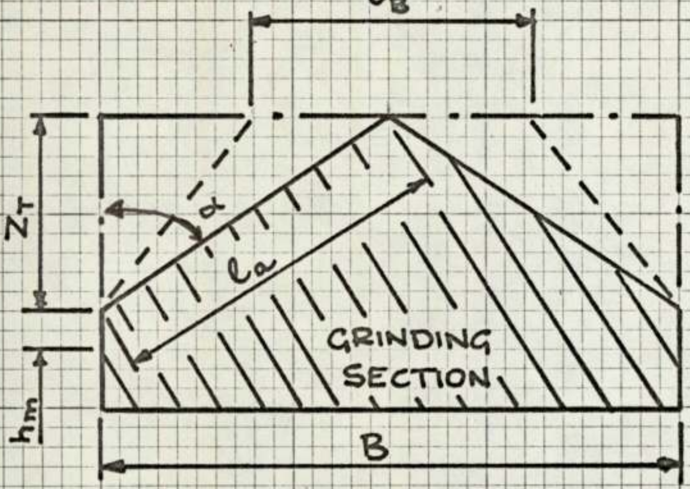


FIG. 11 AFFECT OF HUB MATERIAL ON GRINDING RATIOS (8)

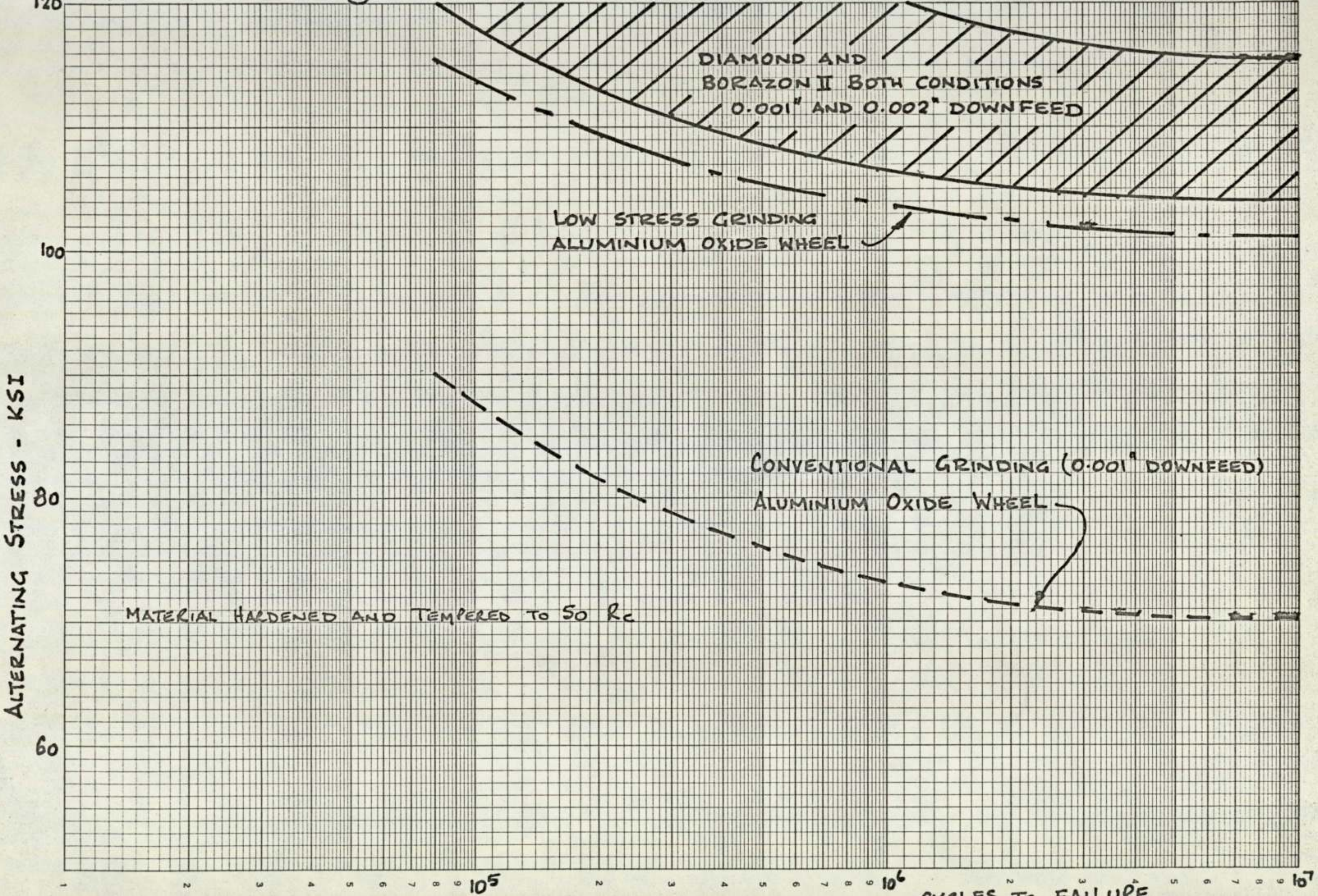


B = WIDTH OF GRINDING SECTION
h_m = AVERAGE WEAR DEPTH
l_a = LENGTH OF WEAR FLATS
l_B = LENGTH OF CENTRE PLANE WEAR FLAT
Z_T = INFEED
α = ANGLE OF WEAR EDGES

FIG.12 FORMATION OF GRINDING SECTION PROFILE (14)

FIG. 13

FIG. 14 Fatigue Characteristics of AISI 4340 (17)



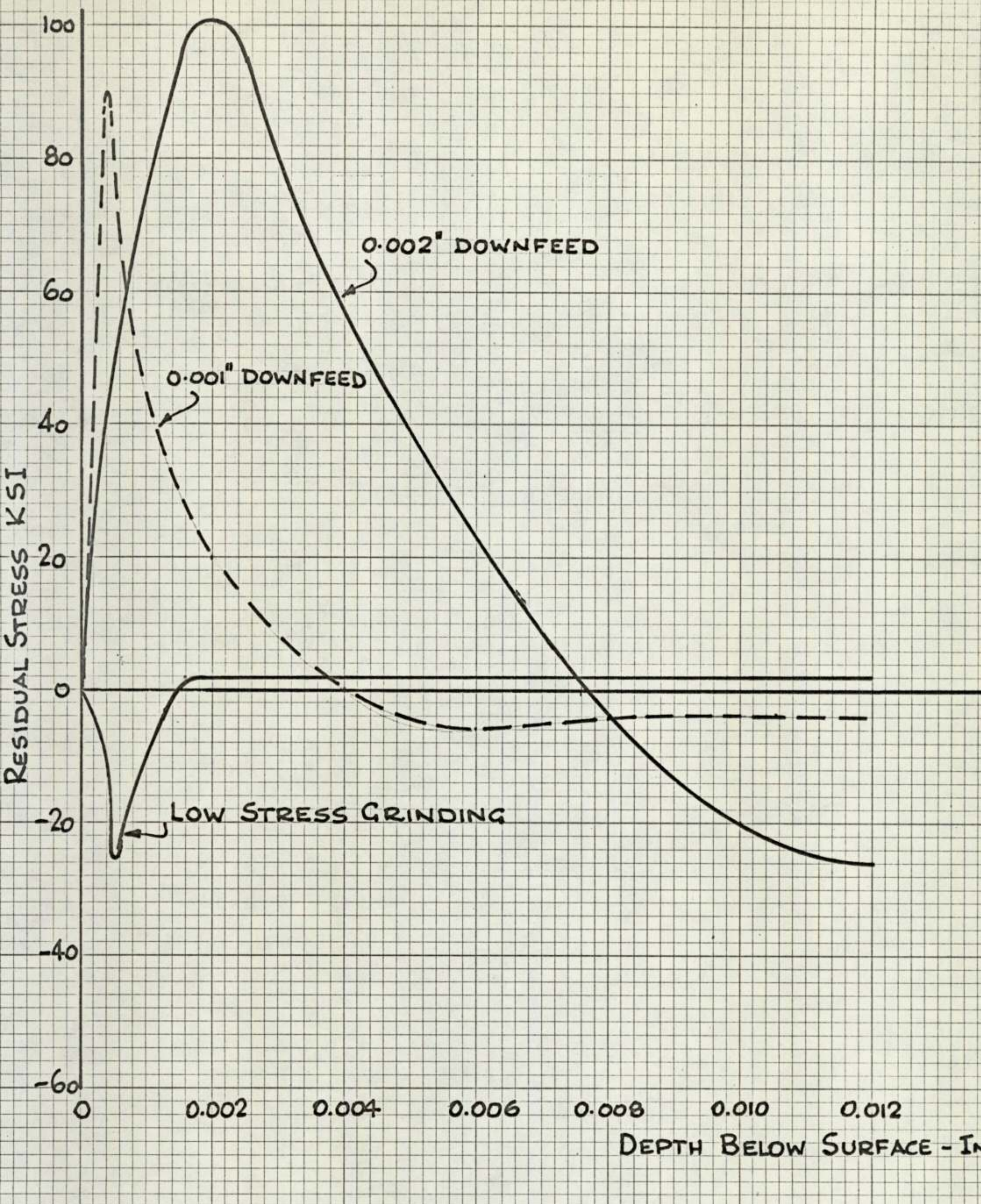


FIG.15 Residual Stress in AISI 4340 with Aluminium Oxide Wheel

(17)

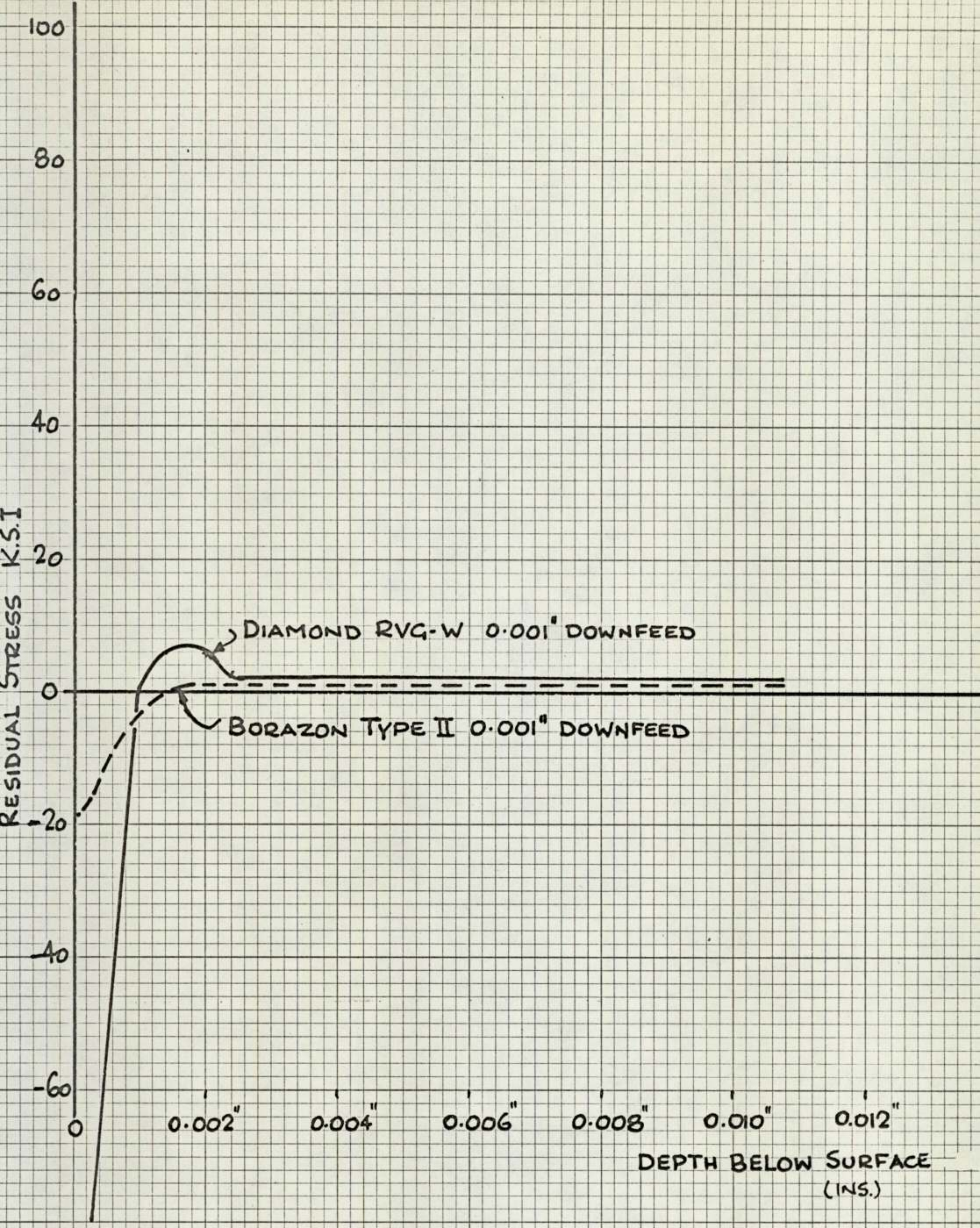


FIG.16 Residual Stress in AISI 4340 with HP-HT Wheels (17)

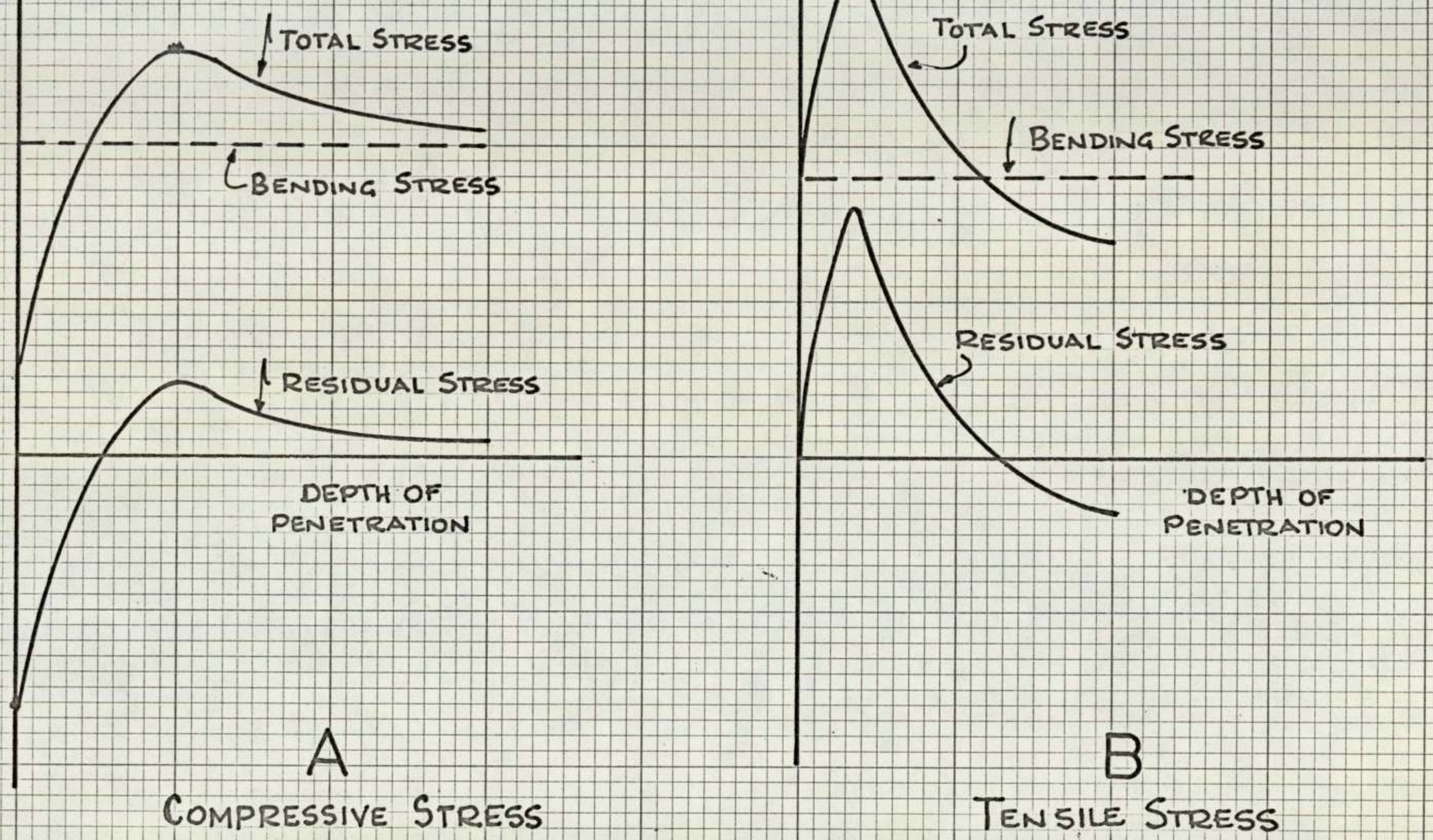


FIG.17 The Effect of Residual Stress on the Effective Stress in Bending (18)

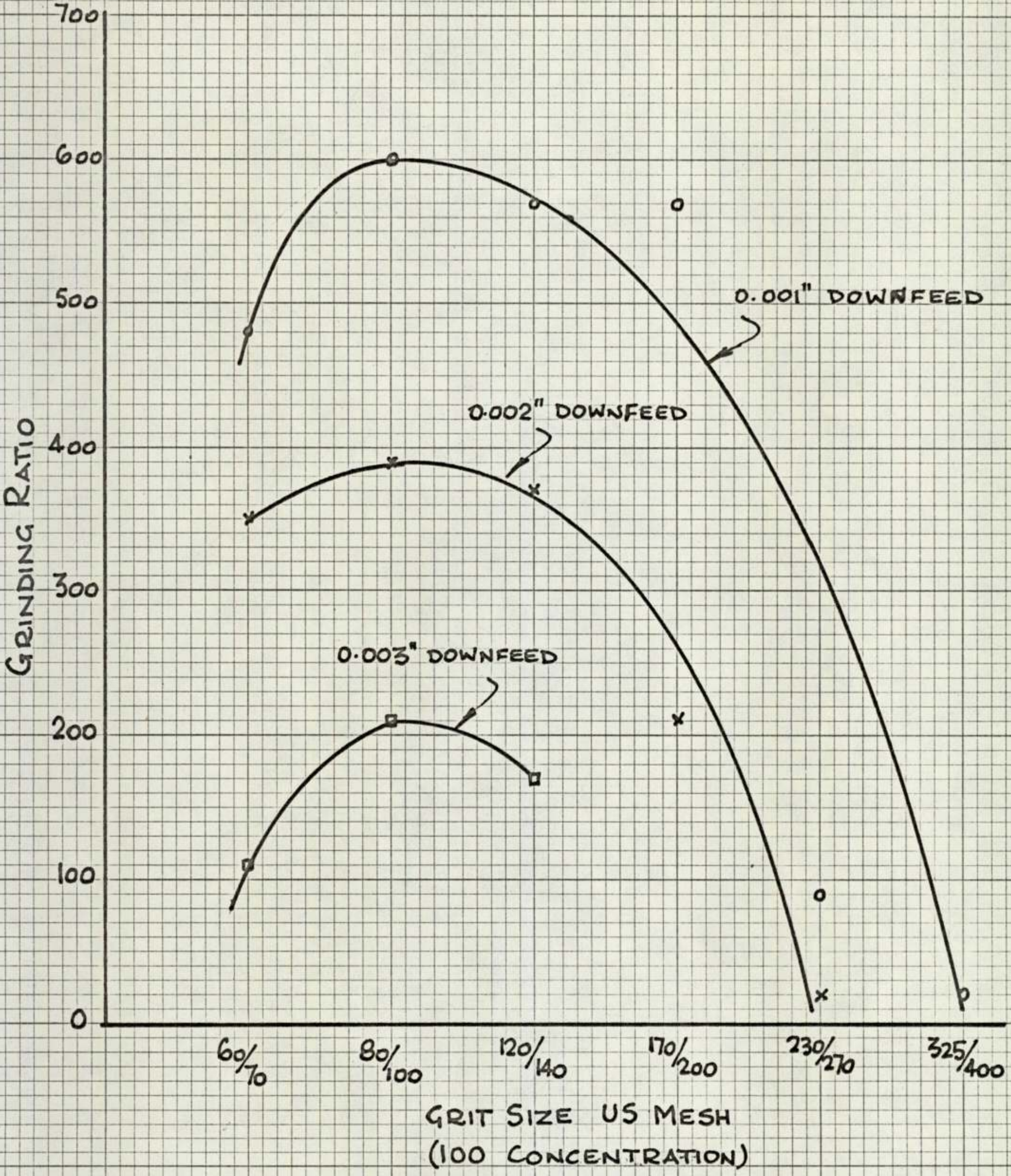


FIG.18 The Effect of Grit Size on Grinding Ratio (13)

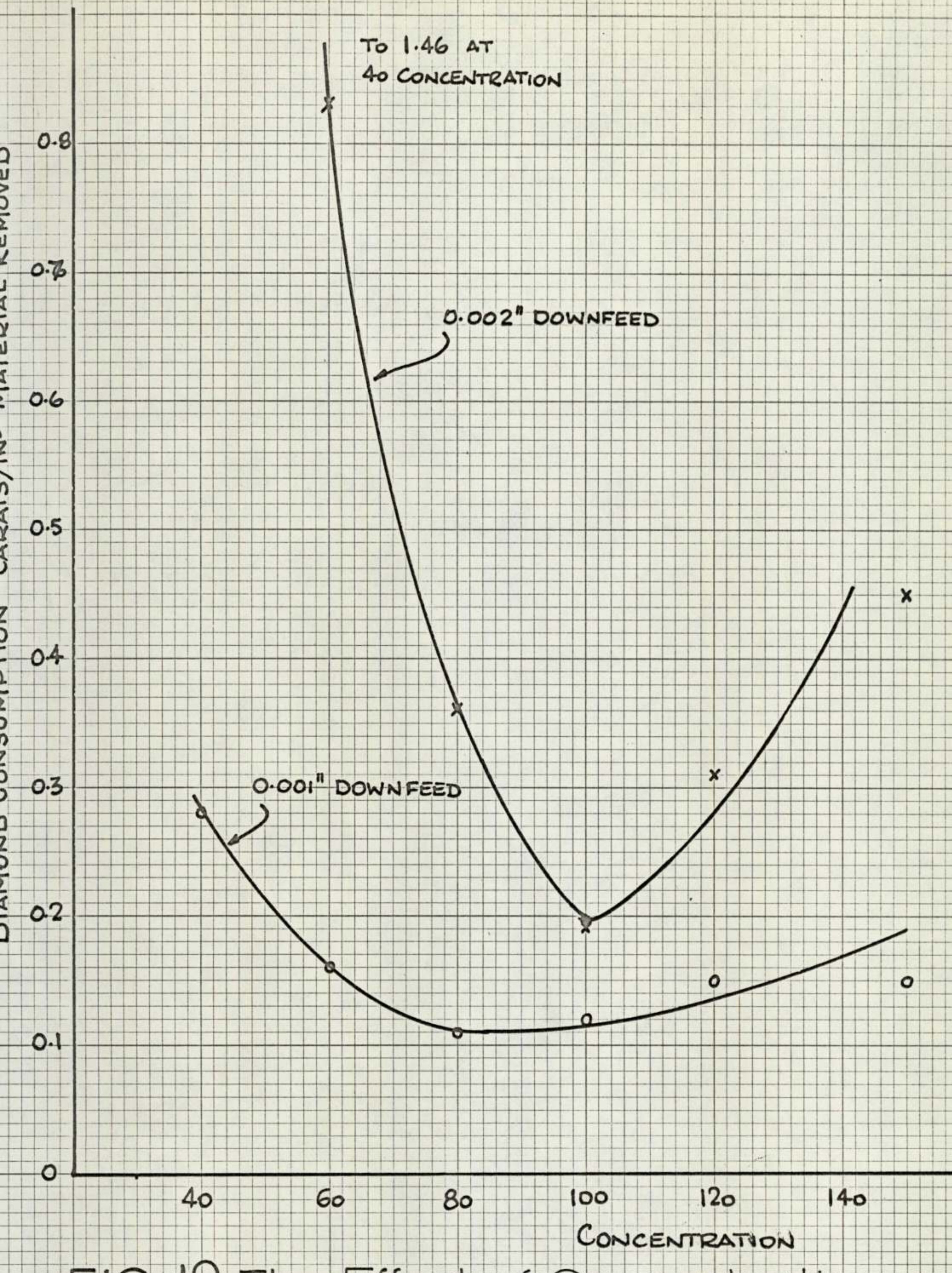


FIG.19 The Effect of Concentration on Diamond Consumption (13)

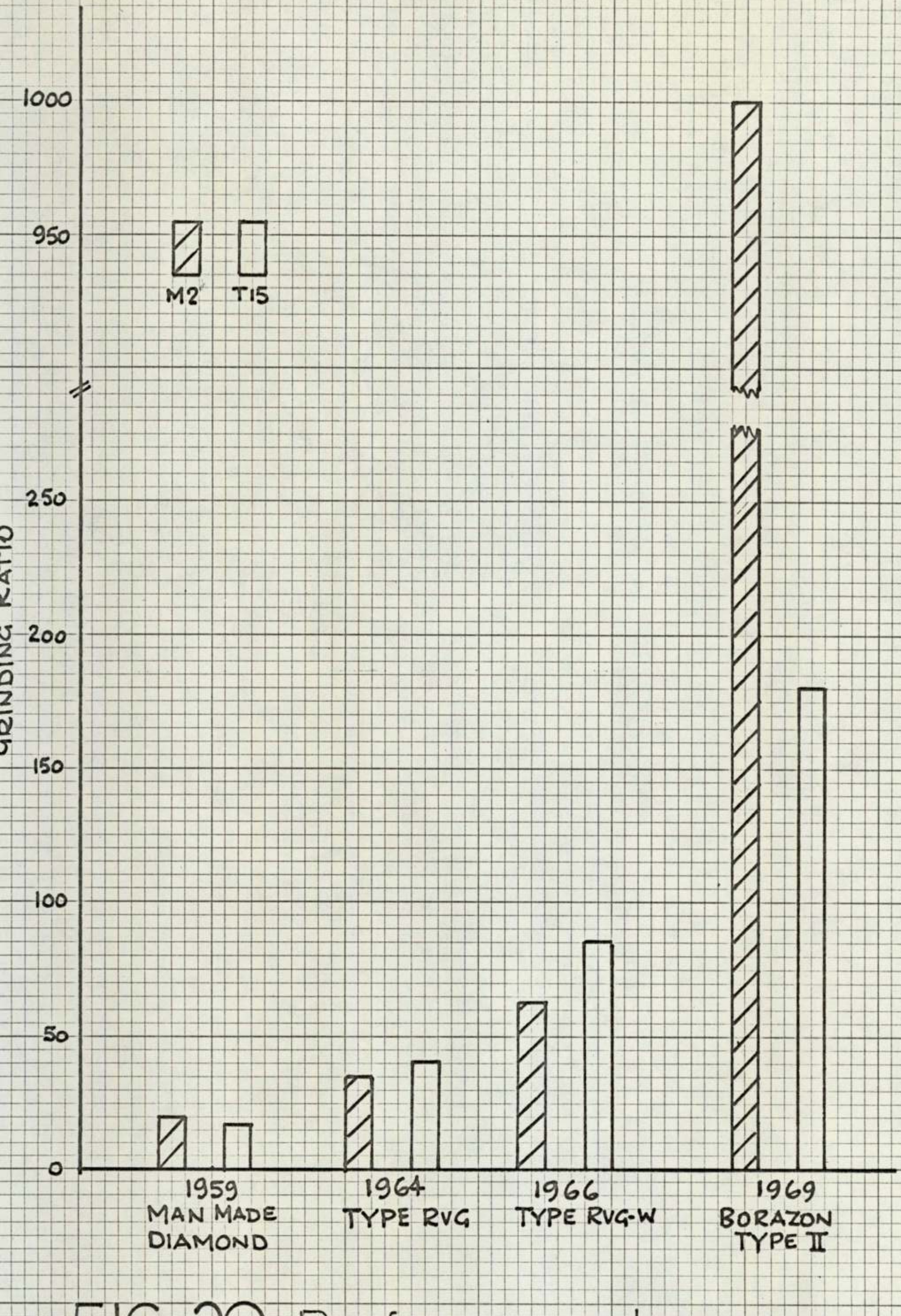


FIG. 20 Performance Improvement of HP-HT Abrasives on Hardened Tool Steels (22)

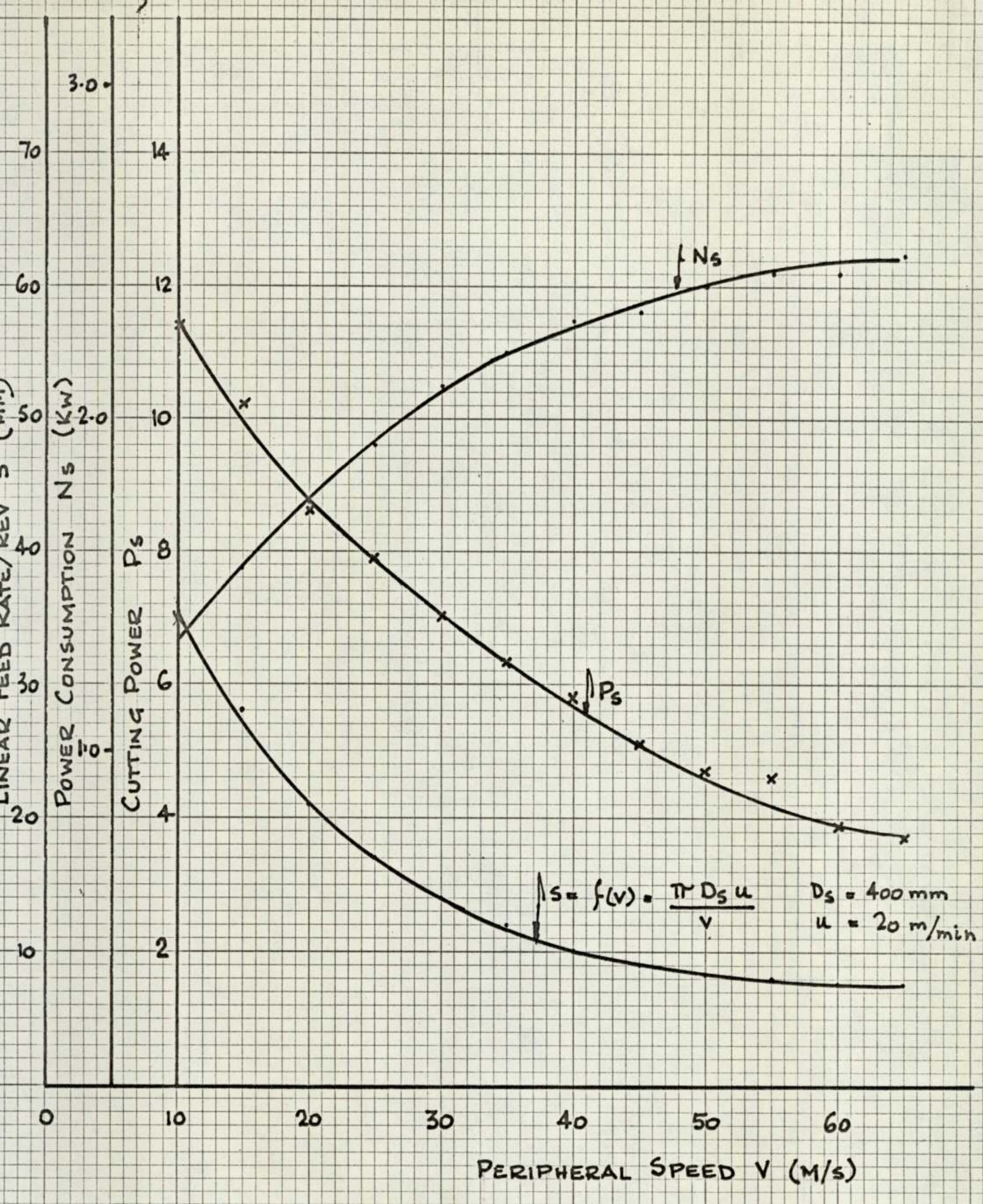


FIG.21 Feed Rate/Rev, Power Consumption and Cutting Power in relation to Wheel Speed (23)

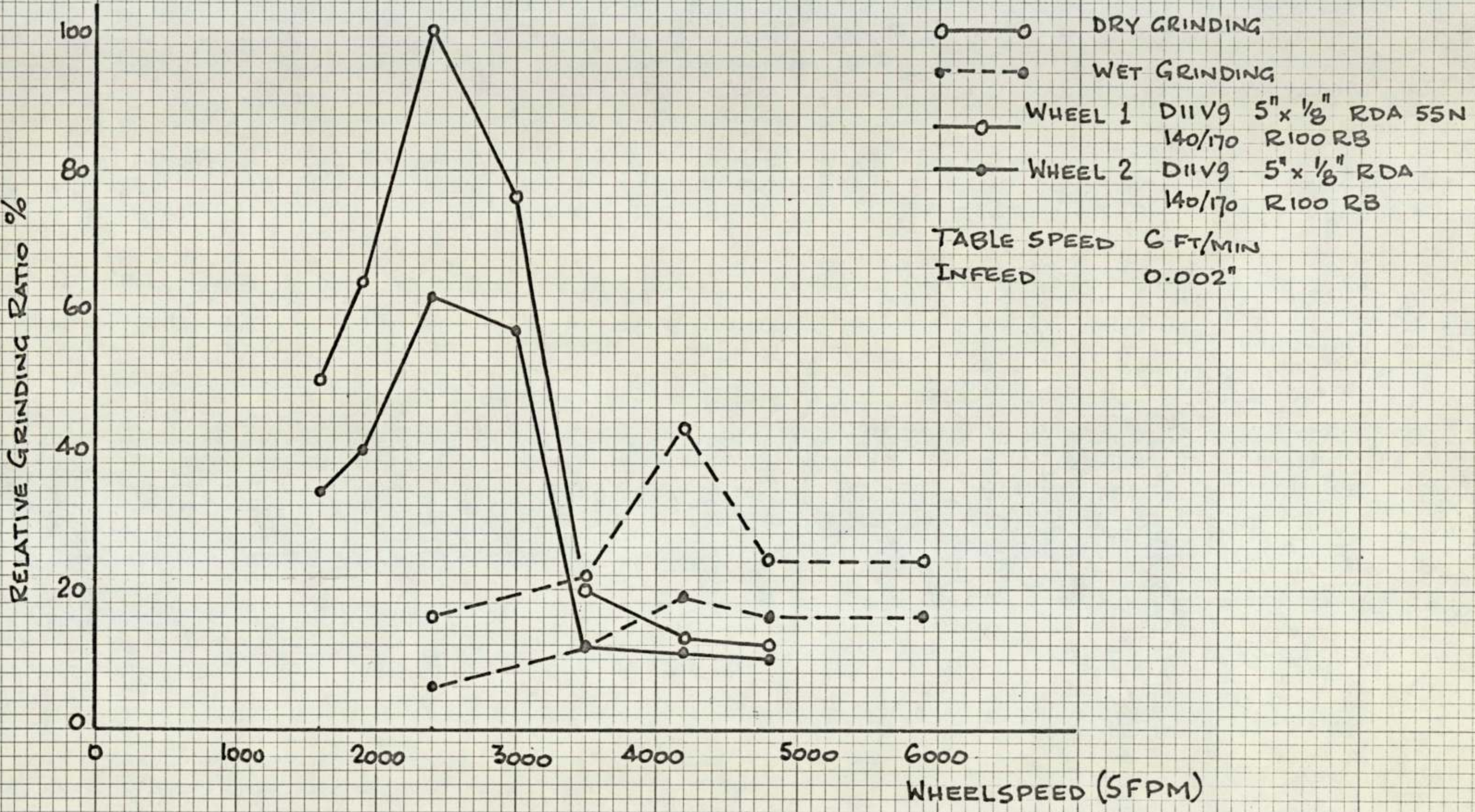


FIG.22 The Grinding Ratio in relation to Wheel Speed (26)

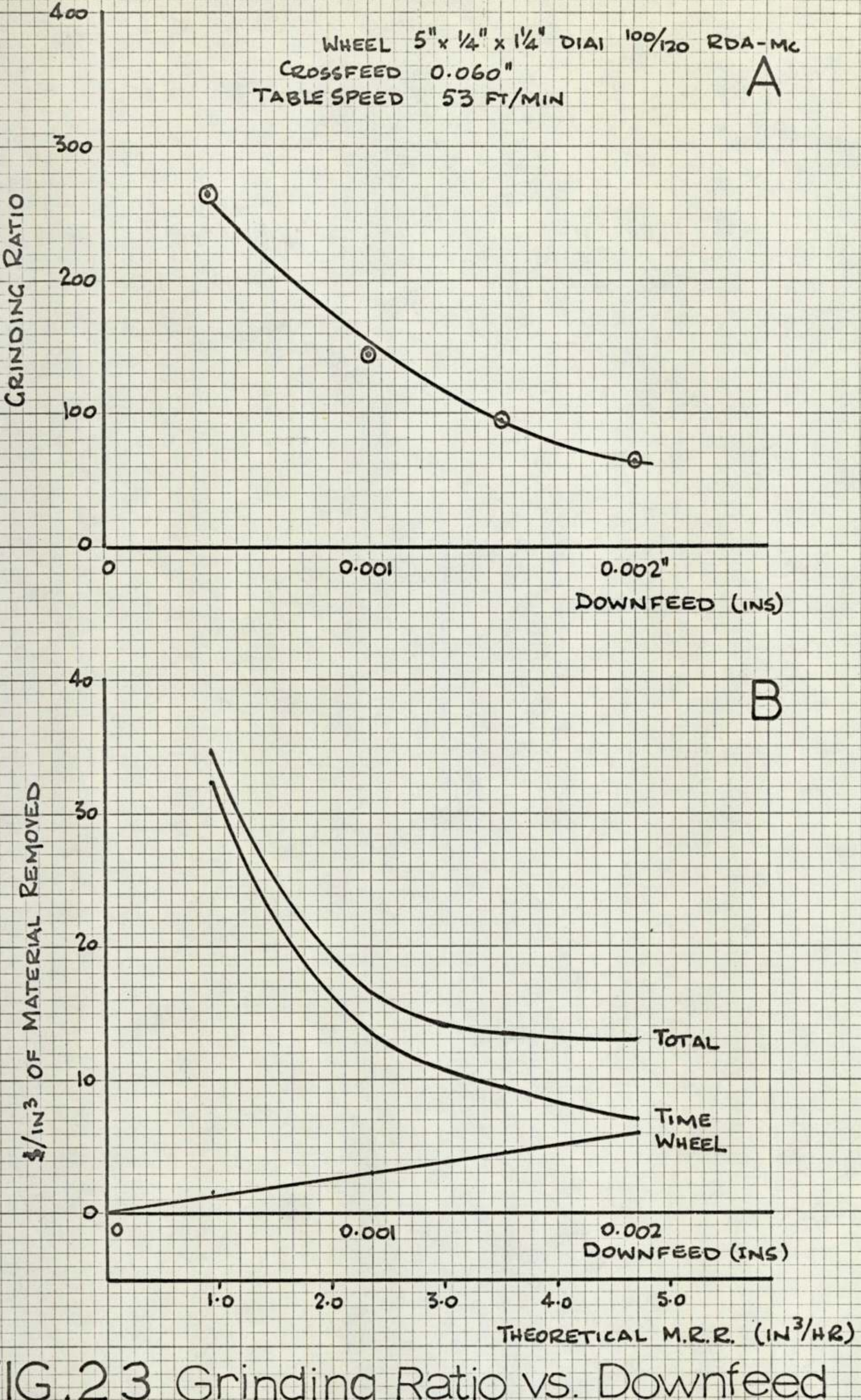


FIG.23 Grinding Ratio vs. Downfeed and Cost vs. Downfeed (25)

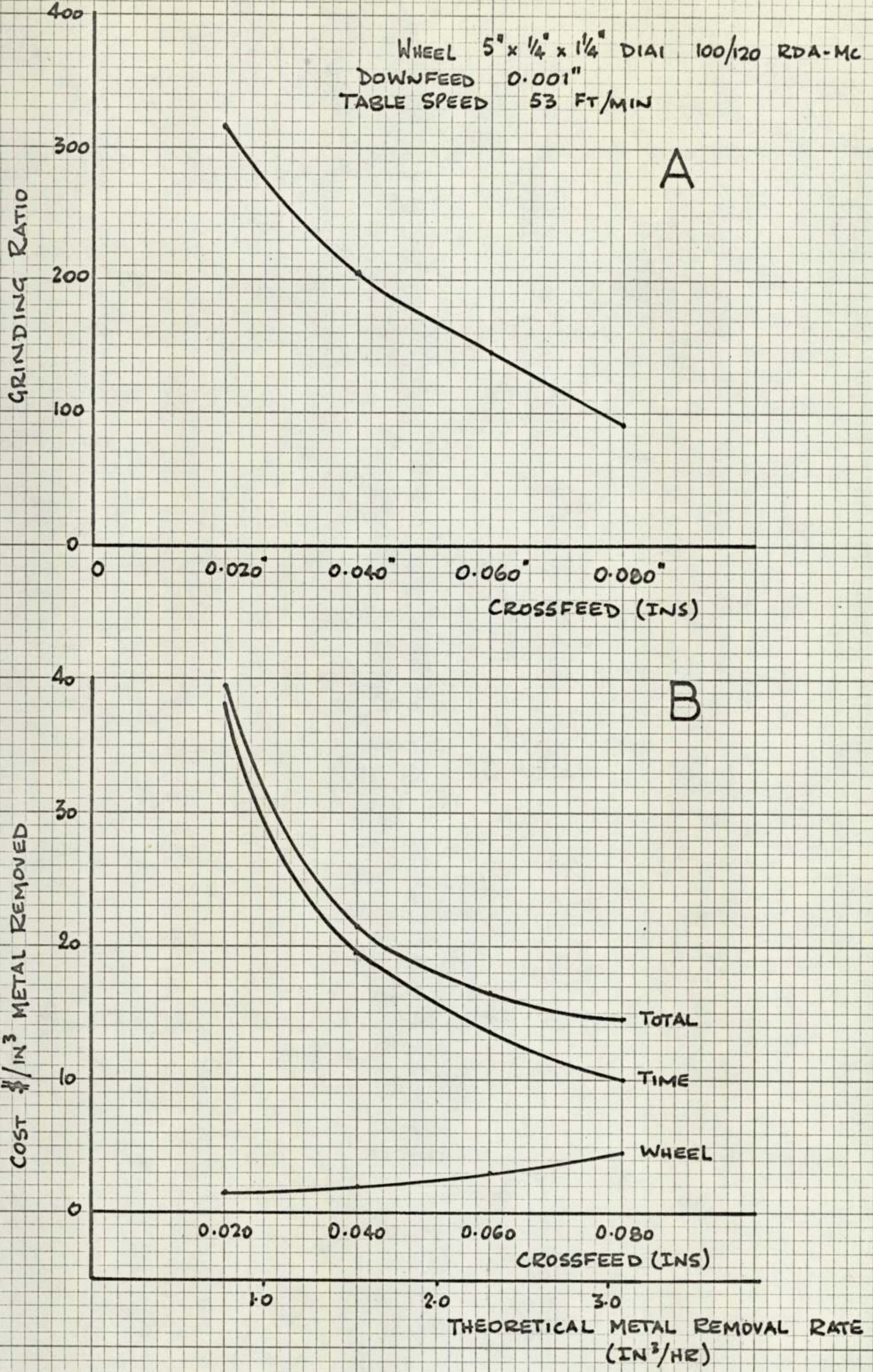


FIG. 24 Grinding Ratio vs. Crossfeed and Cost vs. Crossfeed (25)

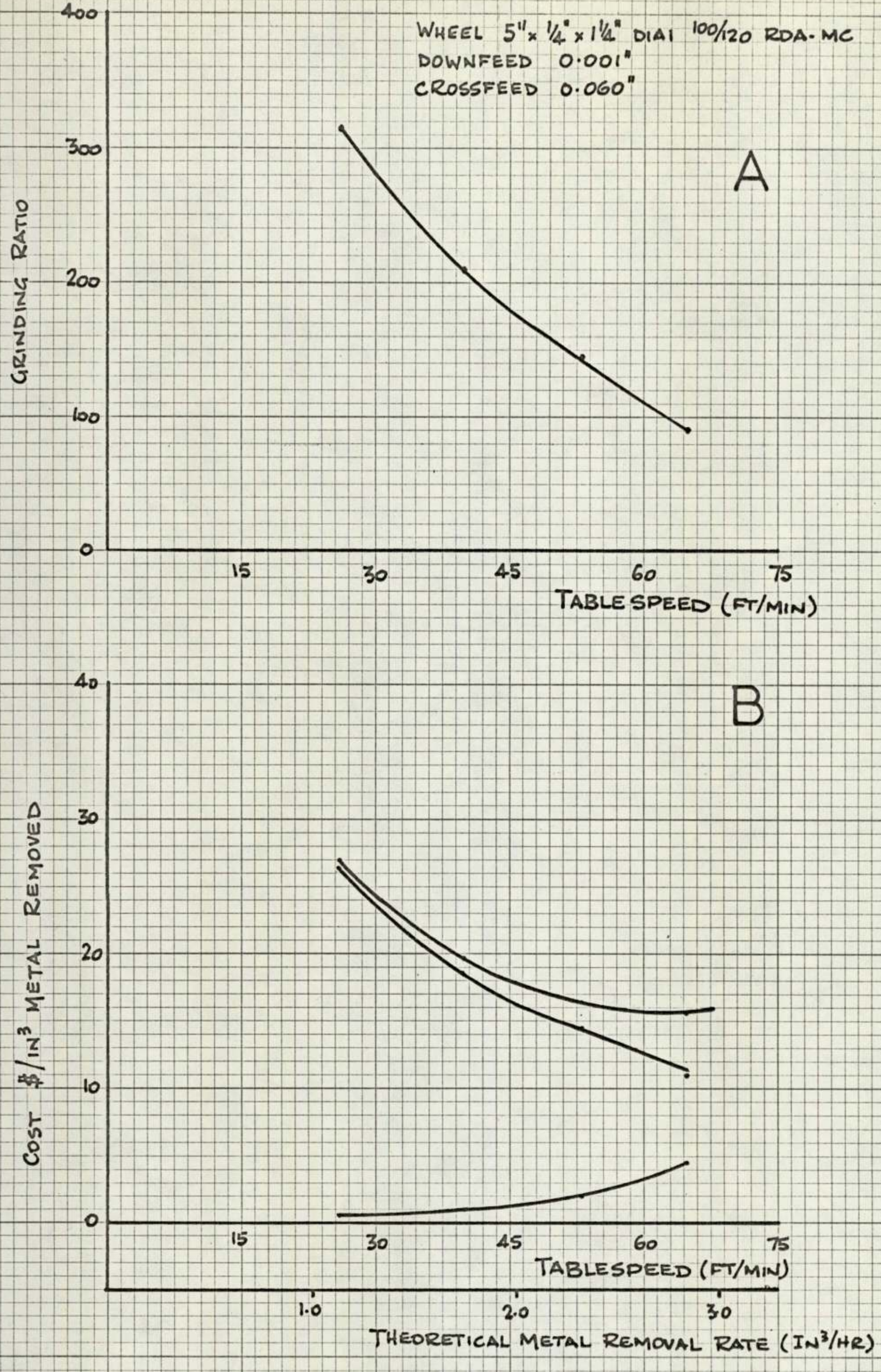


FIG. 25 Grinding Ratio vs. Tablespeed and Cost vs. Tablespeed (25)

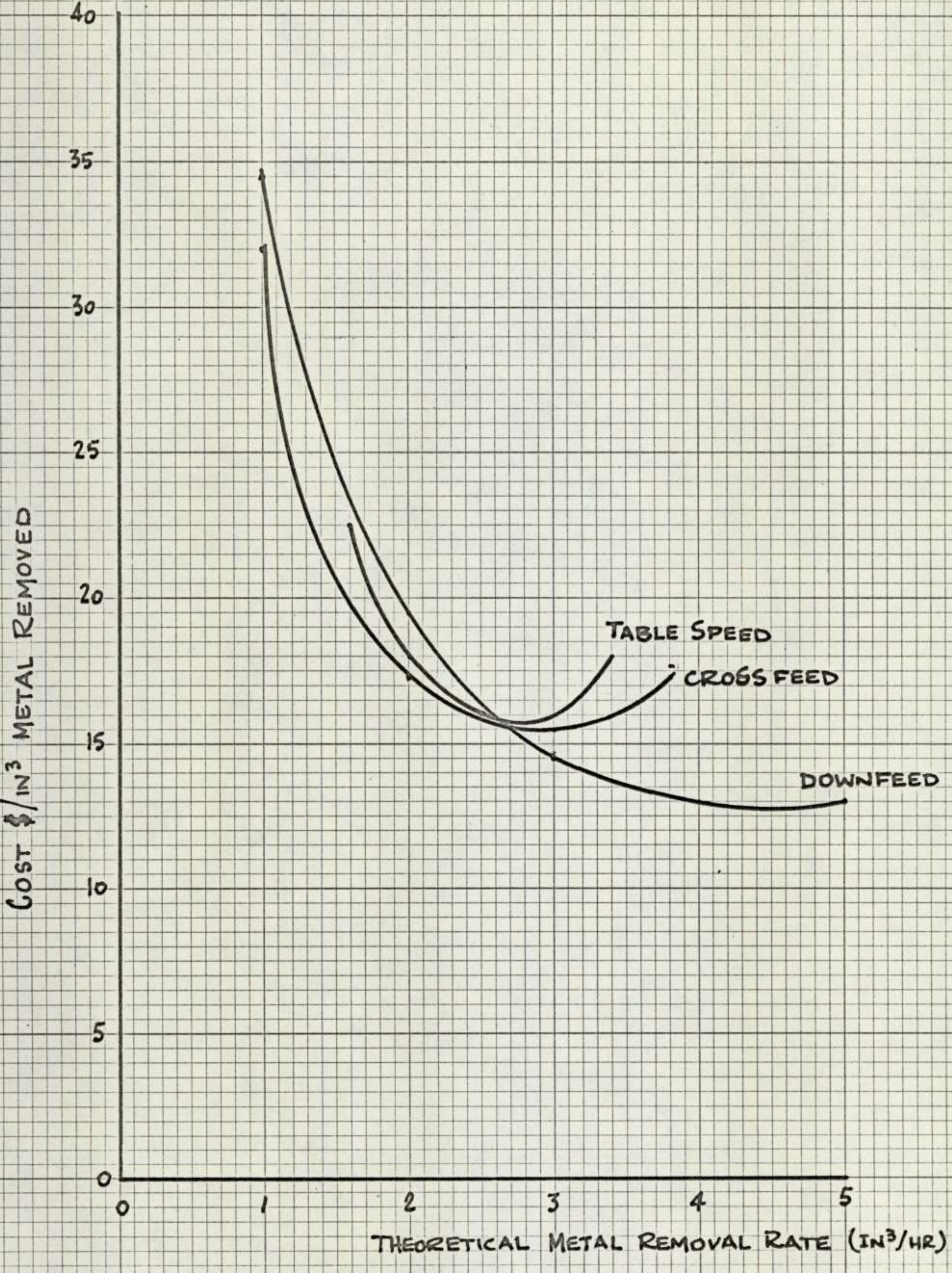


FIG.26 Cost vs Metal Removal Rate

FIG. 27 Wheel Efficiency - Clad and Unclad Grits (25)

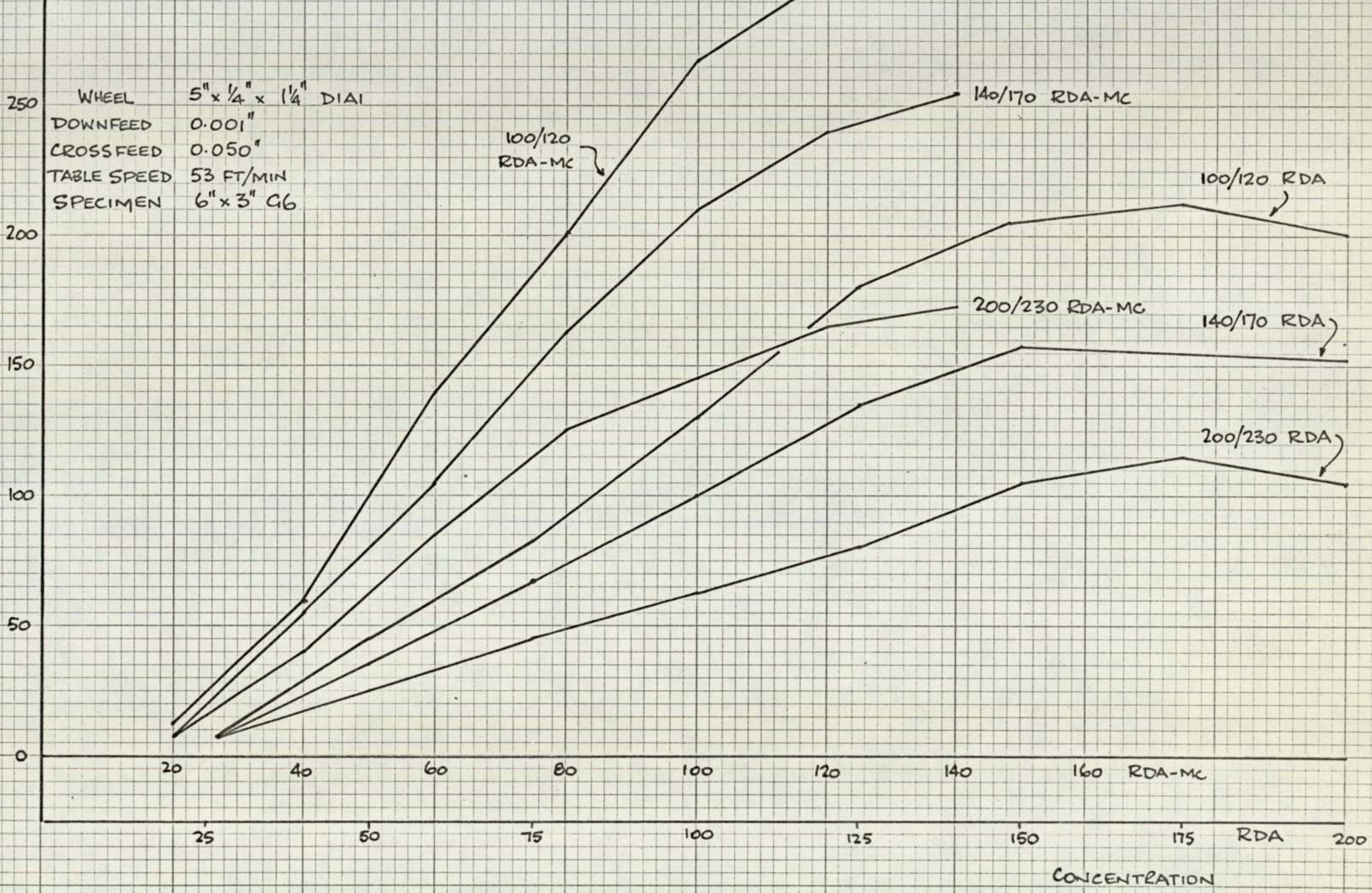


Fig 28 Grinding Ratio vs Concentration (25)

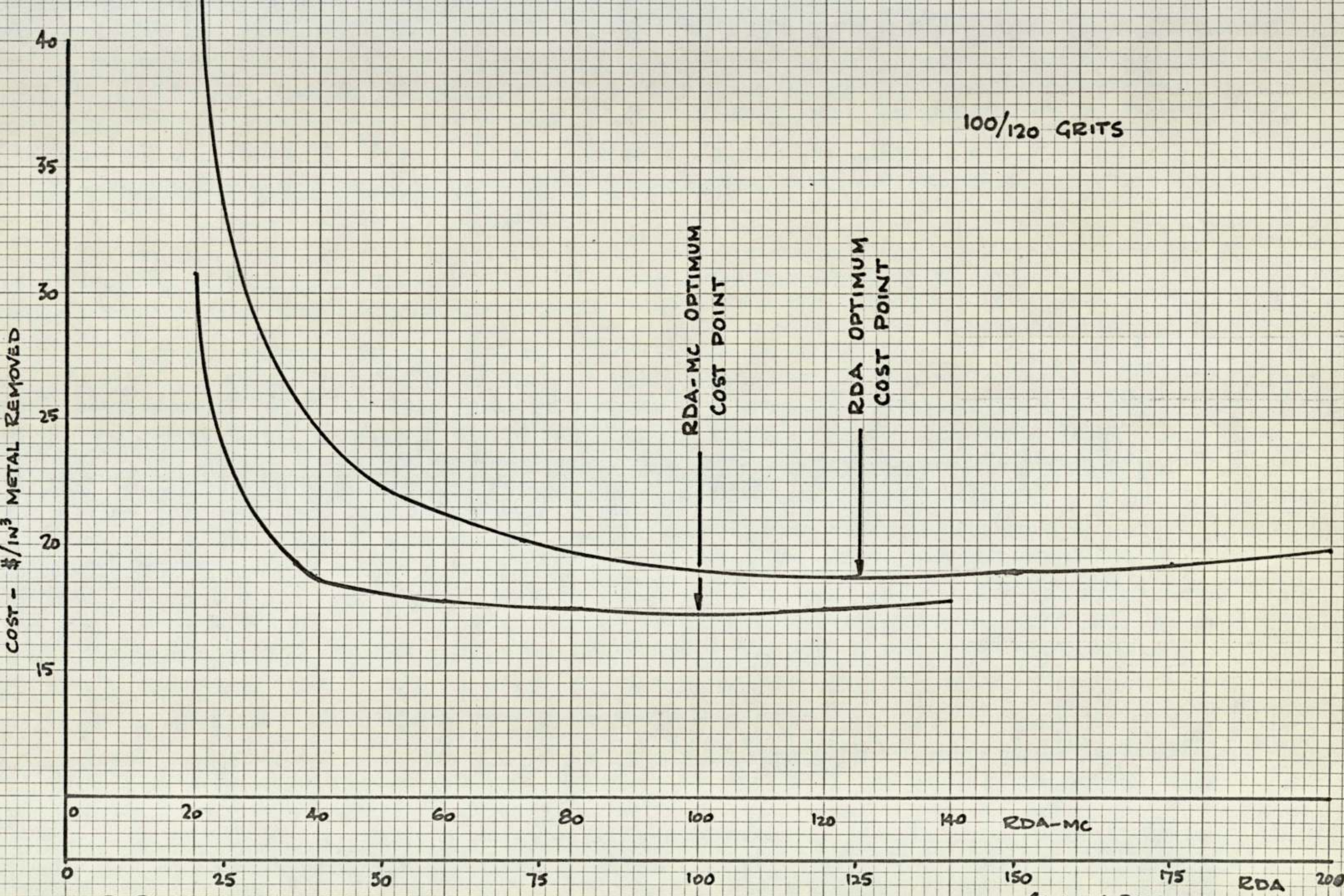


FIG. 29 Total Cost vs Concentration (25)

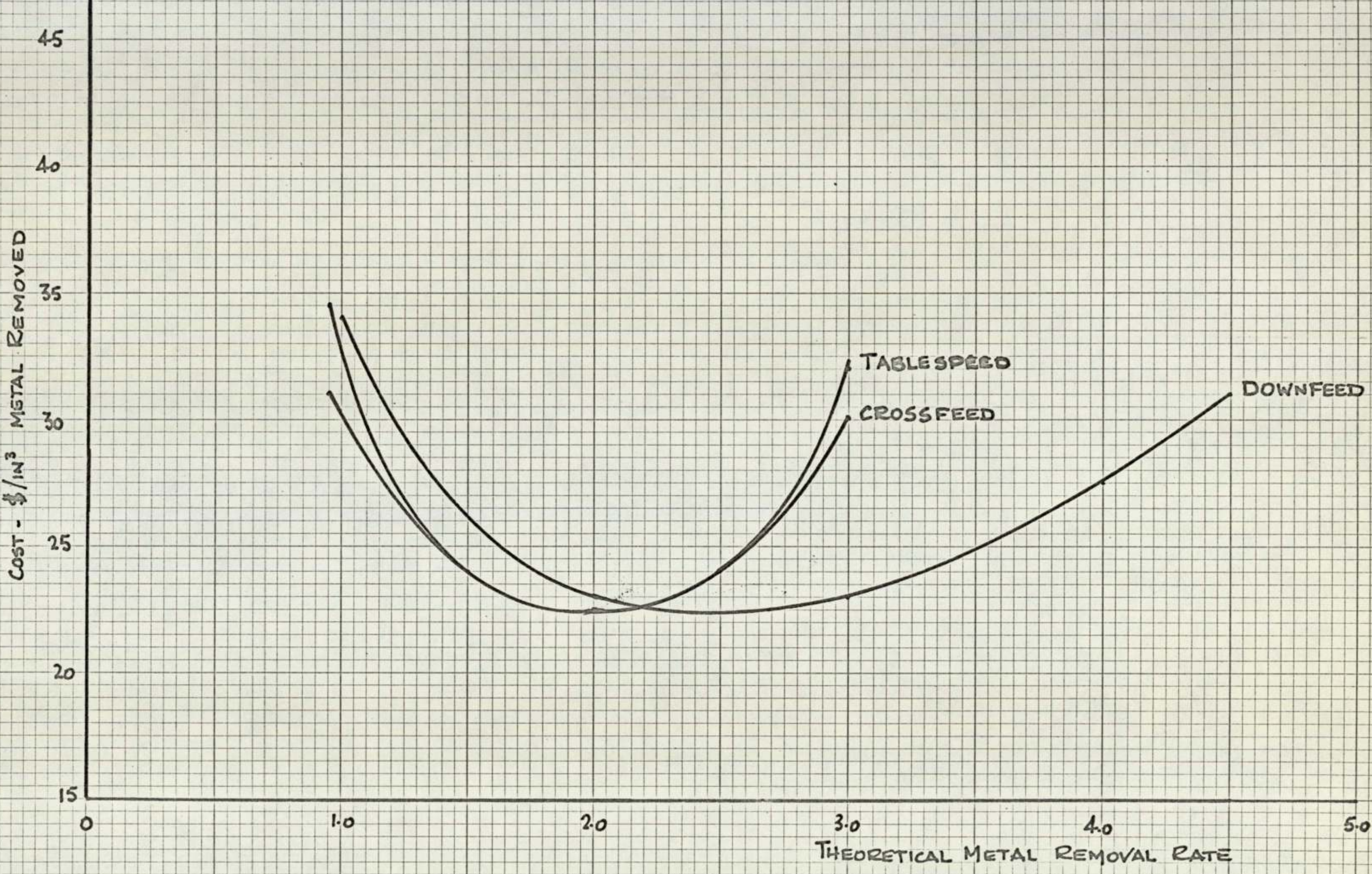


FIG.30 Cost vs Metal Removal Rate (25)

Capacities

Swing over table diameter	320 mm (12.5")
Swing inside guard	230 mm (9.0")
Maximum length of hole	75 mm (3.0")
Maximum diameter of hole	75 mm (3.0")
Minimum diameter of hole	5 mm (0.2")
Maximum included diameter	60°
Table travel - total	270 mm (10.6")
Grinding stroke (adjustable)	0-70 mm (2.75")
wheelhead cross slide travel (manual)	65 mm (2.6")
Maximum wheelhead load	94 kg (207 lbs)

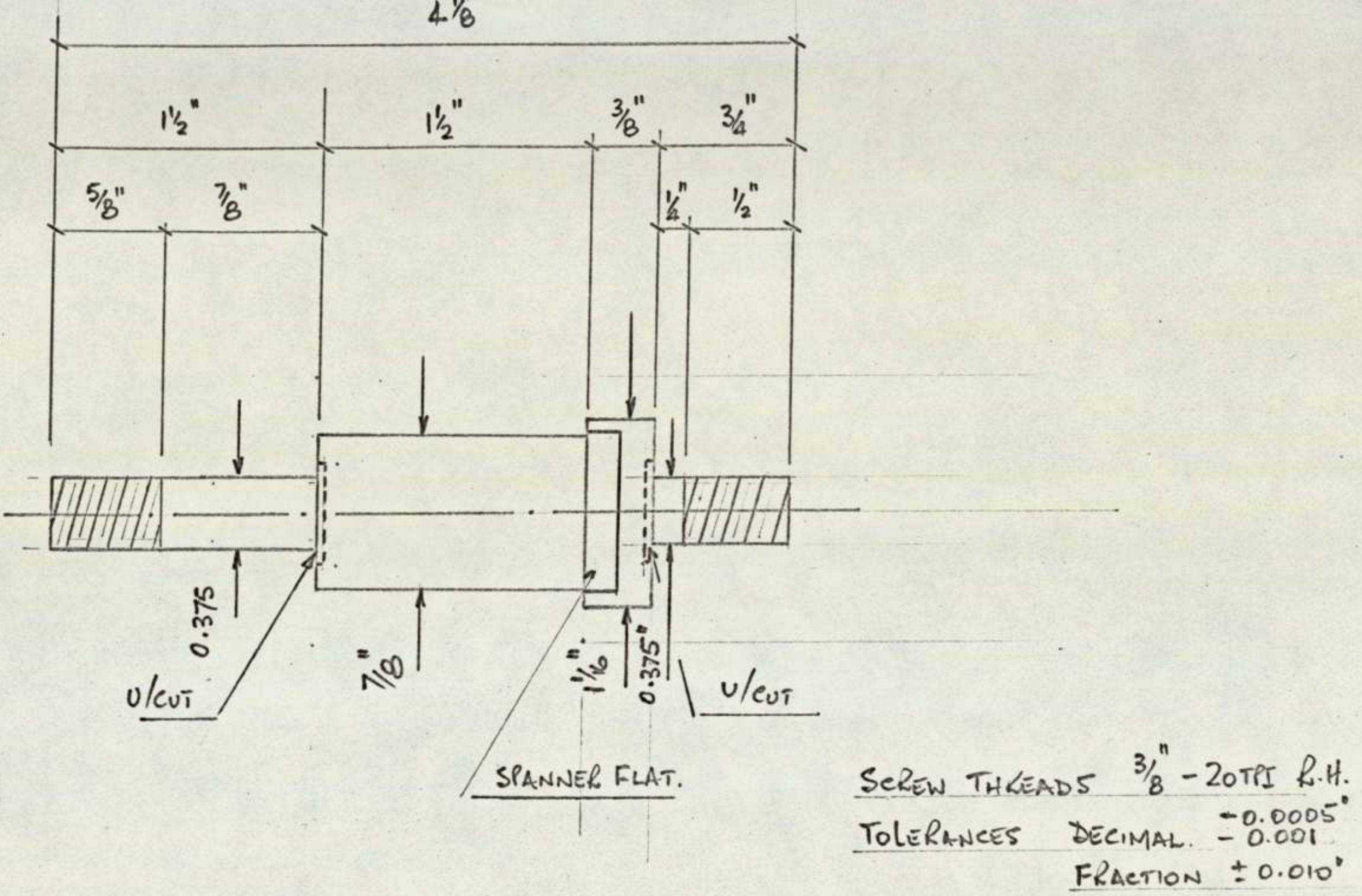
Feeds and Speeds

Table speed (rapid traverse)	5 in/min 16 ft/min
Table speed (dressing)	0-5 in/min 0-16 ft/min
Table speed (grinding)	0-5.5 in/min 0-18 ft/min
Workhead speed	0-1500 RPM
Cross feed increments (at both ends of table stroke)	0.0005 - .0275 mm 0.00002" - 0.0011"
Maximum feed movement	1 mm 0.040"

Drive

Workhead motor D.C.	¾ HP 0-2800 RPM
Wheelhead motor 50 Hz	4 HP 3000 RPM
Table drive motor DC	½ HP 0-720 RPM
Coolant pump motor	⅛ HP 1500 RPM

Fig. 31. Grinding Machine Specifications



SCREW THREADS 3/8" - 20TPI R.H.

TOLERANCES DECIMAL $^{+0.0005"}_{-0.001}$

FRACTION ± 0.010"

Fig 32 Wheel Mounting Quill

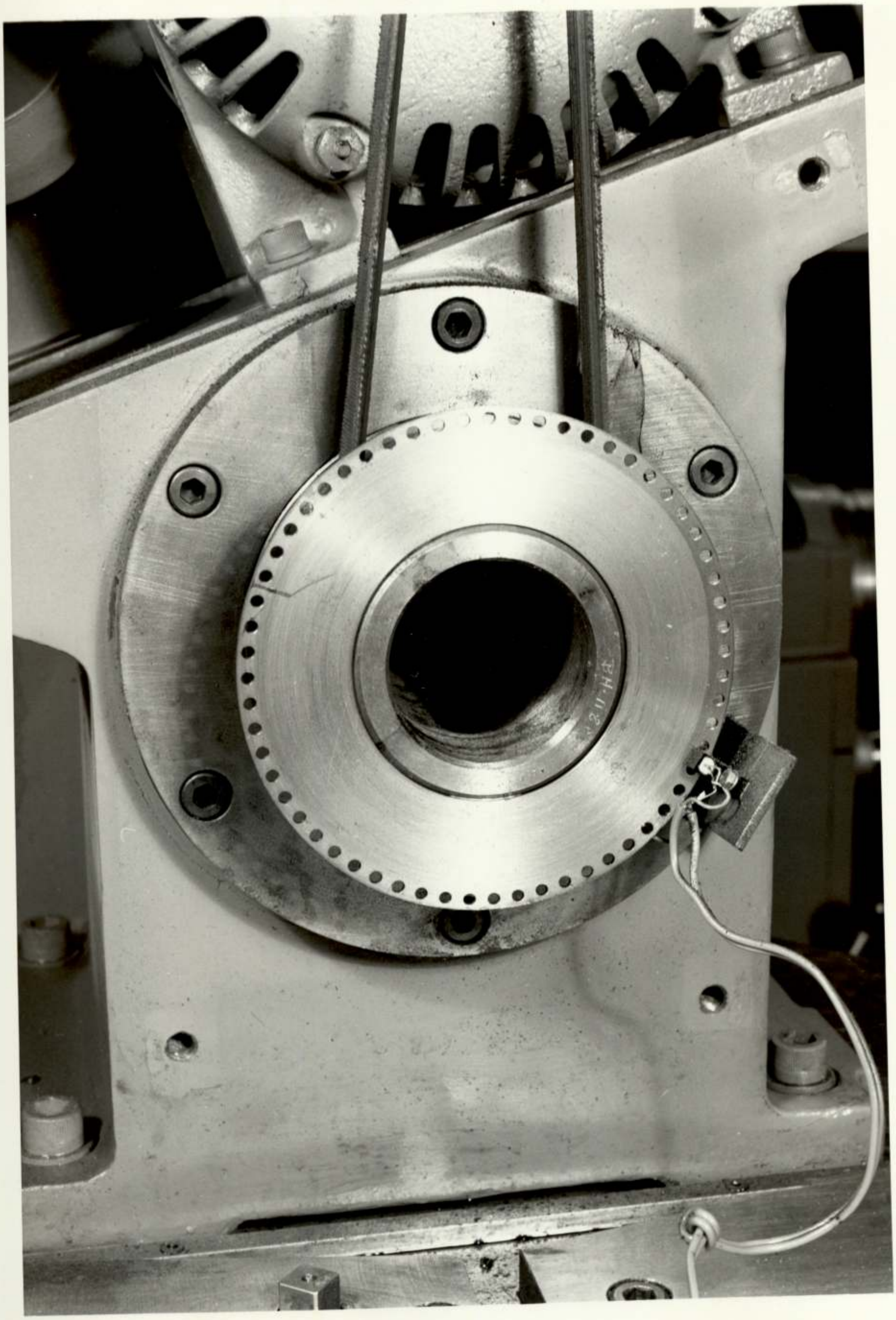


Fig.33

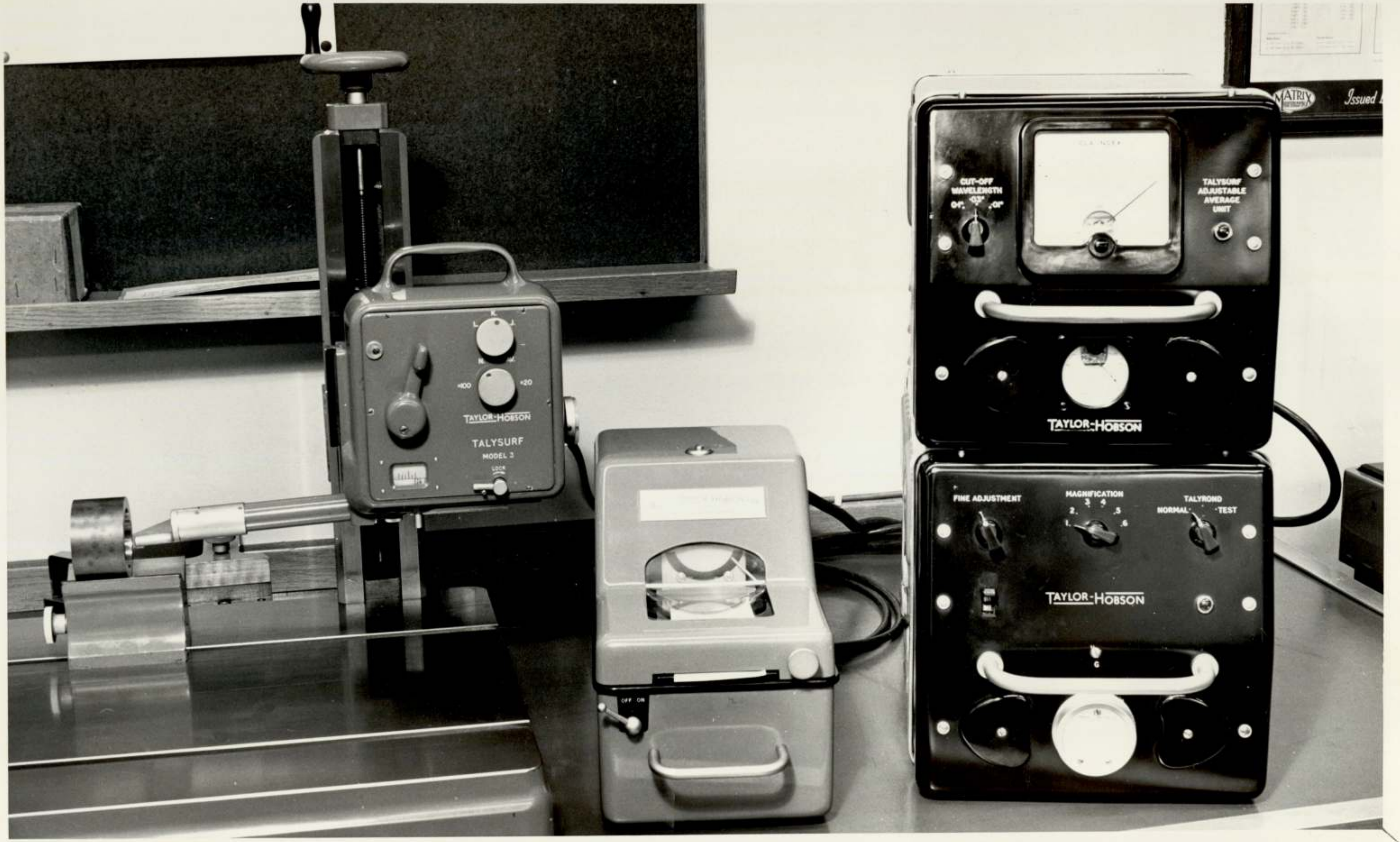

TAYLOR-HOBSON
TALYSURF
MODEL 3
LOCK
+100
+20
CUT-OFF WAVELENGTH
·01"
·03"
·01"
TALYSURF ADJUSTABLE AVERAGE UNIT
TAYLOR-HOBSON
FINE ADJUSTMENT
MAGNIFICATION
TALYROND
NORMAL
TEST
TAYLOR-HOBSON
OFF ON
MATRIX
Issued

Fig.34

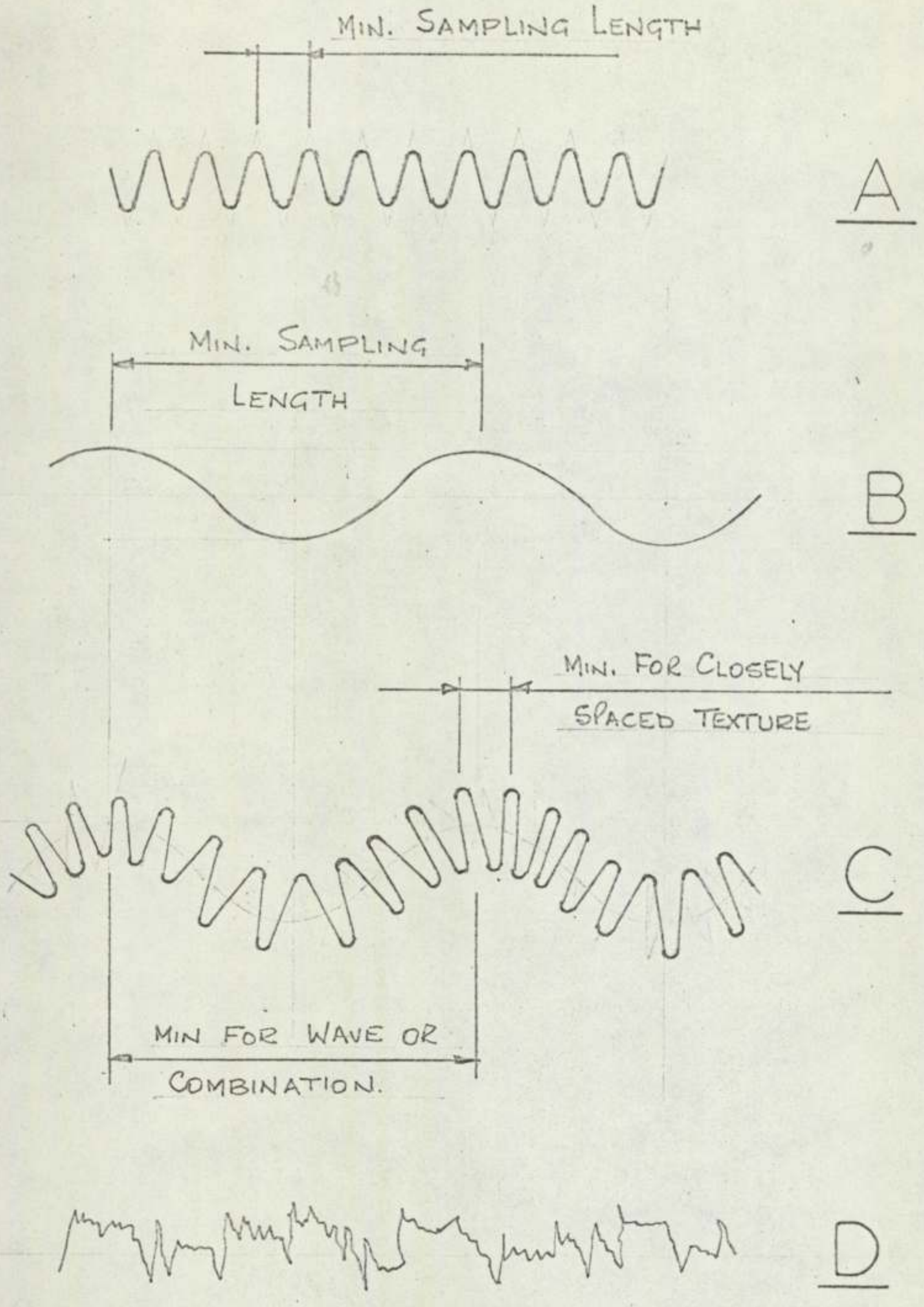


FIG 35 SURFACE FINISH TRACES

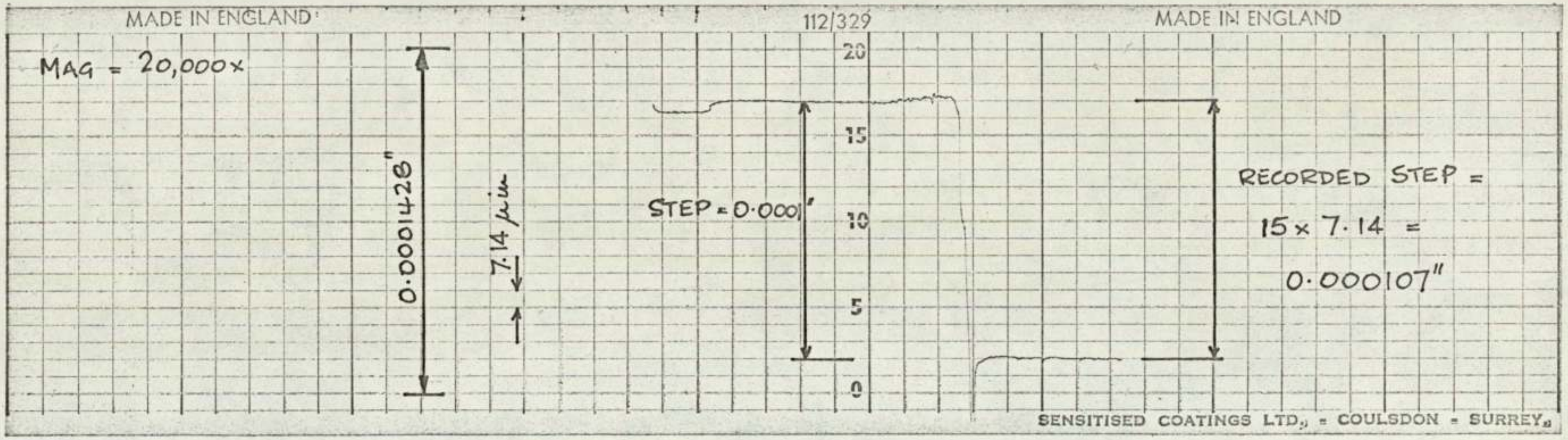
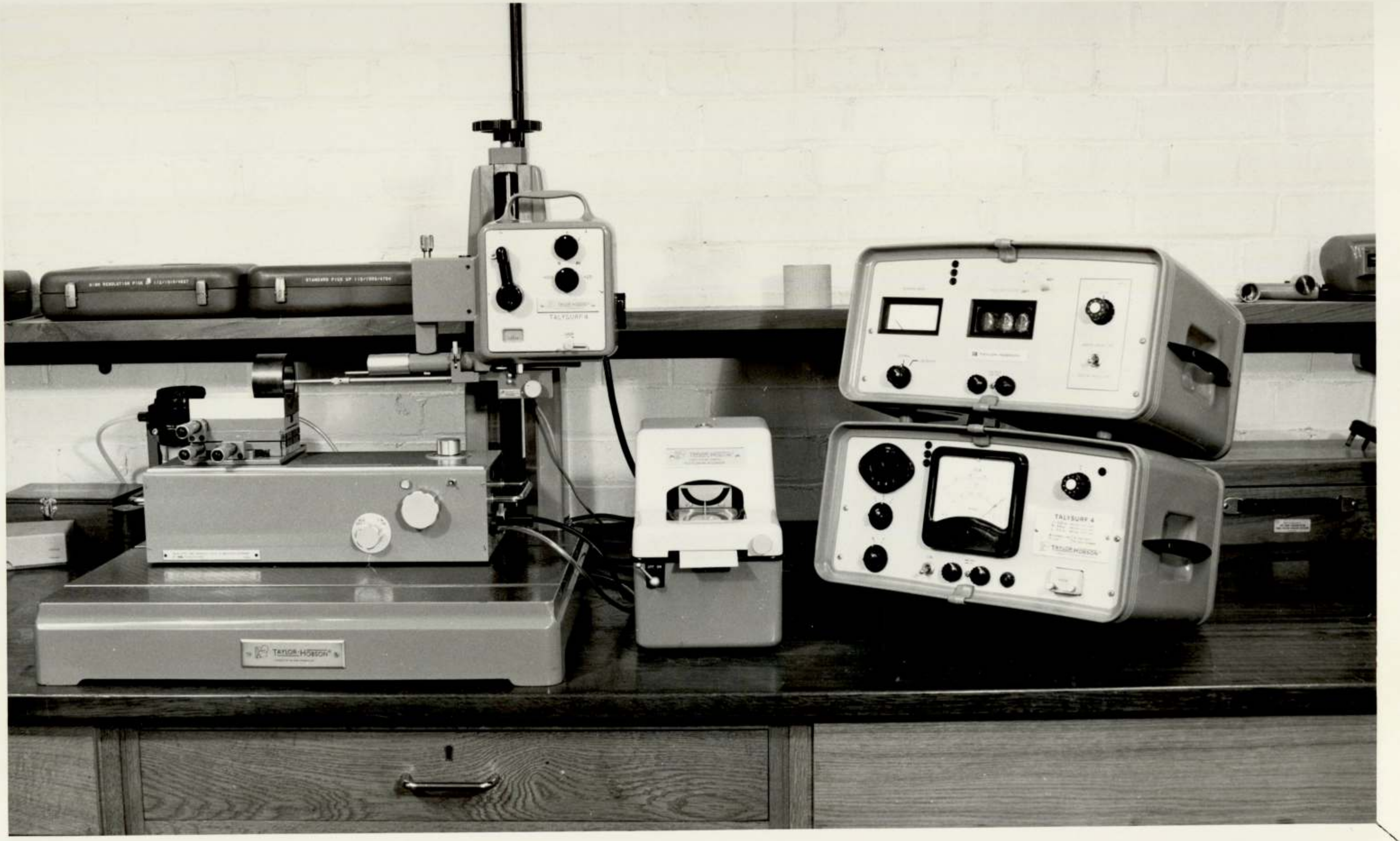


Fig 36 Calibration Check : Air Traversing Table



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

Fig. 37

Fig.38

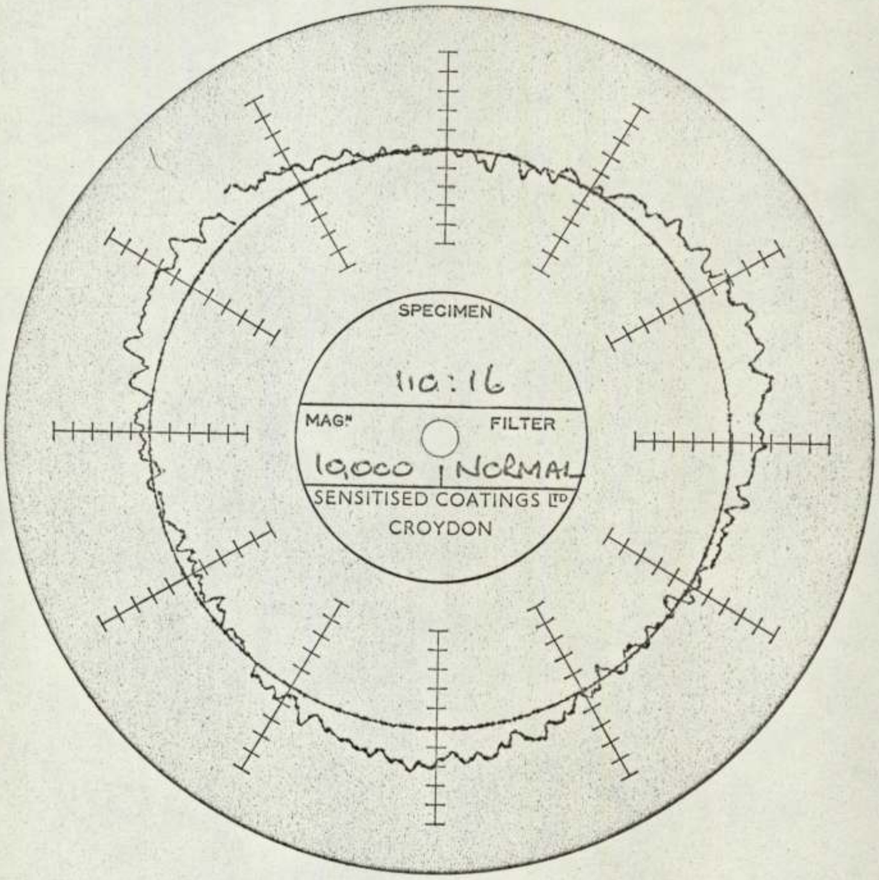


Fig 39 Normal Talyrond Trace

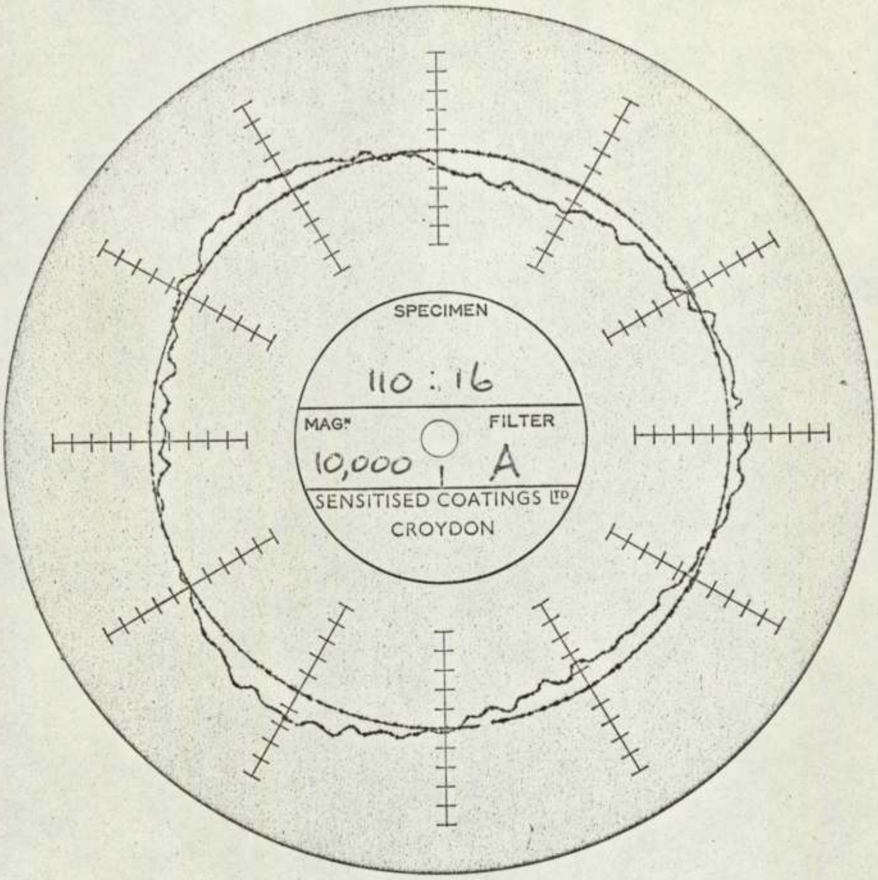


Fig 39 Talyrond Trace: 'A' Filter

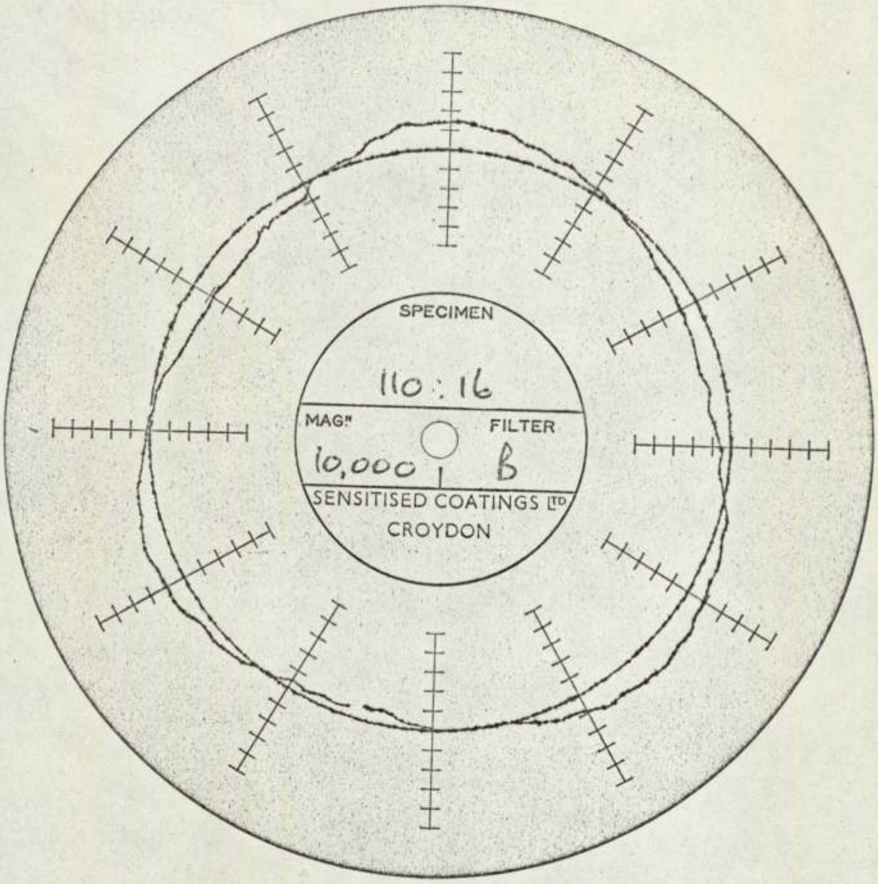


Fig 39 Talyrond Trace 'B' Filter

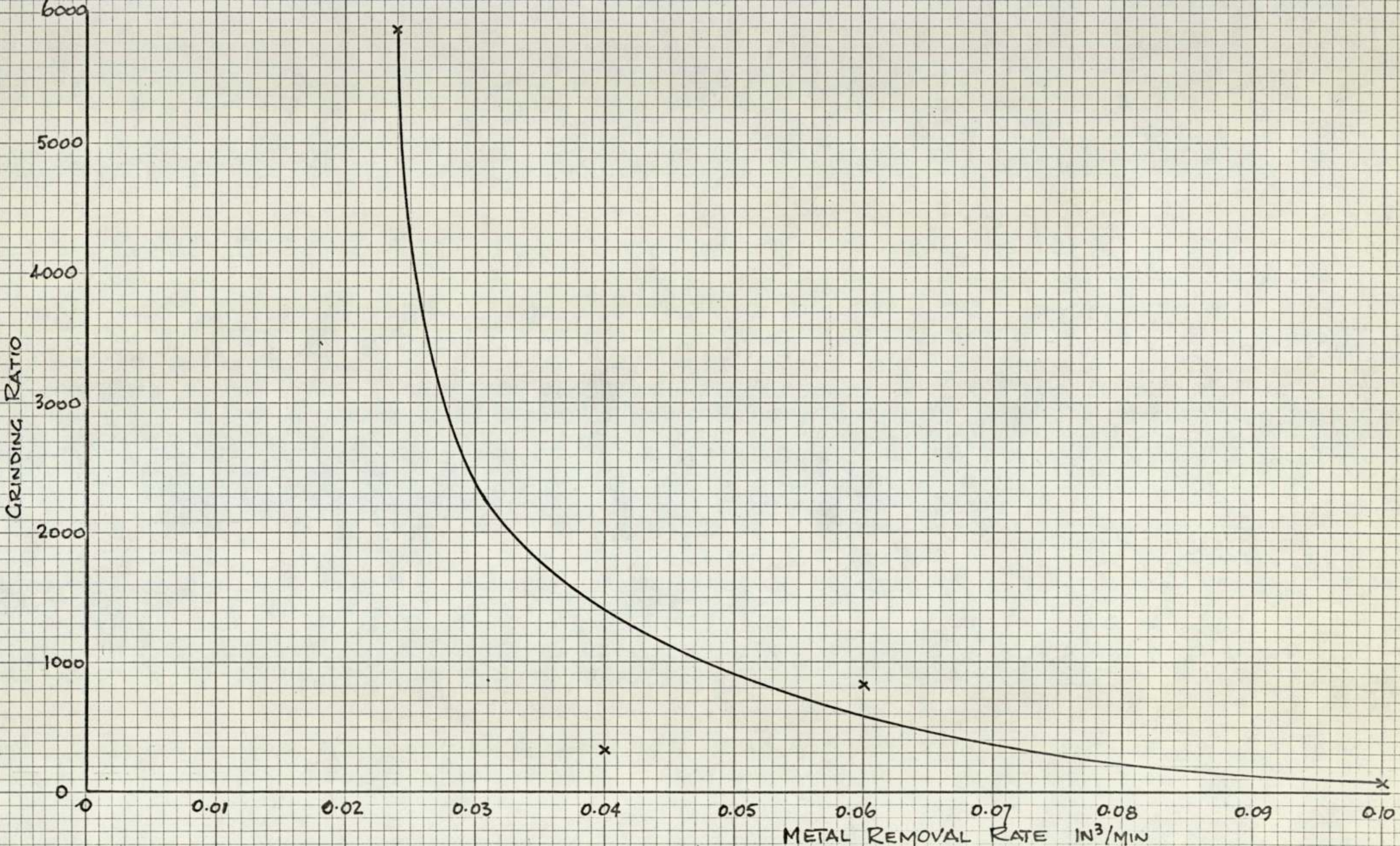


Fig 40 Grinding Ratio vs Metal Removal Rate

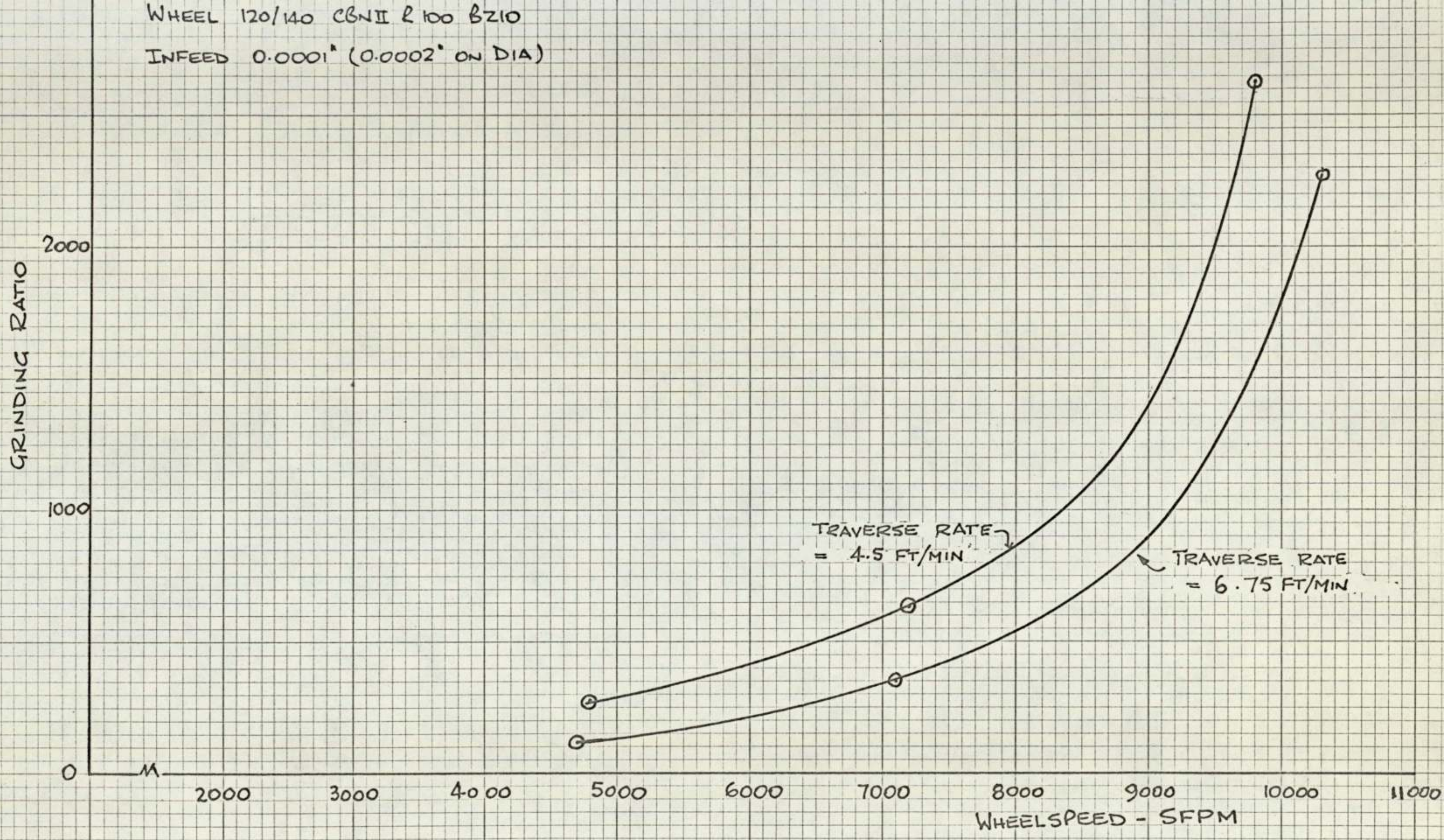


Fig 41 Grinding Ratio vs Wheelspeed

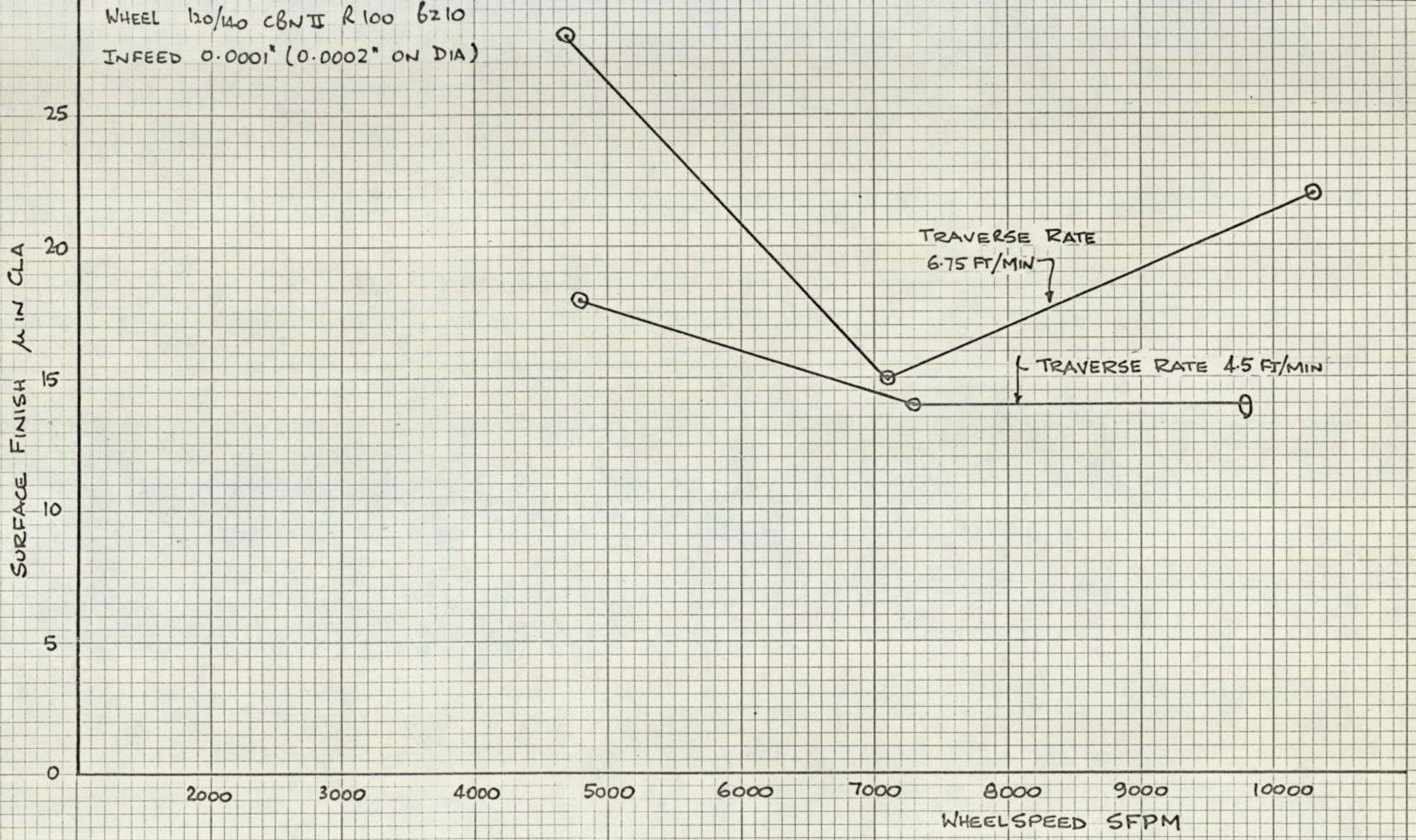


Fig42 Surface Finish vs Wheelspeed

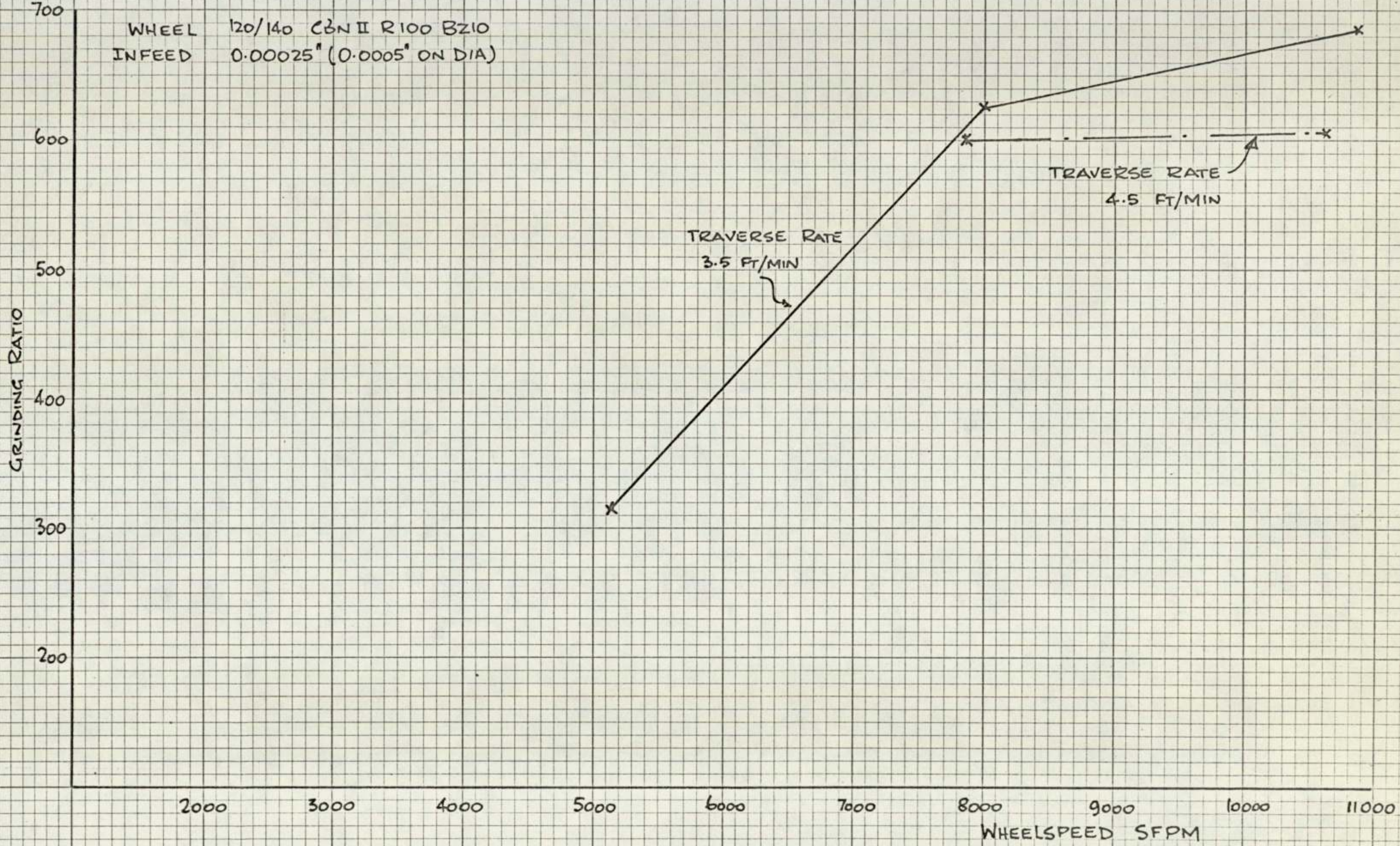


Fig43 Grinding Ratio vs Wheelspeed

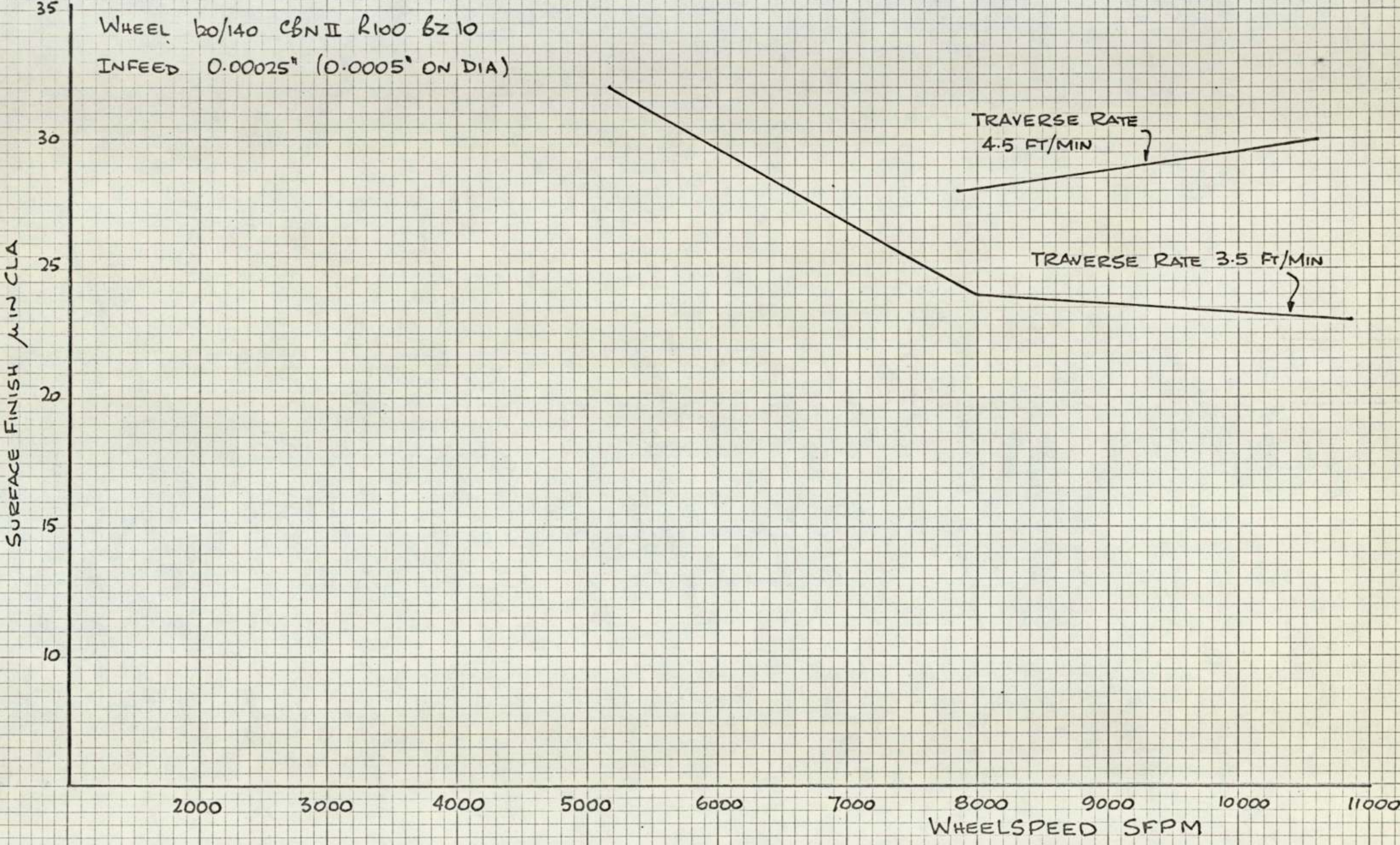


Fig 44 Surface Finish vs. Wheelspeed

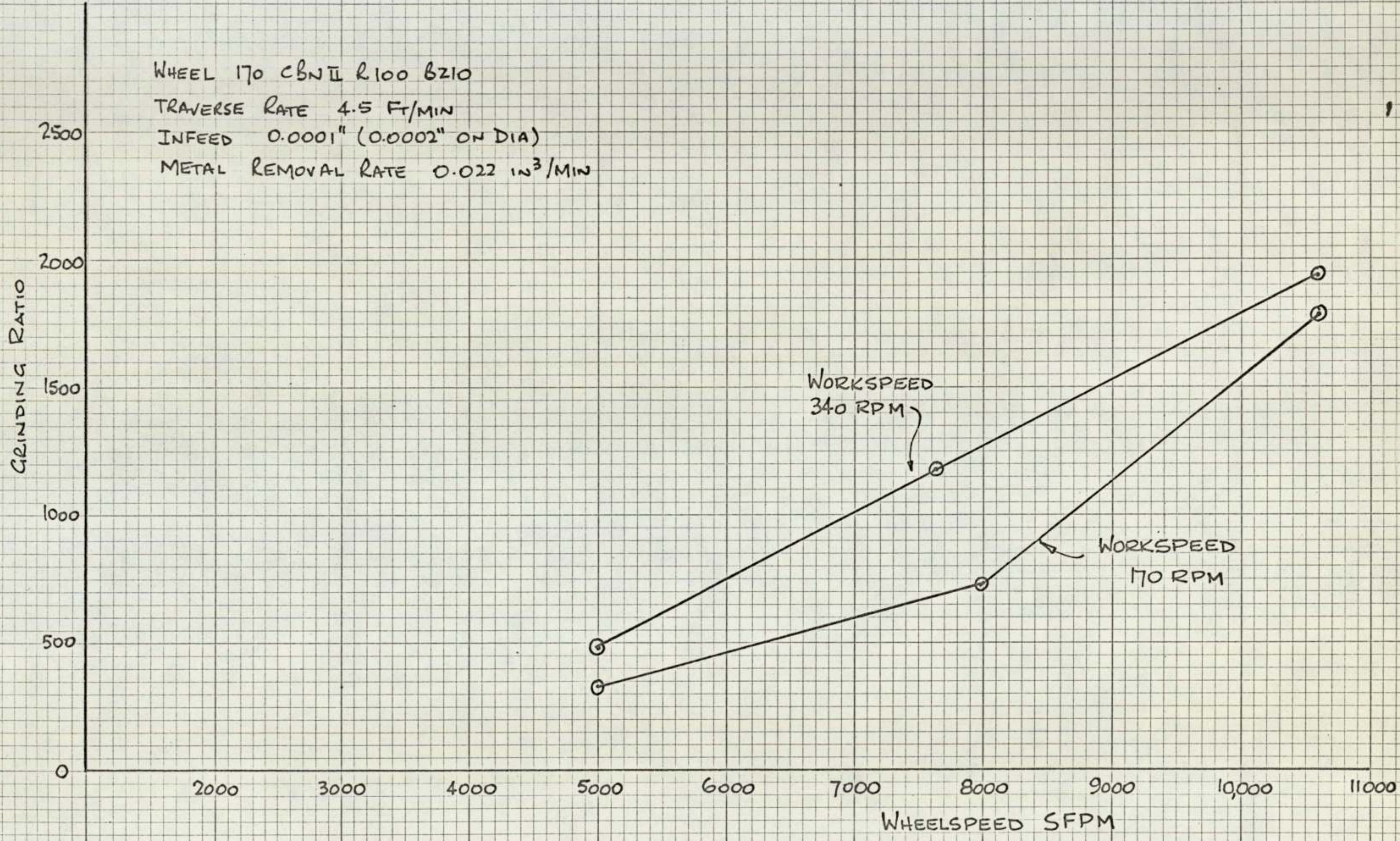


Fig 45 Grinding Ratio vs Wheelspeed

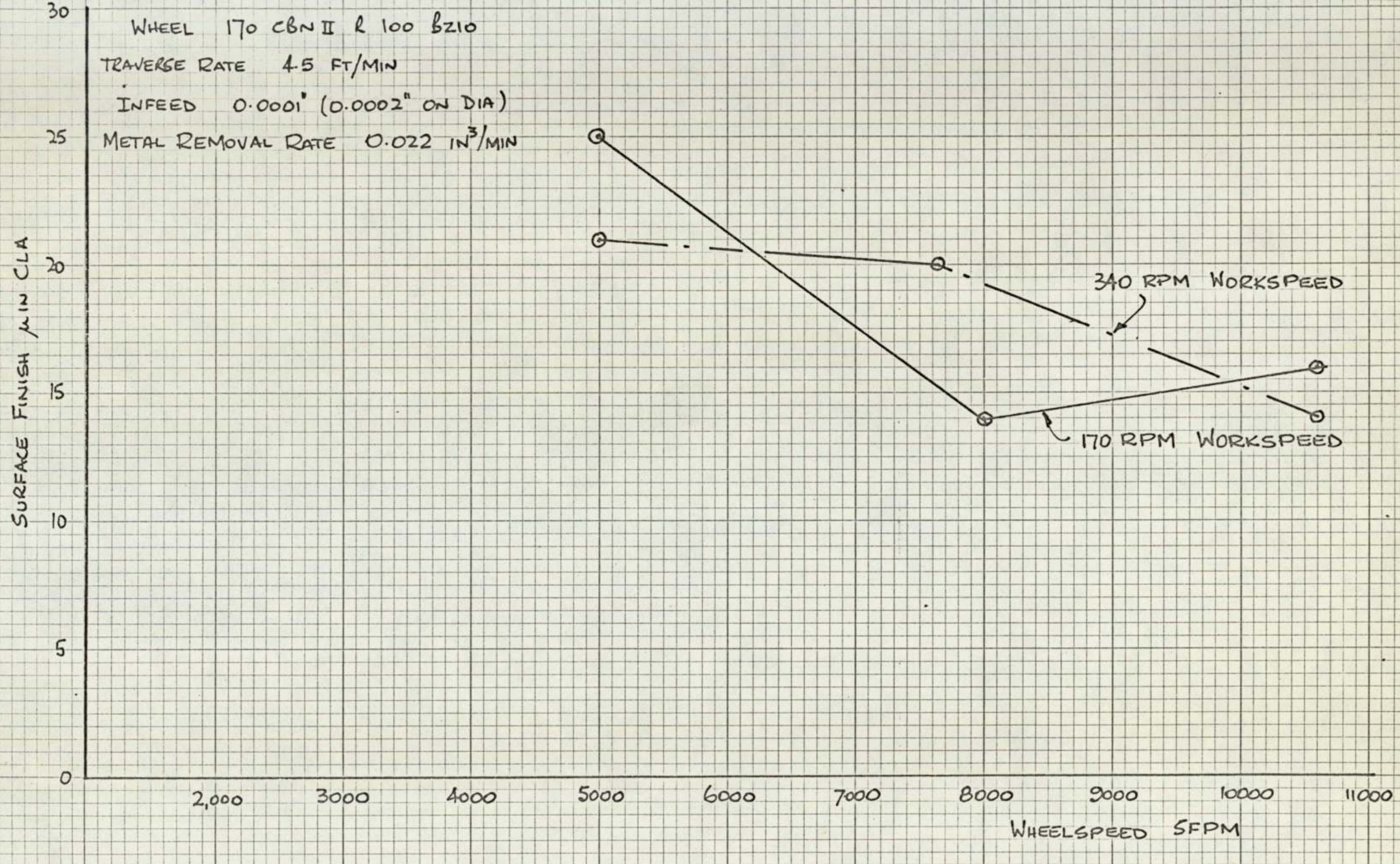


Fig 46 Surface Finish vs Wheelspeed

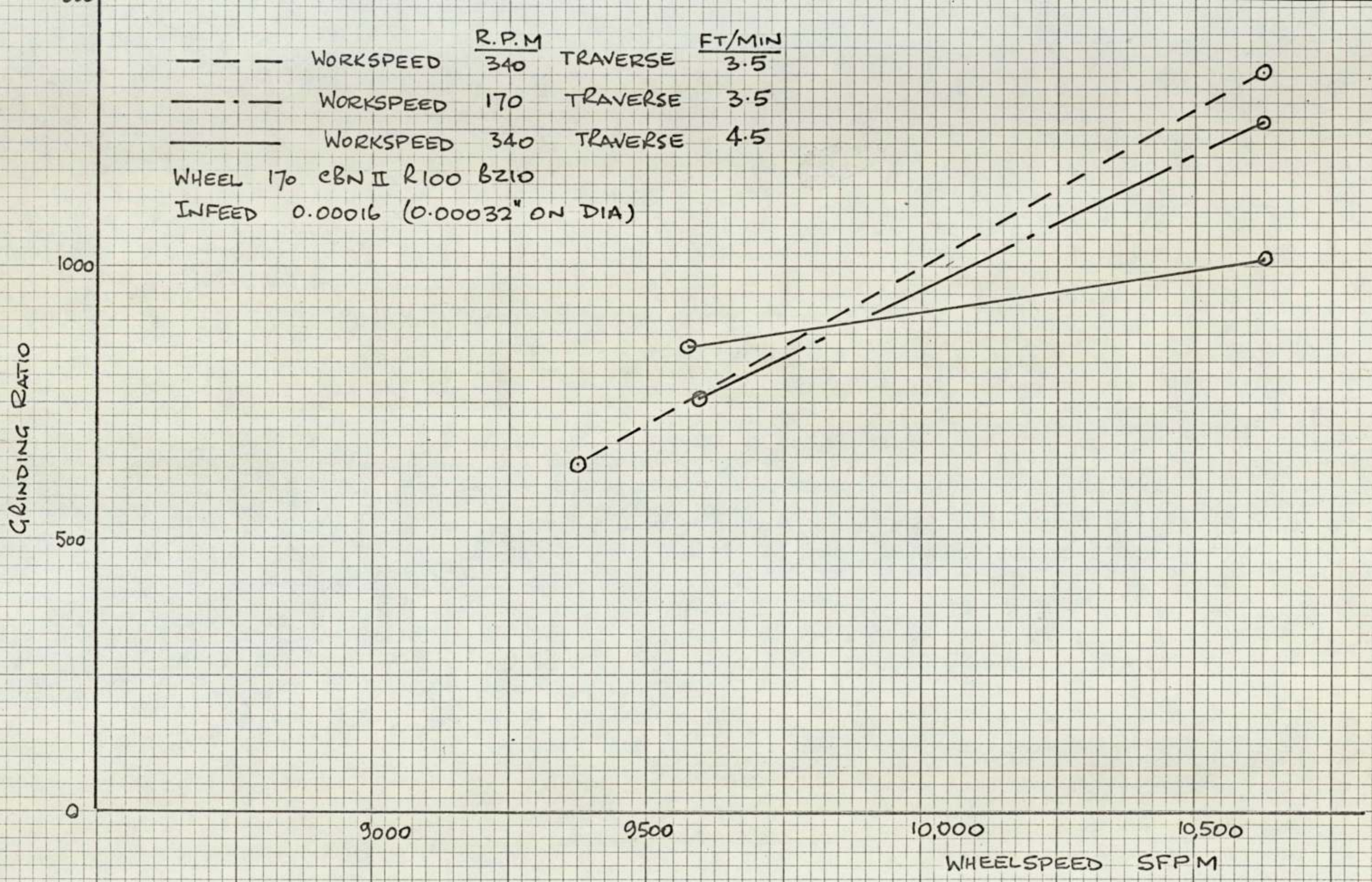


Fig 47 Grinding Ratio vs Wheelspeed

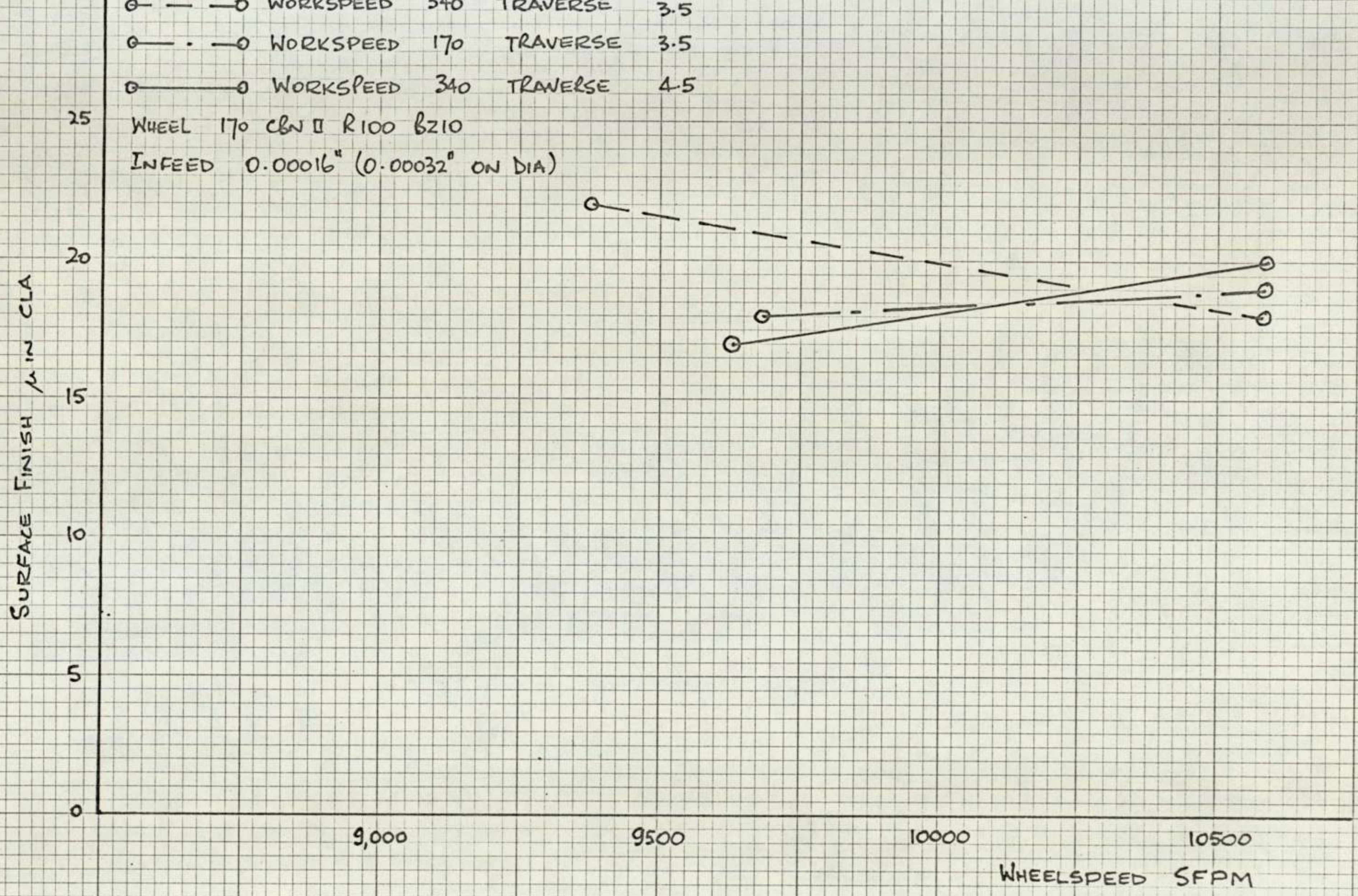


Fig 48 Surface Finish vs Wheelspeed

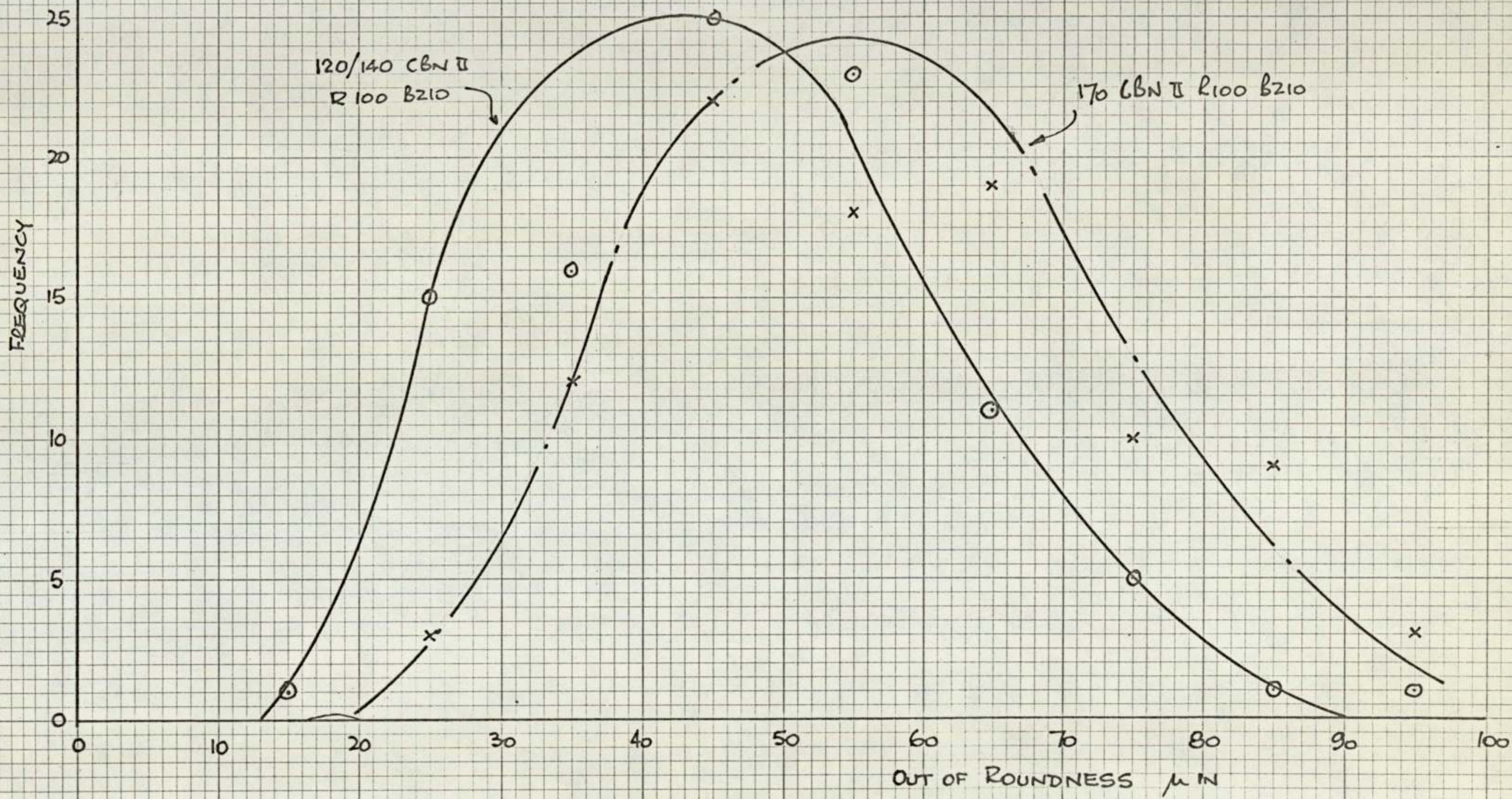
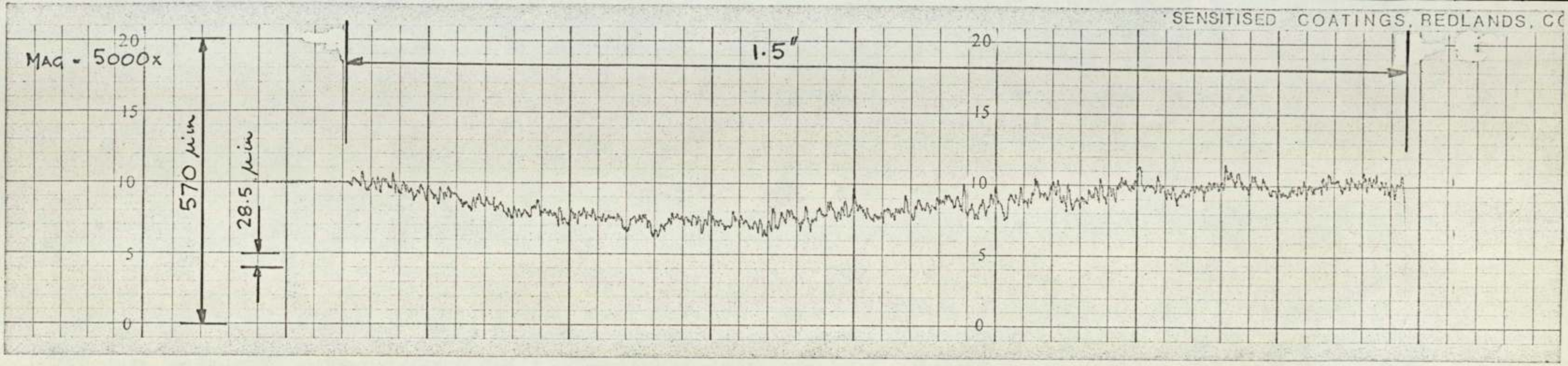


Fig 49 Frequency vs Out of Roundness



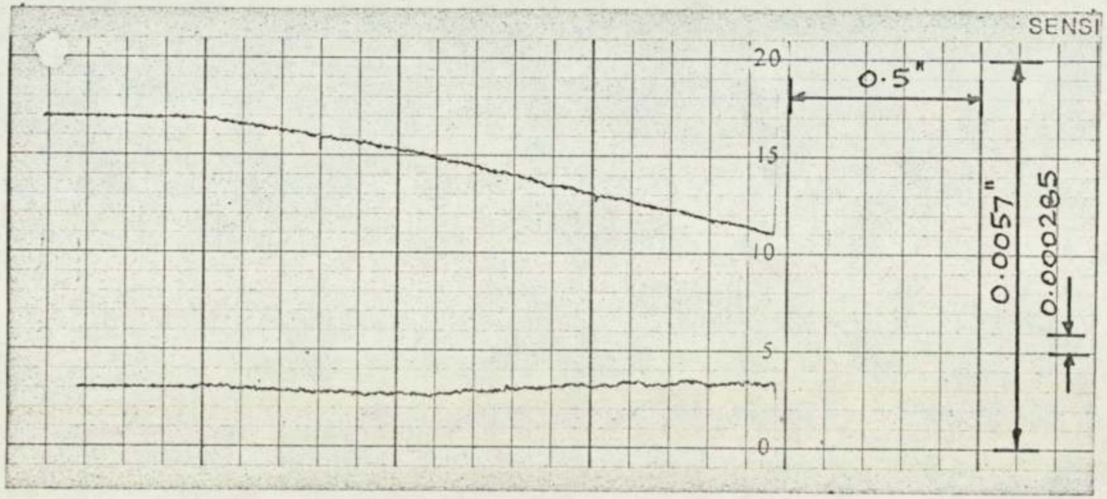


Fig 50 Bore Profile Test No. 64

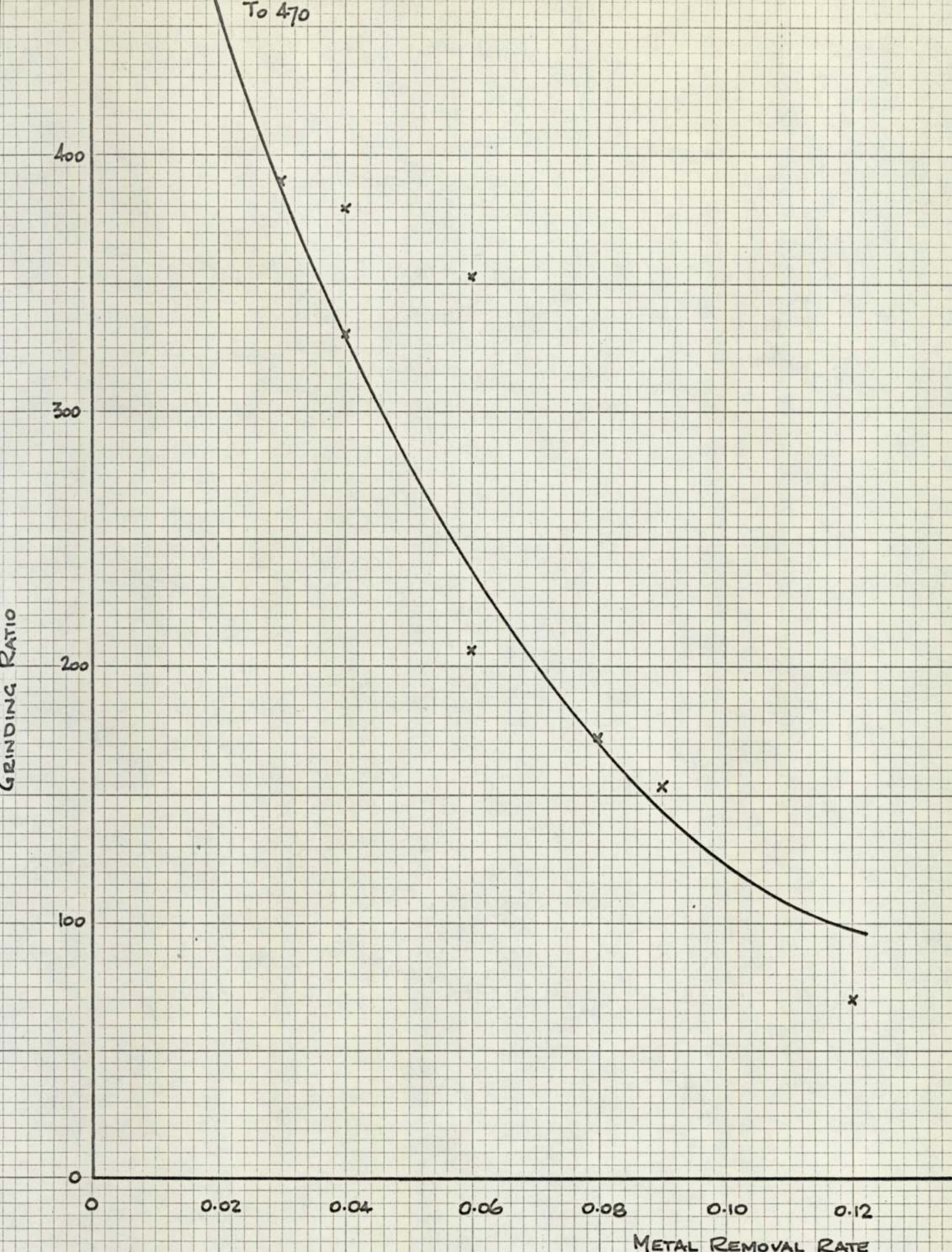
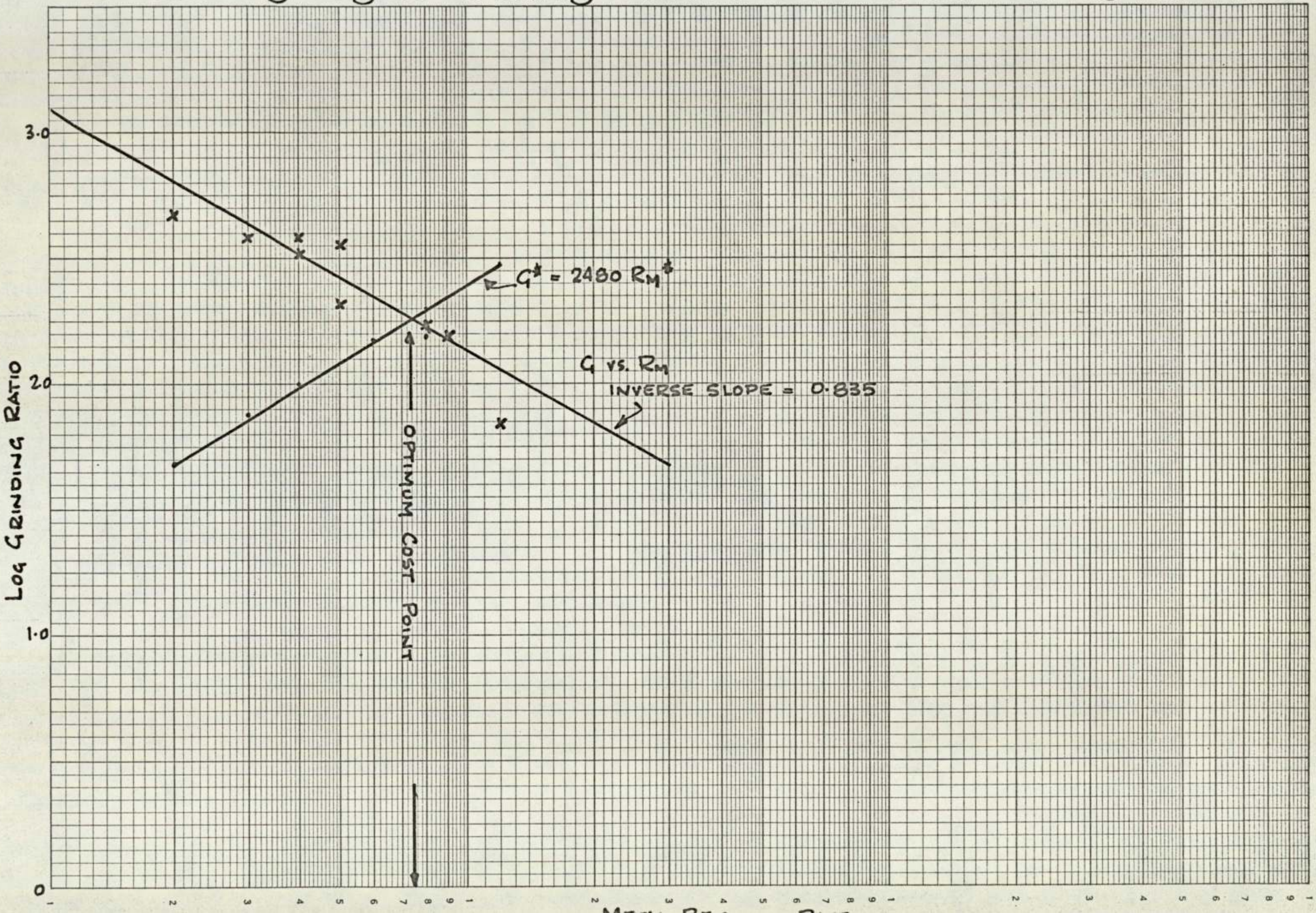


FIG. 51 Grinding Ratio vs Metal Removal Rate

FIG.52 LogLog Grinding Ratio vs Metal Removal Rate



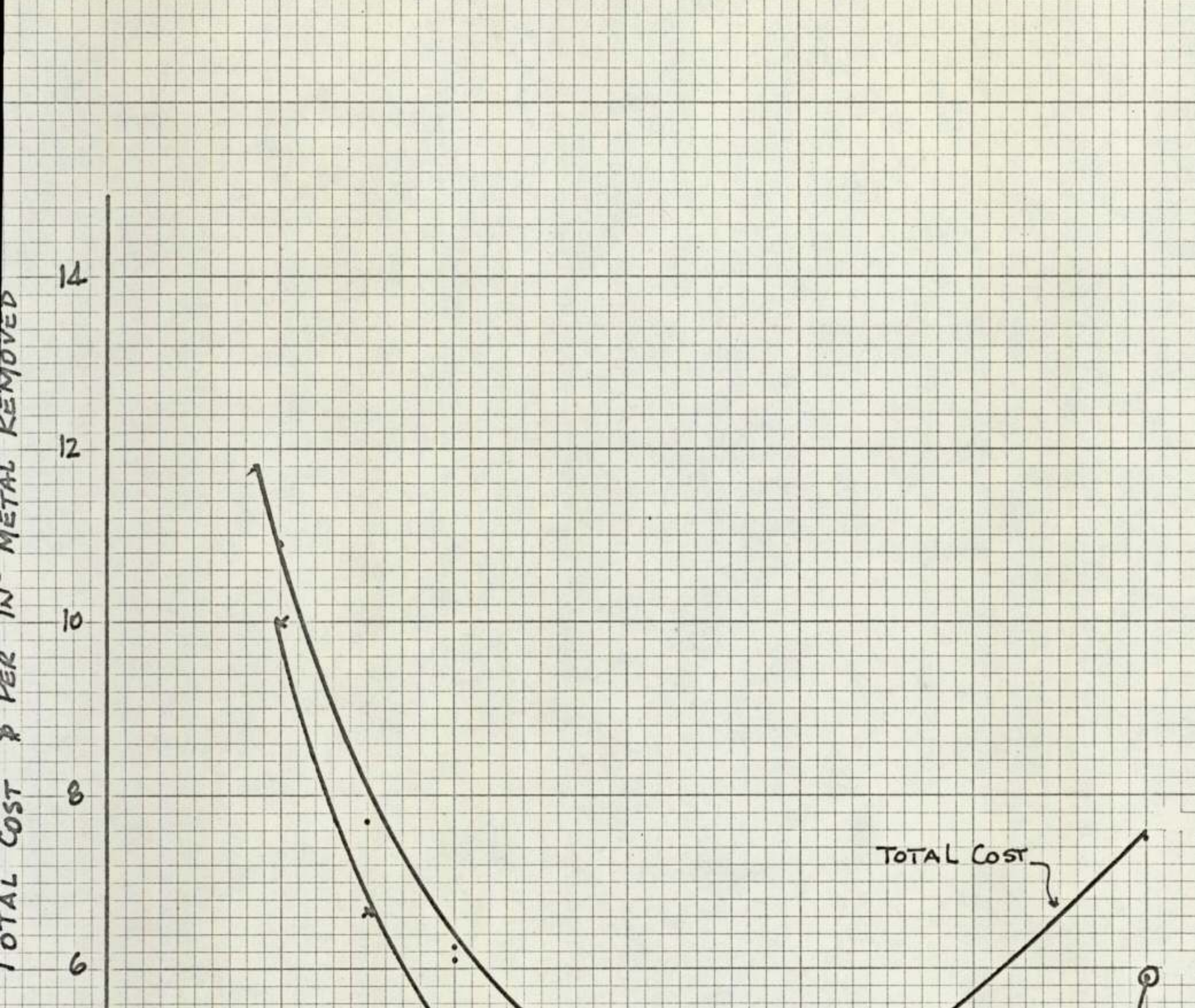
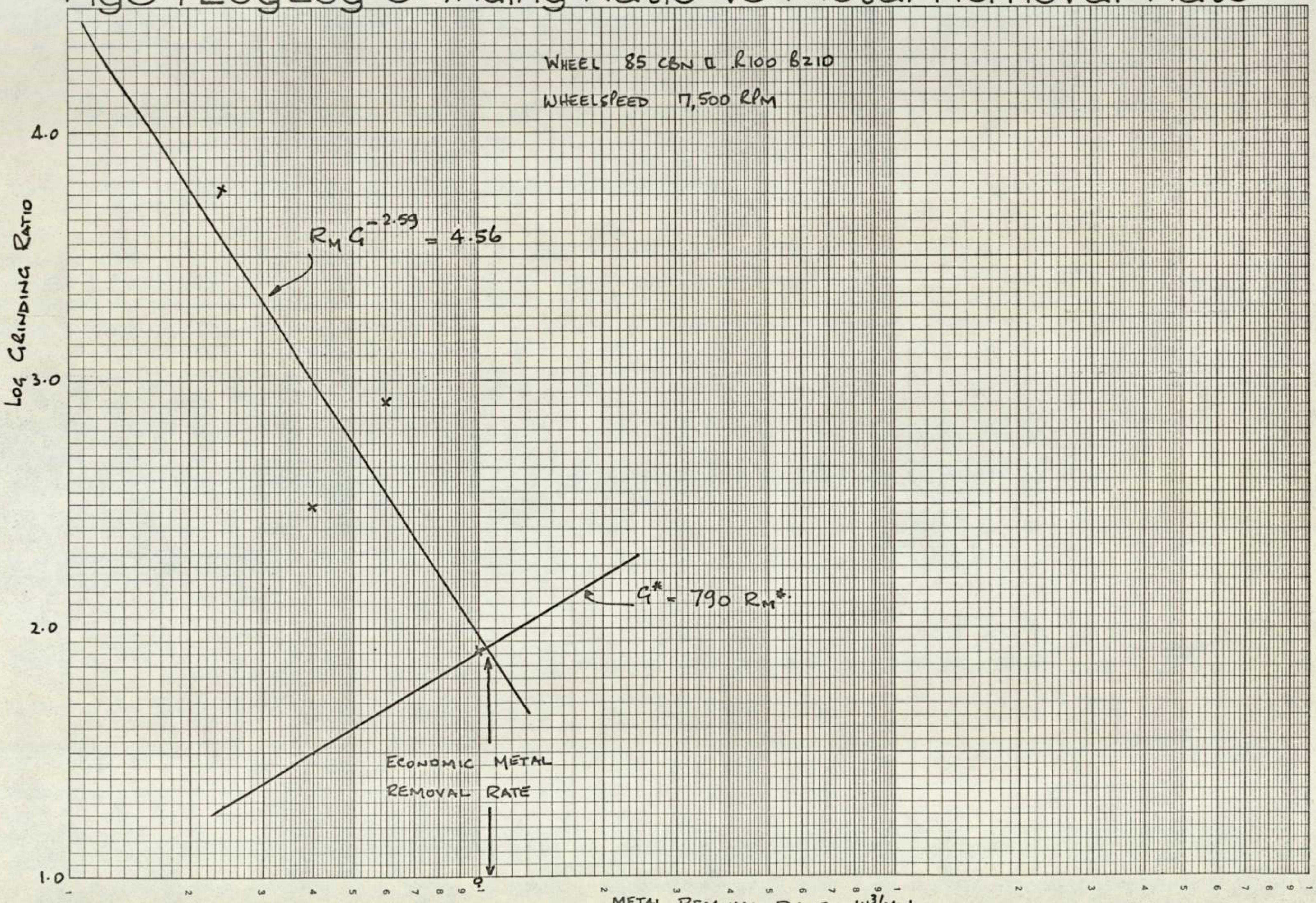


FIG.53 Cost vs Metal Removal Rate

Fig54 LogLog Grinding Ratio vs Metal Removal Rate



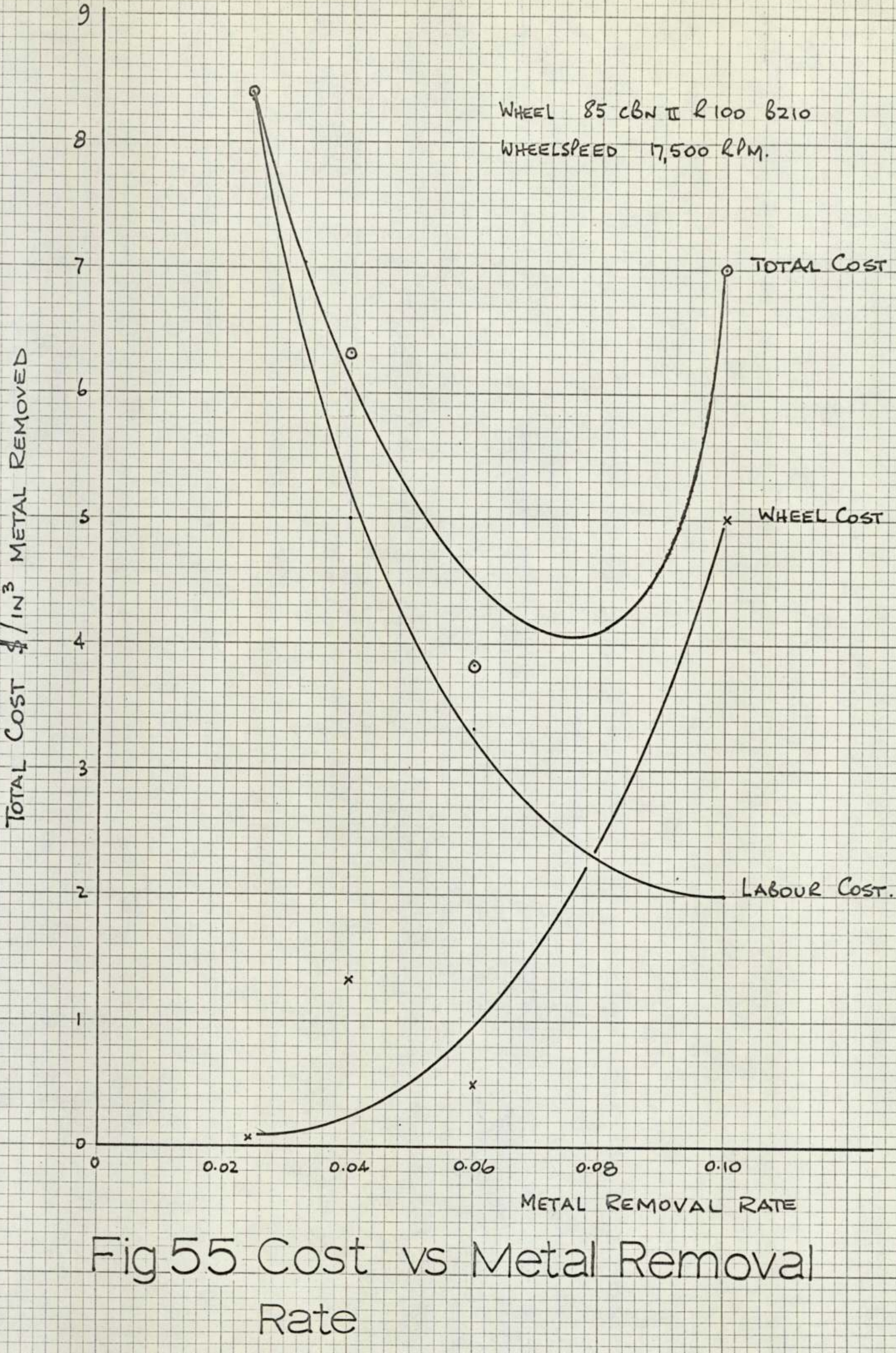


Fig 55 Cost vs Metal Removal Rate

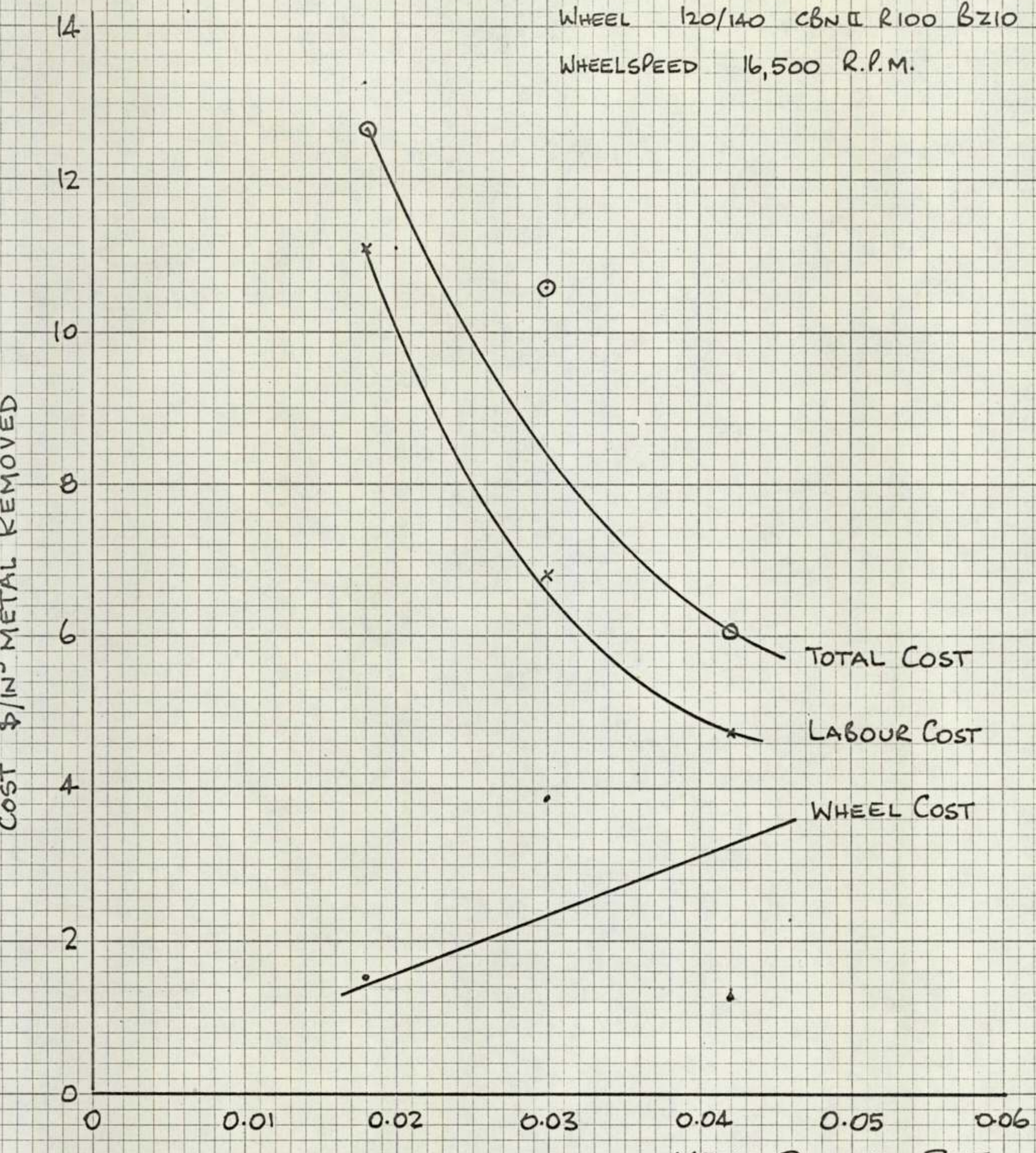


Fig 56 Cost vs Metal Removal Rate

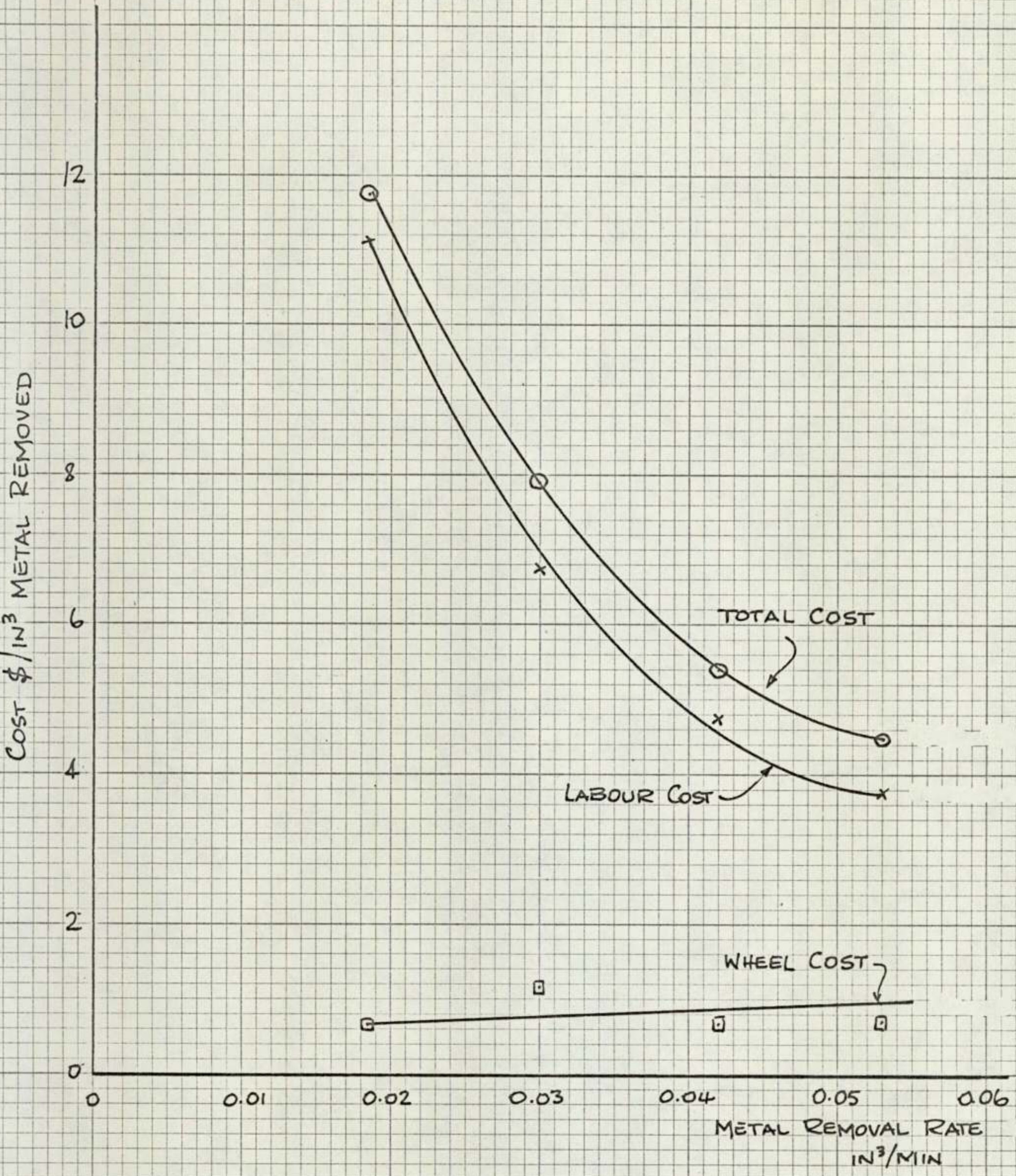
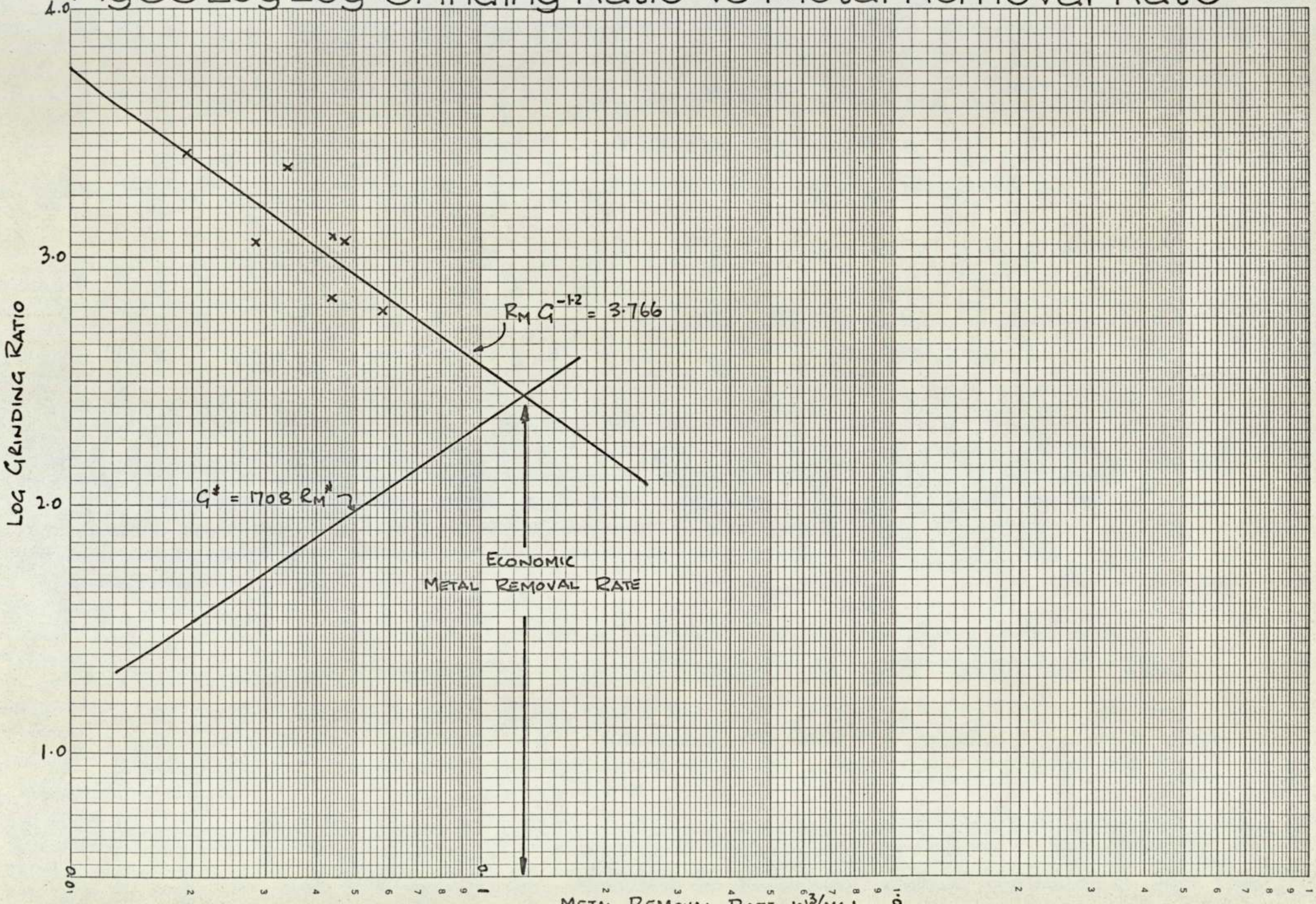


Fig 57 Cost vs Metal Removal Rate

Fig58 LogLog Grinding Ratio vs Metal Removal Rate



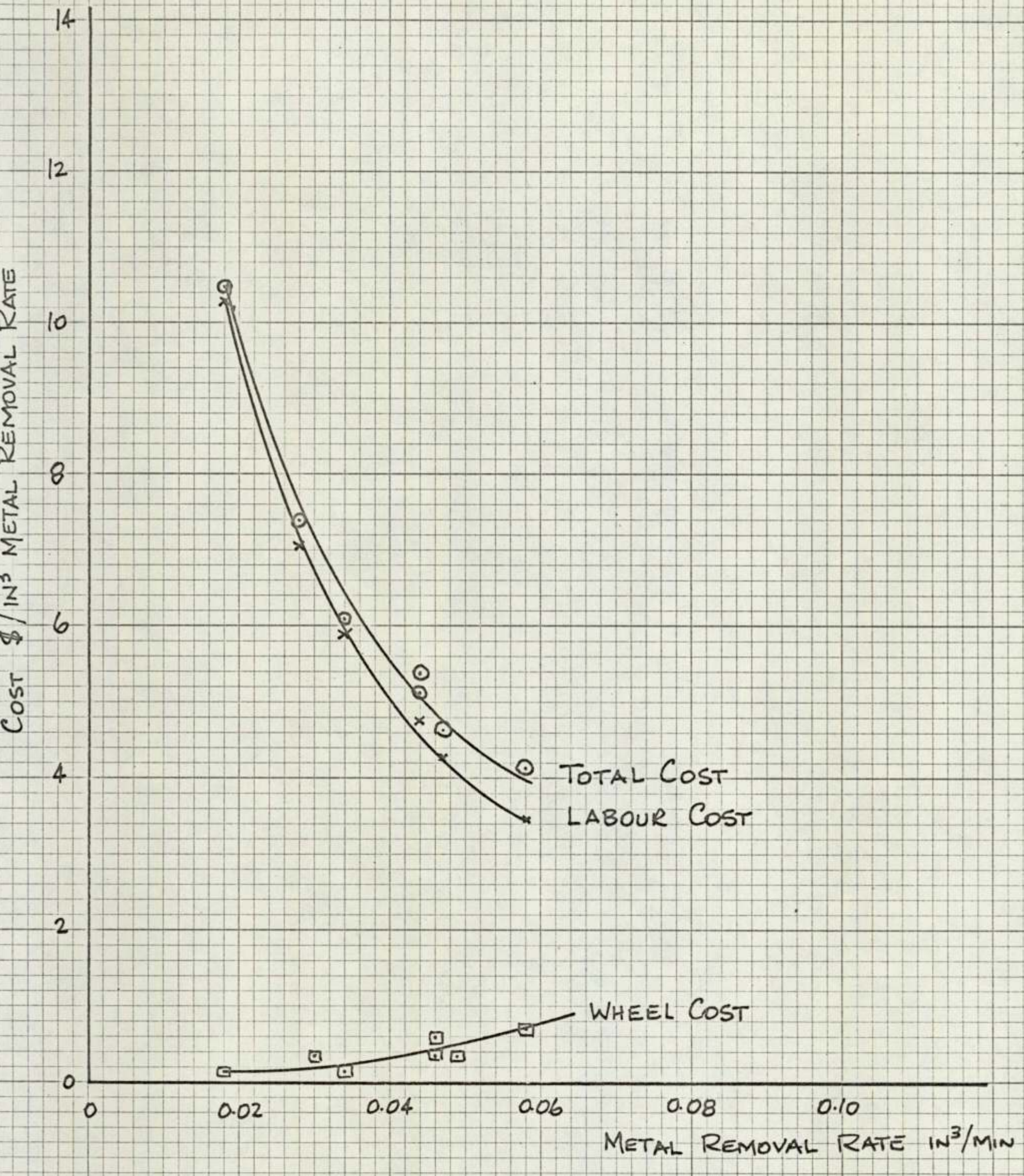
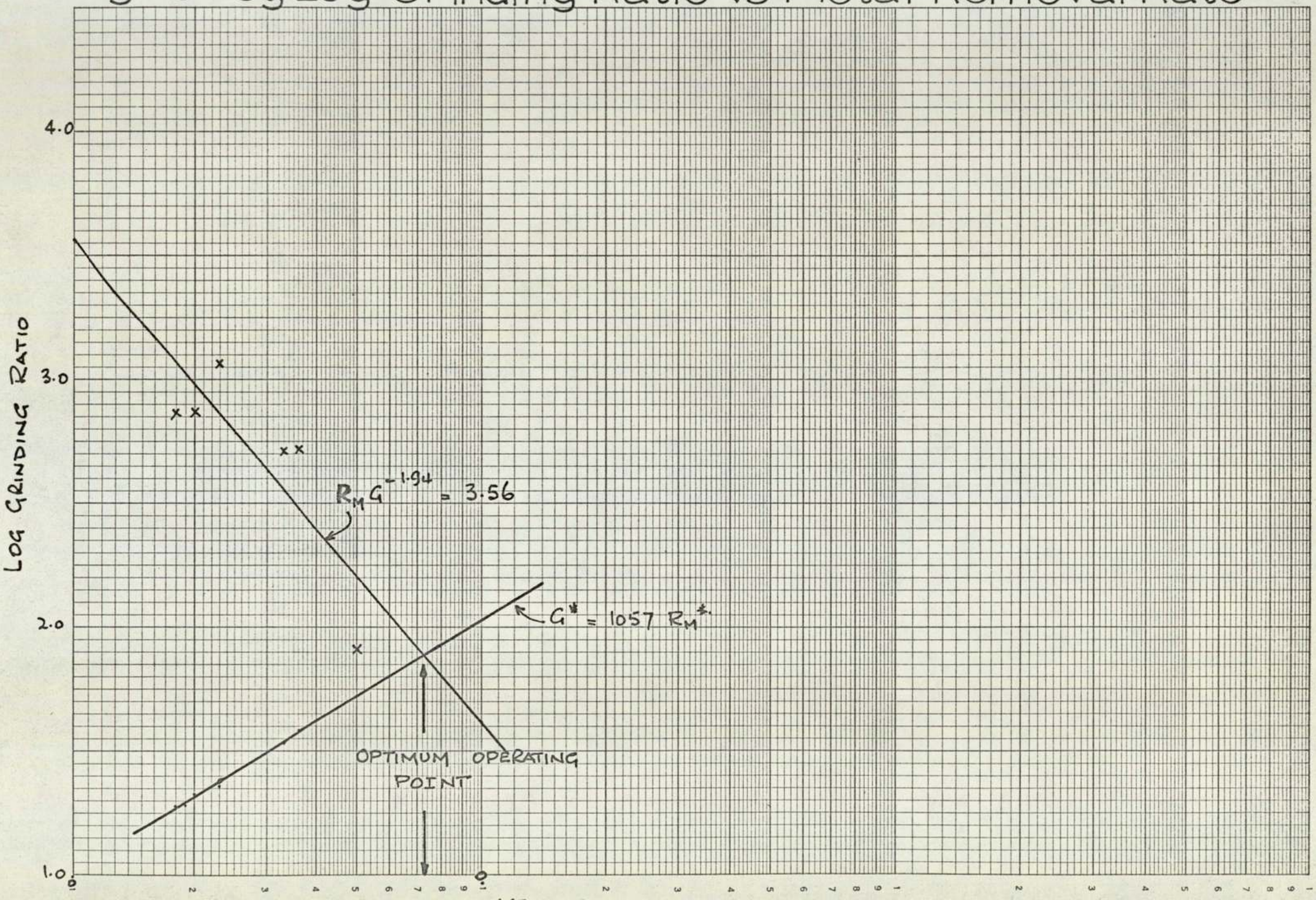


Fig 59 Cost vs Metal Removal Rate

Fig60 Log Log Grinding Ratio vs Metal Removal Rate



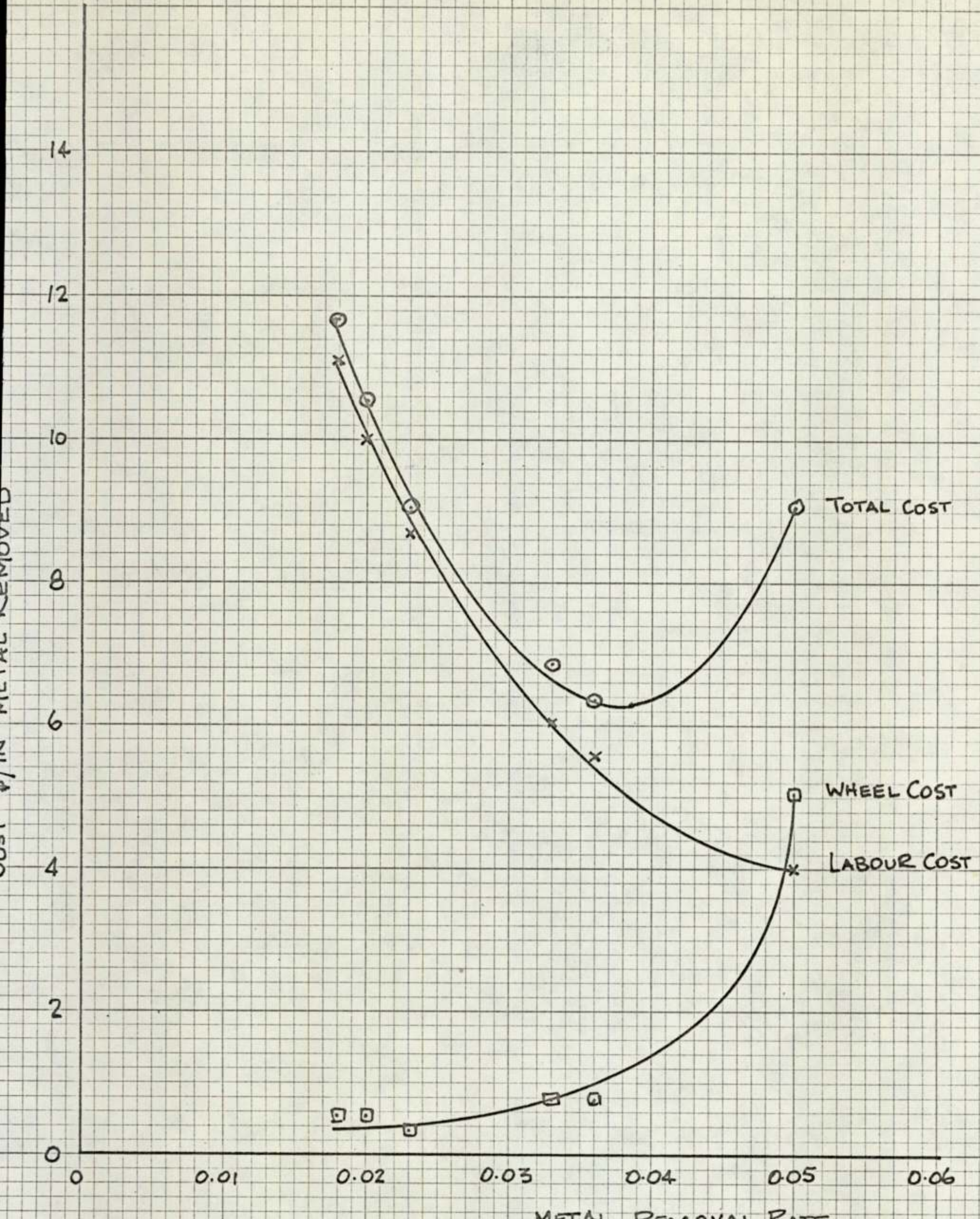
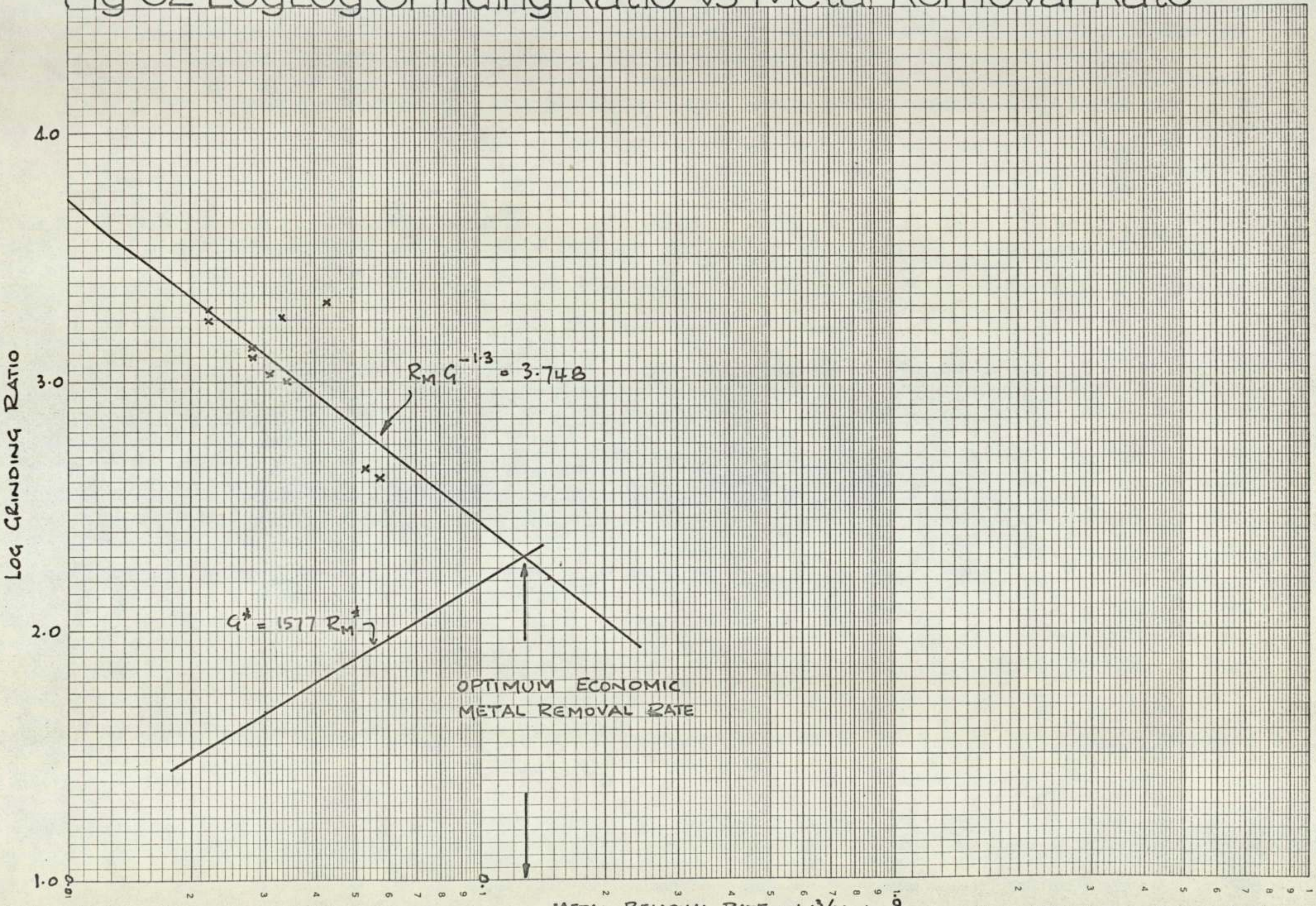


Fig 61 Cost vs Metal Removal Rate

Fig 62 LogLog Grinding Ratio vs Metal Removal Rate



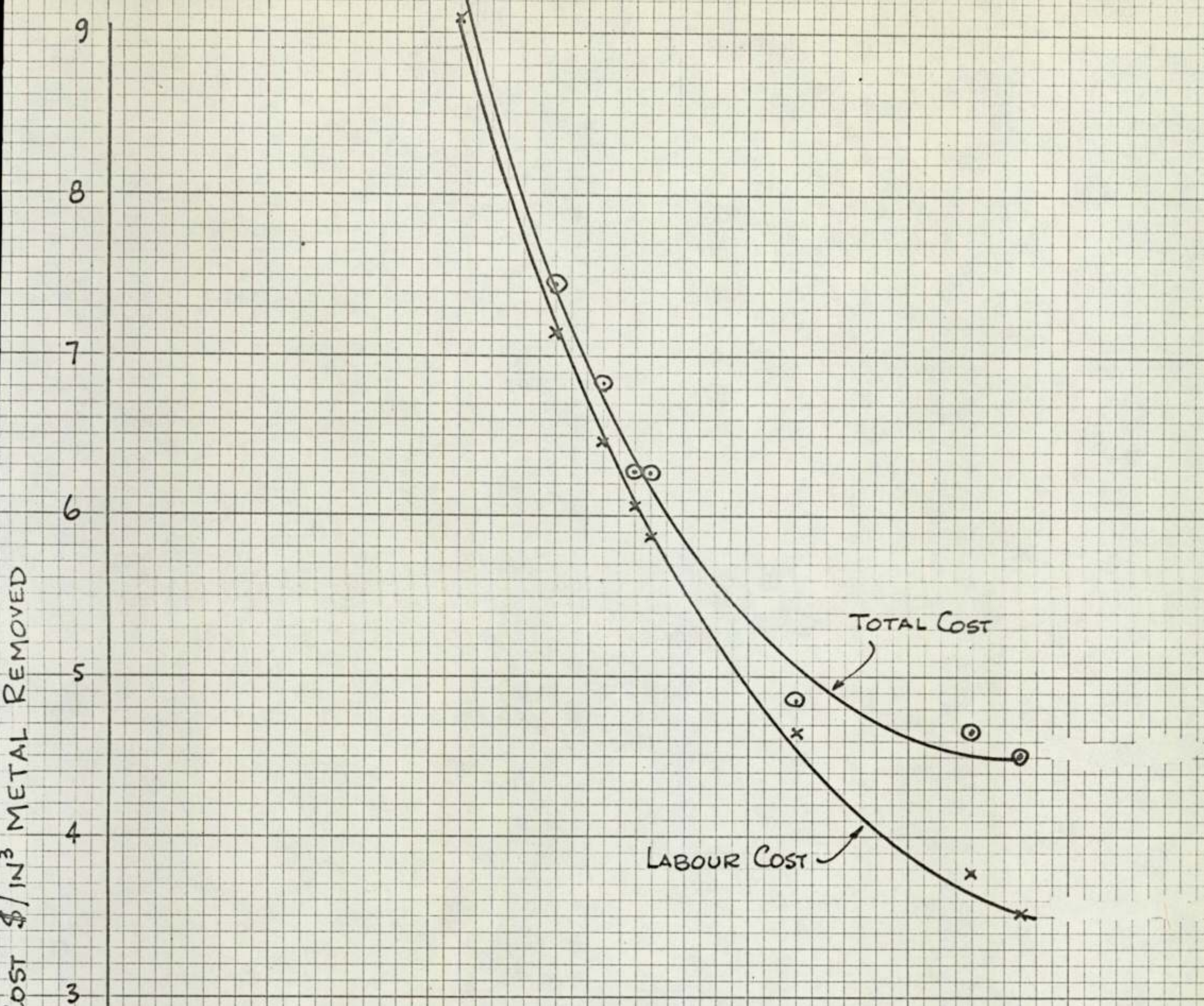


Fig 63 Cost vs Metal Removal Rate

Pick up piece and aside	0.067	
Chuck and remove piece	0.075	
Rapid traverse	0.046	
Dress wheel	0.093	
Compensate for finish grind	0.035	
Splash guard up and down	0.046	
Change wheel	0.061	
Gauging allowance	0.140	
Rough grinding	0.575	
Finish grinding	0.345	
	1.483	mins/piece

Fig. 64

Standard time data work sheet

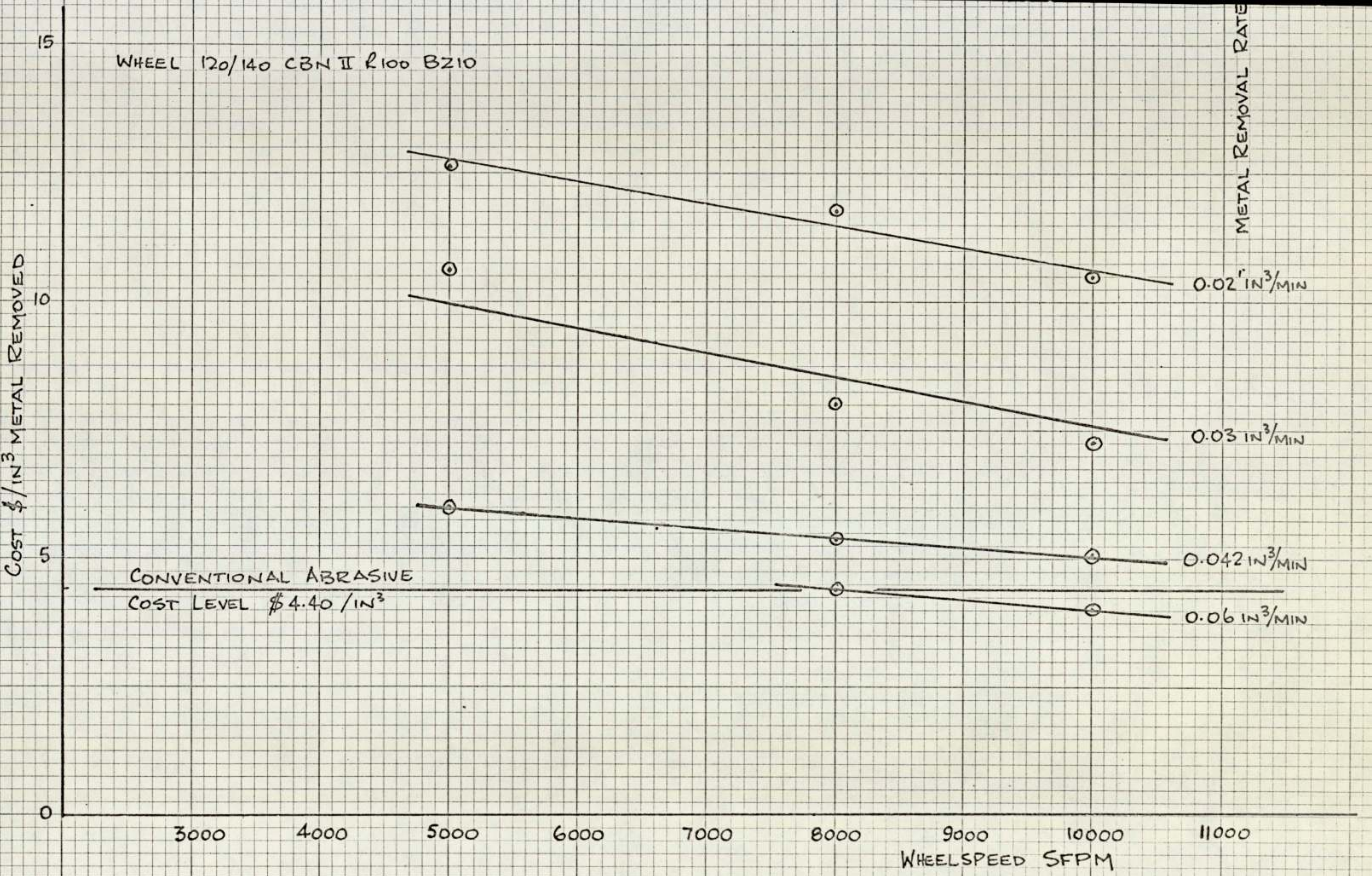


Fig 65 Comparison of Grinding Costs