DRILLING OF GLASS FILLED RESIN BONDED MATERIALS

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SUMMARY

Glass Reinforced Plastic (G.R.P.) laminated sheets have been in use for a number of years and can be drilled using H.S.S. drills although drill wear takes place at a high rate giving an inferior hole quality and delamination of the sheet at the exit side of the hole and, under certain conditions, at the entry side of the hole also.

The object of this project was to investigate the drilling of G.R.P. laminated sheet and to make recommendations for good drilling practice when using H.S.S. twist drills.

Although of a nominally specified amount, the glass content was found to vary considerably between the sheets used. The sheet with the lower glass content (60.78%) was used to determine the effect of variation in drill penetration rate using standard drills while the sheet with the higher glass content (74.32%) presented much more severe drilling problems through early discolouration of the hole and was used therefore to study the effects of variation in drill geometry on cutting performance.

The tests carried out have been quantified in terms of drill quality through the measureable parameters of torque, thrust and drill wear with the establishment of empirical torque and material removal factor (M.R.F.) values and hole quality through the measurable parameters of change in size, shape and surface finish.

Key Words: Drilling

Glass Filled Polymers

DECLARATION

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

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NOMENCLATURE

D = drill diameter 'mm'

r = radius being considered 'mm'

β = radius of the general point expressed in dimensionless form $\frac{2r}{D}$

R = drill penetration rate mm/min

$2t$ = web thickness 'mm'

τ = web thickness/drill diameter $\frac{2t}{D}$

L = lead of drill helix 'mm'

ν = helix angle of the drill

D = helix angle at periphery

$\gamma_f = \nu$ = helix angle equals tool side rake at any radius

α = relief at any radius

α_0 = nominal relief angle at outer corners of drill

α_f = tool side clearance angle equals drill relief angle

δ_c = plan inclination of chisel edge

λ_s = tool edge inclination

ϕ = inclination of cutting lip to the radius in plan

K_r = tool cutting edge angle

$2X$ = drill point angle

P_p = tool back plane

P_f = assumed working plane

P_{fe} = working plane

P_r = tool reference plane

P_n = cutting edge normal plane

P_s = tool cutting edge plane

P_O = cutting edge orthoganal plane

F = feed (mm/rev)

η = feed angle at any radius

NOMENCLATURE cont'd.

V_f = thrust N

T = torque Nm

C, C_3, C_4 = constants for the development of torque values

C_1, C_2, K_1, K_2 = constants for the development of thrust values

a and b = exponents for the development of torque and thrust values

H_v = Vickers Hardness Number

H_B = Brinell Hardness Number

M.R.F. = Material Removal Factor $\frac{(mm^3)}{J}$

$\bar{U}$ = specific cutting energy $\frac{(J)}{mm^3}$

Ra = roughness value 'um'

M.L.A. = (Roundness) Mean Line Average 'um'

L.S.C. = (Roundness) Least Squares Circle 'um'

ρ = specific gravity

σ = tensile strength $KN/m^2 \times 10^4$

$\sigma_1 \sigma_2$ = population standard deviations

α_1 = level of significance

CHAPTER 1.

INTRODUCTION

Glass Reinforced Plastic (G.R.P.) laminate sheets have been in use for a number of years and can be machined using High Speed Steel (H.S.S.) tool bits. The problems associated with machining of this type of material, and especially with the operation of drilling are, undue chipping, splitting and cracking of the brittle resinous surface, discolouration of the hole and delamination, Plate 22. Excessive heat is generated when the tools are not kept free from swarf(1) resulting in both the discolouration of the hole and the drill and also the emission of an unpleasant odour from the burnt material. All machining should be carried out without a lubricant(2) whenever possible because liquids tend to destroy one of the properties for which the material has been designed, namely its electrical property. Without the aid of a lubricant however, dust can form which can be an irritant to the operator. It has been suggested that the glass fibres which are released are not as dangerous as the fibres released from asbestos reinforcement. This has been expanded in more detail in Chapter 4. Various methods may be adopted to collect the dust and swarf mechanically from the work area. During the drill tests carried out for this project an industrial vacuum cleaner was used to remove the dust.

In all cases tools should be kept sharp to obtain a high standard of finish(3). This is the major problem to be overcome due to the abrasive nature of glass fabric base laminates. Tungsten carbide and diamond tools have been recommended by Farrel(1) depending on the length of run of the drilling operation; however these type of tools are costly and without knowing the glass content of the fabric can be uneconomic when compared with High Speed Steel tool bits or drills.

The major cause of difficulty to the drilling operation is the amount of glass per unit area which constitutes the fabric reinforcement. This feature has been expanded in the proceeding chapters.

CHAPTER 2.

GLASS REINFORCED PLASTICS

Laminated plastics are layers of sheet material impregnated with a resin and bonded by heat and pressure to form sheet, rod, tube or moulded shapes. The work described in the present work was carried out on a sheet material E.P. 4[8] defined as a Glass Fabric Reinforced Plastic with an Epoxide Resin binder. The sheet material is referred to as the reinforcement or base and the resin is referred to as the binder. There are many combinations of base and binder depending upon the properties required by the designer, Table 2.1 shows a number of the reinforcements and thermosetting resin combinations which are available.

2.1 Epoxy Resins

The first epoxide resin was made by Moss[9] in 1937, when he reacted glycerin dichlorhydrin with diphenylolpropane and caustic soda. Castan[10] in Switzerland in 1940 published work on the same theme. The use of amines for cross linking epoxide resins was proposed by Castan[11] and independently in America by Greenlee[12] in the late 1940's. With the availability of epichlorhydrin in bulk, commercial production on both sides of the Atlantic was established by 1955.

Epoxide resins are now made by condensing diphenylolpropane with a large molar excess of epichlorhydrin in the presence of ethanol as a diluent and sodium hydroxide as a catalyst. The reaction is continued for some hours at 60°C after which excess epichlorhydrin and the alcohol which is formed are distilled off and the sodium hydroxide removed by washing with water. This process gives a low molecular weight linear polycondensate. Unlike other resins which are self curing the epoxide resins require an added hardener which will react with the epoxy or hydroxyl groups forming cross links which are an essential part of the overall structure of the hardened resin. The most usual hardeners are aliphatic polyamines and acid anhydrides and hence the curable compositions consists essentially of two constituents, the epoxide resin ifself and the hardener. Plasticiser, flexibilisers, diluents and fillers can also be present as modifying constituents.

2.1.1 Properties of Epoxy Resin

(a) Mechanical Strength

Reinforced plastics based on epoxy resins as laminates have good overall mechanical strength and low weight. Epoxy laminated structural members are used in wing and fuselage members of jet aircraft. These structures maintain their strength over a wide temperature range.

Table 2.2 shows some of the mechanical properties possessed by the unfilled casting expoxy resin. Table 2.3 and 2.4 show some of the properties possessed by epoxy glass fabric laminates.

(b) Electrical

Cured epoxy systems show low power factor and high dielectric strength. The liquid forms are used for potting and encapsulating electric coils, switches, and other components for severe environments.

(c) Chemical

Before the hardener is added, epoxy resins are thermoplastic liquids or solids. The polymerised finished product is a thermosetting material which is highly resistant to caustic materials, many solvents and most acids.

Better chemical resistance is provided by the aromatic amine hardeners than by the aliphatic amines. Curing is obtained only at elevated temperatures with aromatic systems while the aliphatic systems cure at room temperature.

(d) Shrinkage

Unfilled epoxy resin shrink in the mould approximately 2 - 3% by volume. Incorporation of fillers reduce shrinkage to the range 0.25 - 1.25% by volume.

(e) Adhesion

Epoxy resins have good wetting and adhesion properties to non porous substrates which permits the bonding together of layers of fabrics and other materials.

2.2 Glass Fibres

It has been known for centuries that molten glass can be drawn into strands. It is also known that during the eighteenth century coarse glass mono-filaments were woven into fabrics and used as heating insulating materials but apart from this did not find many other industrial applications.

During the late 1930's Owens-Corning Fibreglass Corporation of the U.S.A. developed continuous glass fibre strand. It was found that certain types of molten glass could be drawn from orifices situated in the base of an electrically heated platinum crucible, the result being the production of continuous filaments of approximately 10 μm diameter. These strands were gathered together into a multi-fibre strand, sized and wound onto a high speed winding head, and processed into yarn on conventional textile machines. The yarn was then woven into fabric and used as a reinforcement for electrical insulation systems. A glass composition was then developed to give the required electrical properties. This was a glass containing not more than 1% of alkali metal oxide capable of being drawn into fine filaments; the glass became known as 'E' glass(8).

2.2.1 Properties of 'E' Glass Fibres

Most of the early work by Griffith(13), Smedal(14), Murgatroyd(15) and others showed that the tensile strength of 'E' glass filament increased with the decrease in the diameter of the fibre. Recent work by Thomas(16) showed that the breaking strength of 'E' glass fibre was independent of the fibre diameter and was around 345×10^4 KN/m^2 provided that the temperature of the molten glass from which the fibre was drawn was sufficiently high to permit a fibre of uniform diameter to be produced and that the fibre was carefully mounted prior to testing (under normal production conditions the breaking strength of

'E' glass fibre is in the range of 140 - 200 x 10^4 KN/m^2). Table 2.5 shows some properties of 'E' glass fibres.

Amory[17] found that the bending radius at rupture of different types of glass filaments increased with the increase in filament diameter, thus confirming the tendency to use finer filaments for textile processing and coarser filaments for strand reinforcements. Table 2.6 shows various types of filaments, their fibre diameter and bending radius.

In addition to the 'E' glass there are other glasses in commercial use, 'A' glass or High Alkali containing 10 - 15% of alkali, and 'S' glass.

'E' glass is essential for electrical applications and it is desirable to use this material where good weathering and water resistant properties are required.

'A' glass shows lower initial properties than 'E' glass and does not weather as well, but has better resistance to mineral acid attack and is usually used in chemical and nuclear applications.

'S' glass developed by Owens-Corning Fibreglass Corporation is more expensive to produce than 'E' glass but is claimed to be 40% stronger and is resistant to higher temperatures. Table 2.7 shows some mechanical properties of 'E' and 'S' glasses, Table 2.4 shows some mechanical properties of 'E' and 'S' glass with epoxy resin composites.

2.3 Glass Fabric

Yarn is produced from sized cake by first twisting the strands, the sizing being a coating which is applied to the filaments to stop abrasion which produces cracks[18]. It is important that the textile size be removed as this type is not compatible with either polyester or epoxide resin. Size removal is part of the production cycle of the glass reinforced plastic laminate sheet.

A double balanced yarn is obtained by plying a number of the twisted strands together. Designation of the type of yarn is called the "Count", the yarn count is expressed in terms of mass per unit length. The "Tex" system is the mass in grammes of a km of strand.

The yarn composed of 'E' glass is woven into fabric ranging from 30 μm - 560 μm thickness and up to 547 g/m^2 in mass(19).

The weave may be one of a number of constructions - Plain Weave (see Plate 1), Square Weave, Twill Weave, or Uni-directional Fabric, a fabric in which the strength is very high in one direction compared with the other direction, achieved by using heavy yarns in the warp and relatively light yarns open spaced in the weft.

2.3.1 Glass Fibre other than Fabric Form

Glass fibre may be processed in strand form only and not made up into fabric. The strand form may be of the following types:-

(i) Flock - disintegrated strand.

(ii) Chopped strands - available in lengths 6 mm, 12.5 mm, 25 mm, 50 mm, used in the production of "doughs" and "gunks" used in reinforced mouldings.

(iii) Rovings - a number of strands wound into a cheese or cone.

(iv) Woven Roving Fabric - heavier mass per m^2 than conventional fabrics 250 - 850 g/m^2, thickness 0.2 - 0.9 mm, used in composite laminates in conjunction with random chopped strands to give a thinner laminate with improved mechanical strength properties.

(v) Mat - Chopped Strand, continuous strand weave surface. In many applications glass fabrics and woven rovings give greater mechanical properties than those required. Therefore in certain applications a cheaper material is adequate. It was for this reason that mat manufacture was introduced.

2.3.2 Glass Proportions in Glass Fibre Reinforced Plastic

The proportion of glass is determined by the arrangement of fibres and can be divided into three categories.

(i) Fibres randomly distributed in the matrix. The fibres are generally short and because they are randomly arranged the maximum proportion is limited to 50% by weight, although in general this figure lies between 30 - 40%.

(ii) Fibres orthogonally arranged, generally in the plane of the laminate, by being woven into glass fabric or woven rovings. Because of the more orderly arrangement of the fibres the maximum percentage of glass will be higher in this category, generally 40 - 65% by weight.

(iii) Fibres laid in one direction which can be packed more closely therefore giving the highest percentage of glass. The maximum possible percentage of glass is 90.67% by volume although in practice it ranges from 60 - 90% by weight.

2.4 Production of Reinforced Sheets

Although laminates differ widely in composition they are all manufactured by similar processes. The reinforcement is impregnated with the synthetic resin and the resin is dissolved in a suitable solvent. The reinforcement is then passed through the resin solution with which it becomes impregnated, to control the resin content the speed of the reinforcement passing through the resin solution may be varied, or it may be passed through squeeze rolls with a suitable gap between them. The material is wet after passing through the rolls and is dried by heating; this drying removes the solvent and partially pre-cures the resin. The resin impregnated reinforcement is then guillotined to a convenient size. These "pre-pegs" are then stacked between the platens of a heated hydraulic press for 1 - 9 hours depending upon the thickness required and the resin used. After this treatment the layers of "pre-peg" are bonded together to form an almost homogeneous solid sheet. To maintain control of the quality of the resulting batch produced from the press it is recommended that the following sampling test[8] be carried out: 'One sheet of each batch or 10% of the sheets in the batch whichever is the greatest number should be subjected to Mandatory Requirements Test as laid down in BS 3953 - 1976 and shown in Table 2.8. If any of the samples fails to satisfy the limits specified for those tests a further 2 sheets or 20% of the batch whichever is the greatest number shall be tested, and if any of those fail the whole batch may be rejected and repeat type approval tests be carried out'.

Table 2.1 Resin/Reinforcement Combinations (Ref. 4)

Reinforcement	Resin				
	Phenolic	Melamine	Epoxide	Polyester	Silicone
Asbestos Paper	✓	✓			✓
Asbestos Fabric	✓	✓			
Asbestos Felt	✓				
Cellulose Paper	✓	✓	✓		
Cotton Fabric	✓	✓		✓	
Glass Fabric	✓	✓	✓	✓	✓
Synthetic Fibre Paper	✓				

Table 2.2 Resin Properties (Ref. 4)

Tensile Strength	28 - 90 MN/m^2
Elongation	3 - 6%
Compressive Strength	104 - 145 MN/m^2
Specific Gravity	1.11 - 1.4
Tensile Modulus E	24.19 GN/m^2
Flexural Strength	92 - 145 MN/m^2
Specific Strength	25 - 64 MN/m^2
Specific Modulus Average	17 - 22 GN/m^2
Hardness Rockwell M	80 - 110
Burning Rate	Slow
Water Absorbtion %	0.08 - 0.15

Table 2.3 Properties of Epoxy/Glass Fabric Laminates (Ref. 4)

Temperature °C	Flexure Strength MN/m^2	Flexure Modulus GN/m^2	Tensile Strength MN/m^2	Compressive Strength MN/m^2
23	524.4	22.77	379.5	358.5
72	483.0	22.00		
150	379.5	20.00		
205	276.0	19.32		
260	172.5	17.25	310.5	131.1

Table 2.4 Mechanical Properties of Composite Materials (Ref. 5)

Material	Specific Gravity ρ	Tensile Strength $KN/m^2 x10^4$ σ	Young's Modulus E $KN/m^2 x10^7$	Specific Strength σ/ρ $KN/m^2 x10^4$	Specific Modulus E/ρ $KN/m^2 x10^7$
Epoxy Resin with 70 Vol% 'E' Glass	2.1	107	4.8	51	2.3
Epoxy Resin with 70 Vol% 'S' Glass	2.11	207	6.1	98	2.8

Table 2.5 Properties of 'E' Glass Fibres (Ref. 6)

Specific Gravity	2.55
Tenacity	62g/tex
Tensile Strength	175×10^4 KN/m^2
Young's Modulus E	7×10^7 KN/m^2
Extension at Break	2.5%
Poissons Ratio	0.2
Coefficient of Thermal Expansion	$4.7 \times 10^{-6}/K$
Coefficient of Thermal Conductivity	1.05 W/mK
Dielectric Constant	6.44 at 10^2 Hz 6.11 at 10^{10} Hz

Table 2.6 Filament Diameters and Bending Radii (Ref. 6)

Filament Designation	Fibre Diameter µm	Bending Radius to Rupture µm
Beta	3.68	38.1
D.E.	6.40	66.04
G	9.02	93.98

Table 2.7 Mechanical Properties of 'E' Glass and 'S' Glass (Ref. 5)

Material	Specific Gravity ρ	Tensile Strength σ $KN/m^2 x 10^4$	Young's Modulus E $KN/m^2 x 10^7$	Specific Strength σ/ρ $KN/m^2 x 10^4$	Specific Modulus E/ρ $KN/m^2 x 10^7$
'E' Glass Fibre	2.55	170	7	67	2.8
'S' Glass Fibre	2.55	260	8	104	3.2

Table 2.8 Mandatory Requirements and Tolerances for E.P. 4 (Ref. 8)

Mandatory Requirements	Unit Value	Nominal Thickness at which property is measured
Cross Breaking Strength	345 MPa	Not less than 1.6 mm
Electric Strength edgewise in oil 90°C	40 KV r.m.s.	Greater than 3 mm
Loss Tangent 1 MHz	0.03	Not greater than 3 mm
Permittivity 1 MHz	5.5	Not greater than 3 mm
Insulation Resistance after immersion in water	5×10^3 MΩ	Not greater than 25 mm
Burning Time of Test Piece 10 mm x 15 mm wide	15 S	0.8 - 1.6 inclusive

Tolerance on Thickness of 25 mm - ± 1.5 mm

Flatness Departure from 1 m straight edge - 6 mm
Departure from 0.5 m straight edge - 1.5 mm

CHAPTER 3.

THE DRILLING OPERATION

3.1 Drill Nomenclature

Fig. 3.1 shows the features of the drill which are covered by BS 328, Part 1, 1972[20]. The two components of geometry which are capable of alteration and which have been the subject of investigation in the project are (i) the Drill Point Angle, and (ii) the Lip Clearance Angle.

3.1.1 Drill Point Angle

The drill point angle, which may vary from 60° - 180° depending on the work material and the class of work being carried out, is produced from the primary cutting edges so that when the drill is held on its plain diameter in the vertical plane a projection of the drill may be seen with each cutting edge tending towards a point. However the two cutting edges do not intersect, the minimum distance between them being the product of the web or core thickness and the Cosine of the chisel edge angle minus 90°. The half point angle can be considered to be the equivalent of the approach angle in single point cutting tools.

3.1.2 Lip Clearance Angle

Clearance on the drill from the main cutting edges is provided through the contour on the drill. This contour is obtained by holding the drill in a chuck in the horizontal plane and then setting the chuck at an angle equal to the required drill point angle. The drill is then rotated against the plane surface of a rotating grinding wheel producing a conical form between the primary cutting edges. The lip clearance angle can be considered to be the equivalent of the front clearance angle in single point cutting tools.

3.2 The Cutting Elements

Cutting is carried out through two distinct cutting elements (i) the primary cutting edges or lips which lie in parallel planes and are separated by a distance equal to the thickness of the web and (ii) the secondary cutting edge or chisel edge which is a continuation of the primary cutting edges back through the axis of the drill at an angle called the chisel edge angle. The fact that the chisel edge acts as a cutting element has been recognised by a number of workers[21,22,23].

Drills with a chisel edge point as described above[24] have no self centring capability and tend to produce a hole that is neither round nor straight. Therefore it is usual to centre-drill the workpiece before drilling to ensure the drill runs true or to use a drilling fixture with the appropriate drill guide bushes. (Neither of these points were used in the project as the hole centres and drill wander were not to be part of the parameters considered.)

3.2.1 The Cutting Action of the Drill

Although the primary cutting edges are quite efficient cutting elements, the same cannot be said for the chisel edge. If the drill is considered to be rotating with the primary cutting edges making contact with the workpiece material the advancing face of the chisel edge has a very large negative rake angle and the space ahead of this face is restricted leaving little or no area for the chip to escape. Consequently the cutting conditions in this area are extremely unsatisfactory because there is no possibility of free flow of the chip. Therefore after each drill regrind the web thickness should be checked to determine whether it is within the specified limits since the web thickness determines the length of the chisel edge. The web thickness increases as the drill point approaches the shank of the drill, the rate of increase being 0.013 mm/mm of length.

3.3 Drill Geometry

The conventional twist drill described in sections 3.1 and 3.2, has a complex geometry but nevertheless it resembles a conventional single point cutting tool. The difference is the variable inclination and rake angle due to the drill point contour, from the outer nominal radius towards the drill centre. The determination of the true rake angle at any radial location along the primary cutting edge has been defined by a number of workers[25,26].

Various Standards Organisations have also initiated systems for cutting tool nomenclature[27,28,29,30]. However none of these systems are related to the actual cutting operation and therefore other systems have been introduced, namely, BS 1296, Part 2, 1972[31] and the I.S.O. system[32]. These standards provide a means of defining the cutting tool geometry of the tool when it is removing material. The angles are defined with reference to the TOOL in USE system. The Standards[31,32] also recognise the practical implication of tool geometry for manufacturers and inspection and the angles are also specified with reference to the TOOL in HAND system.

Watson and Williams[33] have produced a research paper in which one of its aims is "to present general relationships for a lathe cutting tool and then to show the variations in the cutting conditions on the cutting lip and the chisel edge of a drill as both the radius of the considered point and feed change".

Their paper states that the rake and clearance angle will be functions of the helix angle and nominal relief angle respectively at the periphery hence the helix angle at the periphery is given by:-

$$\nu_o = \tan^{-1} \frac{\pi D}{L} \qquad \text{..... 3.1}$$

The helix angle decreases from this value at the periphery to effectively zero at the chisel edge. If it is assumed that the helix angle decreases uniformly over the cutting lip, the helix angle and the tool side rake angle at any radius will be:-

$$\nu = \gamma_f = \tan^{-1} \left[\frac{(\beta \cos \delta_c - \tau)\pi D}{(\cos \delta_c - \tau)L} \right] \qquad \text{..... 3.2}$$

The nominal clearance has been defined earlier in this chapter and hence for conically ground drills can be obtained from the method used by Galloway[22] who obtained the expression

$$\tan \alpha = \frac{\tau}{\beta}\left[1 - \left(\frac{\beta^2 - \tau^2}{1 - \tau^2}\right)^{\frac{1}{2}}\right] \text{Cotan}\, K + \frac{1}{\beta}\left(\frac{\beta^2 - \tau^2}{1 - \tau^2}\right)^{\frac{1}{2}} \tan\alpha_0 \quad \dots 3.3$$

These values relate to the TOOL in HAND system and therefore before the TOOL in USE angles can be derived the position of the drill in the drilling machine has to be considered. Fig. 3.2 shows the displacement of the above angles and planes relative to the TOOL in HAND system.

The working system set of axes as defined by Watson and Williams[33] coincides with the machine set of axes so that only the feed angle has to be considered. The feed angle η at any radius on the cutting lip is given by:-

$$\tan \eta = \frac{\text{Feed}}{\pi D \beta}\left(\frac{\tau}{\text{Cos}\,\delta_c}\right) \quad \beta < 1 \quad \dots\dots 3.4$$

The model used by Watson and Williams[33] to obtain the necessary relationships and enable the TOOL in USE angles to be developed was a bevel ground drill. The drill used in the present work was conically ground.

It is also stated that over the normal range of feeds only a small change in the parameters is produced at any radius on the cutting lips, and that on the chisel edge the feed angle is more pronounced and the rake and clearance angles change considerably with feed. As the radius is reduced from the chisel edge corner to the centre of the drill the magnitudes of the negative rake angles and the positive clearance angles are reduced. When the clearance angle is less than zero rubbing of the flank on the work surface occurs, and as the feed is increased the radius of the area of the rubbing contact increases.

3.4 Torque and Thrust in Drilling

It is very important to be able to predict the forces acting on the tool when considering the question of the design and application of drills.

The determination of torque and thrust and the power consumed during the drilling operation has been considered by several workers (23,25,34). Boston and Gilbert showed that

$$T = C F^a D^b \qquad \ldots\ldots 3.5$$

where C, a and b were constants for different materials.

Shaw and Oxford (35) stated that the specific cutting energy $\bar{u}$ is equal to the inverse of the metal removal factor (M.R.F.).

$$\text{i.e.} \quad M.R.F. = \frac{\text{Volume removed/min}}{\text{Power Consumed}}$$

$$\text{then } M.R.F. = \frac{\pi \frac{D^2 F N}{4}}{2\pi N T}$$

$$M.R.F. = \frac{D^2 F}{8T}$$

$$\frac{1}{M.R.F.} = \bar{u} = \frac{8T}{D^2 F} \qquad \ldots\ldots 3.6$$

Two further expressions were also developed by Shaw and Oxford (35) for Torque and Thrust,

$$\text{Torque} = C\, H_B\, F^a\, D^b \qquad \ldots\ldots 3.7$$

$$\text{Thrust} = C_1\, H_B\, F^a\, D^b + C_2\, H_B\, D^2 \qquad \ldots\ldots 3.8$$

If equation 3.8 is plotted in log form against both feed and diameter an approximation to the thrust can be obtained;

$$\text{Thrust} = K_1\, F^a\, D = K_2\, H_B\, F^a\, D \qquad \ldots\ldots 3.9$$

Bera and Bhattacharyya (25) developed a model for calculating torque and thrust during the drilling of ductile materials. For this theoretical model they applied the theory of wedge indentation (36) and calculated the indenting component of the thrust force at the chisel edge zone. The torque was calculated by considering the actual variation of chip thickness (37) along the cutting edge of the drill and then applying suitable angle relationships. However due to the brittle nature of the chip produced during the drilling of Glass Reinforced Plastics this approach is limited when compared with the method introduced by Shaw and Oxford[21] and Boston and Gilbert[34].

3.5 Distribution of Heat Generated in Drilling

Schmidt and Roubik[38] have investigated the problem of heat distribution in drilling to determine the amount of heat which goes into the workpiece, chips, and drill at different cutting speeds and feeds.

A tubular test bar of extruded Dowmetal was used as the workpiece, the outside diameter of which was slightly less than the drill diameter, thus making the cutting action of the drill similar to that of a single point cutting tool. The total heat, the heat in the chips, and the heat in the drill were measured separately in a calorimeter, and it was observed that thick chips mean less total work, lower tool temperature, and lower workpiece temperatures and that the major portion of the heat generated in metal cutting is carried away by the chips.

3.6 Drill Wear

An examination of worn drills reveals a wear pattern as follows:-

(i) Outer lip corner wear

(ii) Chisel edge wear

(iii) Flute cratering

(iv) Body land wear

(see Plate 2).

The value of drill wear is used as a basis for tool life analyses into optimum drilling conditions.

3.6.1 Measurement of Drill Wear

Most of the drill wear takes place at the primary cutting edge and at the outer lip corners. Several investigations have been made into the techniques of measuring drill wear. Billau and Heginbotham[39] stated that the width of the wear band produced on the lip clearance surfaces of a twist drill is not quantifiable in the same way as the wear band on the clearance face of a single point cutting tool because of the variation in the rate of wear along the primary cutting edge. They proposed that each cutting edge should be prepared with primary and secondary clearances by grinding the drill to a four facet type drill relief surface. Using an edge of this type a typical wear situation is obtained where the trailing edge of the primary clearance band is undamaged and can be used as a datum for measurement.

Lenz, Mayer and Lee[40] used a Vicker's hardness indentation on the drill as a reference point and wear propagation was observed using a Scanning Electron Microscope at 200x magnification. The drill land provides a clearance during drilling and this margin wears first at one cutting edge and then at the second until all the clearance has been eliminated. The loss of this clearance results in the catastrophic failure of the drill and therefore it would appear that an acceptable criterion of drill life is the point at which one of the lips loses the clearance.

In this work the method used by Billau and Heginbotham[20] was not used because with the equipment available the maximum drill size which could be ground with the four facet relief was 6 mm. The roundness stylus used on the Talyrond 90 measuring instrument could not be used in bores less than 9 mm. in diameter.

The method of Lenz, Mayer and Lee[40] was not fully adopted because the indentation could not be maintained in the same position for all the drills used, hence a compromise was made by checking the corner of each drill before drilling and then at various stages during drilling with the aid of a Nikon projector.

The wear value on a high speed steel drill after drilling a Glass Reinforced Plastic is difficult to estimate because wear on the drill takes place as follows:-

(i) at the corners of the drill,

(ii) along the cutting edge,

(iii) at the drill point.

The model used for the determination of drill wear in the present work is as follows. With reference to Fig. 3.3, A - C is the wear on the corner of the drill magnified 100 X. However the profile shown of cutting edge B - G cannot be the original cutting edge. Because of the symmetry of the drill (Plate 2) a certain amount of the cutting edge must be removed to enable a curve to be produced on the corner of the drill. The object of the model is to obtain the approximate position of the original cutting edge and hence an approximate wear value.

If point A is on the circumference of the drill, then point A_1 will be the intercept on the helix angle. A vertical datum line was constructed through A_1 and an helix angle ν was produced. B was projected to B_1 and where this projection line cut the vertical datum the required clearance angle was produced. The point at which this line cuts the helix at E was assumed to be the original corner of the drill. The point E was then projected across to obtain E_1 and hence the original cutting edge E_1 - H was produced.

Having obtained the approximate original profile the following method was used to obtain a wear value. The line E_1 - F is the elevation line of the lip clearance; thus the point where the curve A - C cuts the line E_1 - F was projected onto the side elevation to obtain X - X_1, the point X_1 being the farthest point that wear can take place along the land between the clearance and helix angles. X_1 - A_1 and X_1 - C_1 were joined to form triangles A_1 X_1 E and E X_1 C_1. The area of these triangles was taken as the wear value.

This method takes into consideration the following features:-

(i) the length and depth of the curve A - C,

(ii) the relative length of wear along the land,

(iii) the position of A_1 and C_1 along the helix and cutting edge respectively.

The above method was compared with the corner area method and the drill wear obtained by each method. However the values of the areas obtained were found to be different due to the greater area obtained by the analytical method. i.e. the area obtained from the corner wear is given by $A \times 10^{-6}$, while the area obtained from analytical method is given by $A \times 10^{-4}$, thus a correction factor was obtained by determining the average of the ratios of the areas obtained analytically to those obtained from the corner area. The corner area for each of the various lip clearance angles was then multiplied by this correction factor and was called the estimated area 'E'. The area 'E' was compared with analytical area 'B' using the Mann-Whitney U test, the result of which showed no significant difference between the two methods. Fig. 7.5 shows the estimated and triangular wear values plotted against lip clearance angle each curve showing minimum wear with a $12\frac{1}{2}^{\circ}$ lip clearance angle.

CHAPTER 4.

EXPERIMENTAL EQUIPMENT

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

4.1 Radial Drilling Machine

The machine tool was a KITCHEN WALKER radial drilling machine having the following tabulated speeds and feeds:-

FAST SPEEDS (rev/min) 1560, 1150, 586, 520, 445, 370, 272, 200, 128

SLOW SPEEDS (rev/min) 316, 233, 115, 105, 90, 75, 55, 40, 25

FEED (mm/rev) 0.088, 0.150, 0.175, 0.250, 0.300, 0.350, 0.400, 0.700, 1.000

The actual speeds were obtained by checking the unloaded drill chuck with a SMITH'S tachometer giving the following results:-

FAST SPEEDS (rev/min) 1660, 1190, 630, 530, 460, 386, 286, 212, 140

SLOW SPEEDS (rev/min) 320, 250, 130, 110, 94, 80, 60, 43, 27

The feed rates were checked by comparing the time scale on the Torque graphical trace with the speed of the graph paper,

e.g. Spindle speed 130 rev/min, Feed 1.0 mm/rev

Average length of graphical trace = 15.9 mm

Length of drilling to clear drill point = 28.25 mm

Paper speed = 75 mm/min

$$\text{Drilling time} = \frac{\text{Trace length}}{\text{Paper speed}}$$

$$= \frac{15.9 \times 60}{75} = 12.72 \text{ secs}$$

$$\text{Feed} = \frac{\text{Drilling length}}{\text{Spindle speed} \times \text{Drilling time}}$$

$$= \frac{28.25 \times 60}{130 \times 12.72} \simeq \underline{1 \text{ mm/rev}}$$

4.2 Cutting Tool

The cutting tool was a High Speed Steel (A.I.S.I. M2) drill of 9.53 mm nominal diameter. A quantity of drills were obtained from the same material batch with the same heat treatment.

4.3 Workpiece Material

The workpiece material was an EPOXY RESIN bonded 'E' Glass Reinforced Plastic Laminate Sheet of 25 mm nominal thickness with a tolerance of $\pm$ 1.5 mm, with flame retardant properties. The BS designation for this material is E.P. 4[8]. Two sheets of length 1220 mm and 610 mm width were used. One sheet had a glass content of 60.78% and was denoted as SHEET 1 and the other had a glass content of 74.32% and was denoted as SHEET 2.

The material was cut into lengths of 305 mm and widths of 56 mm, this allowed for three rows of holes along the length of the sheet with at least 6 mm between each hole. The drilling sequence of holes in the material was arranged to allow at least a spacing of seven holes between each drilling position to ensure that the heat developed did not affect the drilling performance on the following holes.

4.4 Force Measuring Equipment

A mechanical 2 - force drill dynamometer was used for the drill tests to determine torque and thrust values, this was considered to be satisfactory for the work being carried out because measurement of a third component "drill drift" was not a feature under consideration. The dynamometer was fitted with a dial test indicator to obtain the thrust values, and a transducer and TALYMIN 4-10 rectilinear recorder to obtain the torque values. The system was calibrated by means of weights for the torque units and a prooving ring for the thrust units. Plates 3 and 4 show the dynamometer and method of calibration respectively and Chart 1 is the calibration chart for the torque and thrust units and Chart 2 is the calibration chart for the recalibrated torque units (see Appendix 3). Recalibration of the torque units was required because the Talymin 4-10 recorder was serviced.

The dynamometer was clamped to the table of the radial drilling machine with the workpiece clamped to the table of the dynamometer, this is illustrated in Plates 5 and 6. The drilling operation was carried out without the use of a liquid coolant thus enabling the material to retain its required electrical properties.

4.5 Measurement of Drill Parameters

Before the drilling operation commenced the drill was ground to the test drill point angle and lip clearance angle using a BRIERLEY drill grinding machine ZB 25, capacity 1 mm - 25 mm. The angles obtained from the grinding operation were checked using a NIKON projector (Plates 7, 8 and 9) the point angles and a NIKON measurescope for the lip clearance angles.

4.6 Measurement of Hole Parameters - Sheet 1, Specification

The roundness and straightness of the holes used in the tests were obtained with the aid of a TALYROND 90 fitted with the appropriate attachments and rectilinear recorders and computer. Plate 10 illustrates the method used.

The burr or "build up" on the material at the entry and exit of the drill was given through a Talymin 4-10 recorder and motorised table. A suitable stylus was made to the drawing specification shown in Fig. A.2.1. Plates 11, 12 and 13 show the equipment set-up.

The diameter of each hole used in the appropriate test was checked by using a Hole Gauge and a Diameter Measuring Machine. Plates 14, 15 and 16 show the equipment and the method adopted.

The surface finish of the appropriate test holes was obtained with the aid of a SURTRONIC 3, with a digital display of the "Ra" value.

4.7 Glass Fibre Swarf

Before the drilling of the material took place the local Department of Health and Safety was consulted regarding any health hazard to the operator or anyone else working in the vicinity where drilling was taking place. The answer was that at that date, February, 1976, no written information was available but the material in bulk or as swarf was not considered detrimental to the operator.

For this reason all drilling which was carried out on the Glass Filled Laminate Sheet was done with the aid of an industrial vacuum cleaner which removed the swarf at the source i.e. at the interface of the drill and the material, by fitting the nozzle close to the work area.

It was found that when the sheet which contained the high glass content was drilled the chip produced was discontinuous and powdery whilst with the lower glass content the chip was of a continuous nature, see Plate 24. However in each case when the vacuum cleaner was emptied all the swarf found in the cleaner bag was in a powdery form, this is consistent with previous findings[47].

CHAPTER 5.

EXPERIMENTAL PROCEDURE

5.1 Optimum Penetration Rate - Sheet 1

Tests were carried out on the material using various drill penetration rates, combinations of speeds (rev/min) and feeds (mm/rev) were categorised into close cells and referred to as Test 1 etc. Forty holes were drilled through the material at a predetermined penetration rate and the torque and thrust values noted at Hole No's 1, 10, 20, 30, 40. Drill wear was noted at Hole No. 40.

The drill specification for all the tests was as follows:-

Point Angle	$118^\circ \pm 1^\circ$
Lip Clearance Angle	$11\frac{1}{2}^\circ \pm \frac{1}{2}^\circ$
Helix Angle	$30^\circ \pm 2^\circ$
Lip Height Difference	0.025 mm (max)

The roundness of each hole was taken at Hole No's 1, 10, 20, 30, 40. The position that the stylus was fixed in the hole was kept at 190 mm on the vertical column of the TALYROND 90. Both computer and graphical values were tabulated for each test.

The straightness of each hole used in the tests was taken at 0° - 180° and 90° - 270° using a TALYROND 90 with a vertical arm. A starting point of 200 mm was set on the vertical column for each hole and the stylus was allowed to pass through the hole. Graphical traces for each hole at the four specified points were taken from which straightness, taper, and intrusion were obtained. (Intrusion is shown on the graph as the amount above the trace of straightness just before the stylus passes out of the hole, i.e. at the point where the stylus comes into the unloaded condition.)

The value of the burr or "build up" was determined by passing the workpiece, fixed to the motorised table, under the stylus of the TALYMIN 4-10 recorder and the graphical trace for Hole No's 1, 10, 20, 30, 40 across one axis at the entry and exit side of the drilled hole was obtained.

The diameters of Hole No's 1, 10, 20, 30, 40 were checked by placing the Hole Gauge into the appropriate hole and feeling the fit of the measuring contacts in the bore. Measurements over the instruments contact faces were taken by means of a Diameter Measuring Machine which was used for the following reasons:-

(i) when a hand micrometer was used, too many discrepancies where found when rechecking took place,

(ii) greater accuracy of determination is possible using this instrument than with a normal hand micrometer.

The first and last hole of each penetration test was tested for surface finish with the aid of a SURTRONIC 3. Before the tests were carried out the instrument was calibrated. The holes chosen had several positions along the bore checked using a sampling length of 0.8 mm and the highest value was then tabulated and shown in Table 6.3.

5.2 Significance Tests

The following significance tests were used to analyse the results:-

(i) $2\sqrt{N}$ Test,

(ii) SPEARMAN'S Rank Order Correlation Coefficient,

(iii) PEARSON'S Product Moment Correlation Factor.

5.2.1 Drilling Constants C, a and b

Varying feed values from previous tests were taken and graphs of Log T and Log F were plotted. Further tests using different diameter drills were carried out, the torque values noted, and graphs of Log T against Log D were plotted.

From the above graphs the values of the exponents a and b were obtained and the constant C was computed after applying exponents a and b into the equation. Hence the emperical equation for torque, i.e. $T = C\,F^a\,D^b$, was established. Throughout this series of tests the best straight line method was used to obtain the slope values, i.e.

$$\acute{m} = \frac{XY - 4XY}{X^2 - 4X^2} \qquad (48)$$

5.3 Optimum Drill Point Angle - Sheet 2

To determine the optimum drill point angle, tests were carried out using Sheet 2 as the workpiece material. The following drill point angles 100°, 110°, 118°, 130°, 140° were ground on five different drills, the limits on the angles being kept to $\pm 1^\circ$ with a difference in lip height of 0.025 mm maximum.

Each drill in turn was used under the following conditions - Speed 1190 rev/min, Feed 0.088 mm/rev. The torque and thrust values were noted and the drill corner wear was found at Hole No's 30, 60, 90. The above series of tests were repeated to obtain a measure of significance.

The two tests were compared for torque and thrust using the MANN-WHITNEY U Test and the wear value for each drill used compared using the $2\sqrt{N}$ Test. The F Test was carried out to obtain information regarding difference in tests.

5.4 Optimum Lip Clearance Angle

Various Lip Clearance Angles of the following values 8°, 9°, 10°, $11\frac{1}{2}^\circ$, 13°, 16°, 17°, $18\frac{1}{2}^\circ$, were ground on a number of drills. The drill point angle was kept at $130^\circ \pm 1^\circ$ and the lip height difference at a maximum value of 0.025 mm.

Holes were drilled in the material at a speed of 1190 rev/min and a feed of 0.088 mm/rev. Torque and thrust values were noted for each drill and the wear value calculated using the modified drill wear method.

CHAPTER 6.

INFLUENCE OF DRILL PENETRATION RATE ON DRILL AND HOLE QUALITY

Prior to the actual drilling project taking place a preparatory series of holes were produced using a standard 9.53 mm diameter twist drill, point angle $118^{\circ} \pm 1^{\circ}$, lip clearance angle $11\frac{1}{2}^{\circ} \pm \frac{1}{2}^{\circ}$, to determine if there were any health hazards from the glass composition of the swarf produced by the drilling operation. It was possible that the swarf was an irritant and that the laminate could emit the type of odour which is a characteristic of certain other types of reinforced plastic laminate sheets when burning occurs due to the action of the drilling operation. It was found however that the chips produced from the drilling operation were of a continuous nature and were easily collected by means of an industrial vacuum cleaner and that no detectable odour was given off by the material.

6.1 Variation of Drill Penetration Rates

Because the material appeared to present few problems when drilled with a conventional twist drill, the first series of tests was carried out to obtain the optimum penetration rate of the drill. The penetration rate applies to any size of drill diameter and was used as a parameter in the tests because only one size of drill was used. An important feature however which must not be overlooked is that of the volume of material removed. This can be used instead of the penetration rate when varying drill sizes are being used as part of a test. The material removal rate is given by the product of the hole area and the penetration rate.

A standard H.S.S. twist drill was used and the effect on both the drill and the hole was noted at various penetration rates. The proceeding work in this chapter divides the information obtained from the tests into two categories, (i) Drill Quality, which determines how the penetration rate affects the drill parameters, and (ii) Hole Quality, which determines how the penetration rate affects the parameters of the drilled hole.

6.2 Drill Quality

6.2.1 Drill Wear

It was found in all the tests carried out that the measurable drill wear took place on the corners of the drill. The method of obtaining drill wear was described in Chapter 3. Table 6.1 shows the tests carried out on penetration rates with the relevant drill wear value expressed as a quantitative value and also as a percentage of the lip clearance land removed during the drilling operation. When the results were analysed it was found that there was a direct relationship between the two methods of expressing drill wear and that in every one of the tests carried out the greatest drill wear took place when the penetration rate was the product of the highest speed and the lowest feed used in any of the tests.

A possible reason for the change in the drill wear pattern is the structure of the material used and the manner in which the drill approaches the material to be removed. The sheet is made of layers of glass fabric and the resin binder. Thus when a high feed rate is used the corners of the drill are not allowed to work through the same distance per revolution in the hard glass matrix as a drill with a low feed rate with the result that less wear takes place on the drill with the higher feed rate. A further possible reason for drill wear is expanded on in the next section.

6.2.2 Torque and Thrust Forces

Bera, Bhattacharyya[25] and other workers[34,35] have resolved the torque and thrust values into two components, (i) the torque and thrust required for cutting only, and (ii) the torque and thrust required to overcome friction at the cutting faces. The resultant of the two components is given by:-

(i) Total Torque = Torque when cutting + Torque to overcome friction

(ii) Total Thrust = Thrust when cutting + Thrust to overcome friction

The results shown in Table 6.2 are total values in each case and it can be seen that in each series of tests the difference between the torque and thrust values obtained at the beginning and end of the test is greatest where the largest amount of wear takes place on the drill.

As stated earlier in this chapter the measureable drill wear takes place on the corners of the drill, and as described in Chapter 3, this corner wear results in a slight displacement of the primary cutting edges of the drill. The wear takes place due to the friction between the cutting edges and the hard glass matrix of the material. With the wear of the cutting edges taking place during the drilling operation each hole drilled increases the rubbing area between the cutting edges and the material and hence the torque and thrust elements due to friction will increase. Thus the distortion of the true cutting conditions requires greater values of torque and thrust forces to accomplish the drilling operation. The biggest changes in these values take place where the greatest wear takes place, i.e. with a penetration rate having a high speed low feed combination.

As stated earlier, thrust forces become greater with an increase in feed and when high feed rates are applied the value of the thrust force is a major factor in maintaining a steady value for the surface finish of the hole. Table 6.3 shows the "Ra" values for the first and last hole of each penetration test with the relevant thrust values. When low feed rates are used, up to 0.40 mm/rev, it can be seen that high "Ra" values are produced. This is due to two factors (i) the material under the action of the thrust force is resilient enough to accept the load without permanent set and (ii) the drill wear distortion does not create the ideal cutting conditions and hence the glass part of the matrix tends to become enlarged by a rubbing action of the drill spreading the ends of the cut glass fabric. The two conditions become complementary and produce a surface which is much more open and hence rougher. However when the higher feed rates are applied the resulting thrust forces are high enough to compress the material, thereby tending to fracture the glass fabric in the resin binder in the vicinity of the drilling operation. The material removal during the drilling operation under high feed conditions is by cutting of the resin binder with the fractured glass inclusion, the result of which produces less frictional resistance to the drill and hence less wear.

The structure of the material before and after the drilling operation can be clearly shown with the aid of surface projection. Before drilling, the ends of the glass fabric are shown to be an orderly arrangement in the resin binder (Plate 17). After drilling with a low feed the structure is shown to be less orderly with the ends of the glass fabric shown to be slightly enlarged (Plates 18, 18a, 19). When the high feed is used the structure is shown to be compressed and elongated and more orderly arranged (Plates 21, 21a). It is from the structural conditions in the three states that the conclusions in the preceeding paragraphs have been derived.

6.2.3 Estimated Values of Torque and M.R.F.

It has been previously shown in Chapter 3 that the value of the torque T may be estimated from the equation[34]

$$T = C\,D^{a}\,F^{b} \qquad \text{..... 6.1}$$

The values of the exponents a and b were determined by plotting Log T against Log D for exponent a, and Log T against Log F for exponent b (Figs. 6.1, 6.2). Exponents a and b were found to be 1.5 and 0.7 respectively, giving

$$T = C\,D^{1.5}\,F^{0.7} \qquad \text{..... 6.2}$$

When T was taken from the results of the drill tests and inserted into equation (6.2) a value for C was obtained for each of the tests giving an average value of C to be 0.22 with a standard deviation of 0.027. Therefore for this particular material a reasonable value for C is 0.22, and

$$T = 0.22\, D^{1.5}\, F^{0.7} \qquad \text{..... 6.3}$$

The Material Removal Factor (M.R.F.) is an indication of the machinability of a material, is a function of the drill diameter, feed and torque, and is independent of speed. It has been previously shown in Chapter 3 that the M.R.F. value is given by:-

$$\text{M.R.F.} = \frac{D^2 F}{8T} \qquad \text{..... 6.4}$$

Table 6.4 shows a summary of the M.R.F. values over the range of feeds used for the tests. The M.R.F. values were obtained by inserting the value of the torque for the given feed into equation (6.4). An empirical formula for the M.R.F. may be obtained by using equation (6.3) to determine T and then inserting this value of torque into equation (6.4) from which,

$$\text{M.R.F.} = \frac{D^2 \times F}{8 \times 0.22 \times D^{1.5}\, F^{0.7}} \qquad \text{..... 6.5}$$

$$= \text{M.R.F.} = \frac{D^{0.5}\, F^{0.3}}{1.76} \quad \frac{\text{mm}^3}{\text{J}} \qquad \text{..... 6.6}$$

From Table 6.4 it can be seen that the best values of M.R.F. occur when a high feed is used for the penetration rate. The reason for the improved M.R.F. values when using high feeds has been presented earlier in the chapter implying that with high feed low speed penetration rates more of the total torque is used for cutting and less is absorbed in overcoming friction.

6.2.4 Power Consumed and Change in Power Consumed

Power is the product of the torque and the distance the drill turns through in a given time, i.e. Power = Torque x Angular velocity. In all of the tests carried out it was found that the power consumed at the drill point at the last hole of each test was lowest when the penetration rate was a product of a lower speed and high feed. In addition, if the difference between the power consumed at the last hole and the power consumed at the first hole is called the "change in power" then the change in power is seen to be lower when the penetration rate is the product of a low speed and a high feed. A possible reason for this has been discussed in the previous paragraph 6.2.3 in relation to change in torque. Power values and change in power values are shown in Table 6.2. Figs. 6.3 and 6.4 show the power consumed at hole no. 40 plotted against measured drill wear and the change in power plotted against measured drill wear respectively. It can be seen that with low power change values the values of measured drill wear are also low. It would appear from the above that when the penetration rate is the product of a low speed and high feed a smaller proportion of the total torque is used to overcome friction accompanied by a smaller amount of drill wear and change in power.

6.3 Hole Quality

The preceeding sections have discussed the effects on the drill after drilling G.R.P. laminate sheet. The following sections will discuss the effects on the hole. The hole qualities which were measured were size, shape, and surface finish.

6.3.1 Hole Diameters

In all but one of the tests carried out the diameter of the first hole drilled was within 0.023 mm of the nominal diameter of 9.53 mm. The diameter of the drilled hole changes as the drill wears. The greatest change takes place with those drills which show the greatest wear namely those drills which have been used at the lower feed rates. This change in diameter is quite reasonable when the effect of the drill wear is considered. When the drill corners wear the sizing part of the drill is slightly removed and hence with increase in drill wear the change in the diameter of the drilled hole will increase. Table 6.5 shows the diameter of the holes drilled for various penetration rates.

6.3.2 Hole Roundness, Taper and Surface Finish

The values obtained for taper from the TALYROND 90 graphical trace show that there is very little taper in the holes, the largest average value being 3.5μm/25 mm, which for most practical purposes may be ignored. The taper values together with the maximum deviation from a straight line in the bore are shown in Table 6.6.

The roundness of each hole used in a particular test is used as a comparison between the holes drilled at a predetermined penetration rate. It can be seen from Tables 6.7 and 6.9 that the best values for roundness occur when high feed rates are used. This may be due to two possible reasons (i) when a high feed rate is used the drill is not allowed to stay close enough to one spot long enough to chip off the resin between the glass fabric causing irregularities which are transmitted through the stylus of the TALYROND 90 to the graphical trace and (ii) the effect of compression of the material discussed in 6.22 when high feed rates are used causes the material in the bore to present a more solid resistance to the drill and leave the bore rounder due to less irregularities.

The surface finish of the bore shows some important features. When a test consists of feed rates which are close to each other in value there is very little difference in the "Ra" values, Table 6.3. When a test consists of feed rates which have high and low values then the "Ra" value is lower with the higher feed rate. A possible reason for this effect of high feed rates producing better "Ra" values has been presented earlier in paragraph 6.22 when the effect of compression of the matrix was discussed.

A feature which was discovered from the taper tests was that of intrusion. The intrusion is the material of the bore which is left in the mouth of the hole after the completion of the drilling operation. It is shown in the graphical trace as a large movement of the stylus in the load-on direction just as the stylus is leaving the mouth of the hole. A schematic impression of intrusion is shown by Fig. 6.5 and as a computable value in Trace 1 (1190 rev/min, 0.088 mm/rev).

Table 6.6 shows the value of the intrusion at the exit side of the drill. The intrusion is shown to increase with increase in drill wear. At the higher feed rates the value of the intrusion is shown to remain relatively constant over the range of holes drilled, but at the lower feed rates where the rate of drill wear increases rapidly the value of the intrusion fluctuates.

A possible cause of the intrusion is that it could be part of the burr on the side of the material where the drill breaks through. This burr is drawn back into the mouth of the hole when the drill is withdrawn. This appears to be a feasible explanation because the burr on the drill entry side of the material is greater than that which appears at the drill exit side. The effects of burr are discussed later in paragraph 6.3.3. Fig. 6.6 shows the average value of the intrusion at diametrically opposite points on the perimeter of the hole i.e. at 0° and 180°, at 90° and 270°, plotted against hole number for all of the tests. This figure also includes the burr "build up" at the exit side of the sheet.

6.3.3 Burr "Build Up" and its Possible Removal

The burr referred to in the preceeding paragraph may be defined as a ridge or lump which may be more or less sharp[41]. The burr which forms on metal from a cutting operation can be assumed to be due to the tool not being as sharp as it should be. In the case of the drilling operation the drill partly cuts but also acts as a punch forcing the final piece of material in the bore down and around the periphery of the hole. When the burr which appears on G.R.P. laminated sheet is analysed its formation is not quite the same as that which appears on metal.

With a laminated structure the burr is partly formed by the tool wearing and also by delamination of the outer layers of the sheet, Trace 2. In the case of drilling, lifting occurs at the entry side due to the withdrawal of the drill and at the exit side of the material as the drill breaks through.

Table 6.8 shows the burr build up at the entry and exit sides of the material. It can be seen from Fig. 6.7 that in all the tests the build up on the material at the entry side of the hole is greater than at the exit side of the hole. A possible reason for this has been discussed in 6.3.2 i.e. that the material is drawn back into the mouth of the hole on the return of the drill producing a small burr and high intrusion at the exit side of the material and a larger burr and small intrusion at the entry side. This can be seen clearly from Trace 2 and 2a where delamination is shown at both entry and exit on Trace 2. Trace 2 shows delamination of the surface;this can be seen also from Plate 22 and 22a. Trace 2a shows a burr without delamination and this effect is shown by Plate 23 and 23a.

The removal of the burr on G.R.P. laminate sheet can require a further operation during the machining operation such as linishing. Removal of the burr is not completely carried out using a drill or similar tool without a countersinking effect taking place. In Chapter 2 the nominal flatness of a satisfactory sheet was quoted as a maximum gap of 6 mm between the sheet and a metre straight edge. It can be seen from Table 6.8 that if one edge of the hole is higher than the other the removal of the burr completely is not so easily carried out without more of the edge on one side being removed when a rigid tool such as a drill or countersink rose is used to remove the burr.

Graphical Trace 3 shows the flatness of the motorised table on which the workpiece was supported whilst passing under the stylus of the TALYMIN 4-10 Recorder and the relative flatness of the sheet. The length of the trace has a horizontal magnification of 1. Further traces numbered 4 and 5 show the amount of burr removed by rotary and hand linisher with the greatest amount and most evenly displaced being removed by hand linishing. When the value of the burr build up is plotted on the intrusion graph for the same conditions as shown in Fig. 6.6 it can be seen that when the size of the burr build up at hole no. 40 lies between the intrusion values of the entry and exit, there is only a small change in the diameter of the hole from that of the first hole drilled and that when the size of the burr build-up lies outside the intrusion values then a greater change in hole diameter has taken place. This effect of change in diameter discussed in 6.31 occurs to a large extent where the greatest wear on the drill takes place.

The effect of the drill withdrawal on intrusion may be carried a stage further to give a possible reason for the disposition of the burr and intrusion and its effect on the change in diameter of the hole. As the drill wears on its corners it is not able to clear the skin of the material away from the perimeter of the drilled hole at the exit side of the material to produce a clear hole. On its return the drill due to the rounded corners of the primary cutting edge cannot draw back into the mouth of the hole the stronger fibres now surrounding the perimeter of the hole. This then results in a greater value for burr build up and a small value for the intrusion, although the main reason for the larger changes in diameter is drill wear.

6.4 Summary of Results

Tables 6.10 and 6.11 summarise all the results obtained from the tests carried out, and various statistical tests have been applied which show the following points:- (Appendix 5 page 110)

(i) There is a correlation between change in diameter of the drilled hole and drill wear. The greatest change in diameter occurs with the greatest drill wear.

(ii) There is a correlation between the change in diameter of the drilled hole and the roundness of the hole. With the largest change in diameter there will be the higher ranges of roundness values (L.S.C.).

(iii) There is a correlation between the change in roundness of the drilled hole and drill wear. The roundness deteriorates as the drill wears.

(iv) There is a correlation between the feed rate and the surface finish "Ra". The "Ra" value improves with increase in feed rate.

The above features (i), (ii) and (iii) should show correlation because they are all dependent factors. However point (iv) is contrary to the normal machinability feature of a metal, namely that surface finish should improve with a low feed rate because the machining wavelengths are closer together thus decreasing the average roughness height.

When drilling this type of material using high speed steel twist drills, longer tool life and better hole qualities are obtained when the penetration rate is a combination of a low speed and a high feed. Bogdanov[42] quotes speeds of 15 - 20 m/min when turning glass reinforced plastic using high speed steel tool bits, i.e. 500 - 650 rev/min drill spindle speed when using a 9.53 mm diameter drill. It has been shown however that in the case of the drilling operation it is the feed rate which is the important parameter. The feed rate influences the thrust force which by compressing the material produces in the material the optimum cutting condition.

P.E.R.A.[43] have developed a formula for feed rate to suit most materials using the hardness of the material from which;

$$\text{Feed} = \frac{2.2\ D^{0.7}}{H_v} \qquad \ldots\ldots\ 6.7$$

When the values of hardness of the material used in the present work, i.e. 45 - 55 H_v, are inserted into equation 6.7 then feed rates of 0.5 mm - 0.625 mm/rev are obtained. These values are within the range of values obtained from the experimental work found to give best results i.e. at feeds above 0.4 mm/rev.

Table 6.1 Drill Wear and Penetration Rates

Tests to obtain the optimum feed rate (mm/rev) given that the penetration rate "R" is the product of the feed (mm/rev) and the speed (rev/min).

Test 1 $\bar{R}$ = 132 mm/min, Range 10 mm/min

Speed rev/min	Feed mm/rev	"R" mm/min	No. of holes drilled	Drill Wear $mm^2 \times 10^{-2}$	Drill Wear % lip clearance removed
530	0.25	132	40	1.26	20
460	0.30	138	40	1.18	20
320	0.40	128	40	0.83	10
130	1.00	130	40	0.63	10
Test 2 $\bar{R}$ = 156 mm/min, Range 15 mm/min					
1660	0.088	146	40	4.45	50
630	0.25	158	40	1.97	33
530	0.30	159	40	1.50	25
460	0.35	161	40	1.38	25
Test 3 $\bar{R}$ = 210 mm/min, Range 20 mm/min					
1190	0.175	208	40	1.89	30
630	0.35	220	40	1.81	25
530	0.40	212	40	1.46	20
286	0.70	200	40	0.31	8.3
Test 4 $\bar{R}$ = 294 mm/min, Range 12 mm/min					
1660	0.175	290	40	2.0	30
1190	0.25	298	40	1.57	25
286	1.00	286	40	0	8

Table 6.1 cont'd

Test 5 $\overline{R}$ = 459 mm/min, Range 26 mm/min

Speed rev/min	Feed mm/rev	"R" mm/min	No. of holes drilled	Drill Wear $mm^2 \times 10^{-2}$	Drill Wear % lip clearance removed
1190	0.40	476	40	1.93	30
630	0.70	440	3	Drill Jammed in hole	
460	1.00	460	3	" " " "	
Test 6 $\overline{R}$ = 101 mm/min, Range 6 mm/min					
1190	0.088	104	40	3.39	50
250	0.40	100	40	1.69	13
140	0.70	98	40	0.83	8
Test 7 $\overline{R}$ = 364 mm/min, Range 14 mm/min					
1190	0.30	357	40	1.57	25
530	0.70	371	40	1.26	15
Test 8 $\overline{R}$ = 406 mm/min, Range 30 mm/min					
1660	0.25	415	40	4.41	50
1190	0.35	416	40	1.89	25
386	1.00	386	40	1.26	12

Table 6.2 Torque, Thrust, Power, Power Change, M.R.F. and C values

Test 1 Speed = 530 rev/min, Feed = 0.25 mm/rev, R = 132 mm/min

Hole No.	Torque Nm	Thrust N	Power W	Change in Power W	MRF $\frac{mm^3}{J}$	C
1	2.28	323	126		1.26	0.2
10	2.46	323				
20	2.65	376				
30	2.65	475				
40	2.83	565	157	31	1.02	0.25
Speed = 460 rev/min, Feed = 0.30 mm/rev, R = 138 mm/min						
1	2.46	323	118		1.40	0.19
10	2.65	376				
20	2.83	427				
30	2.83	475				
40	3.02	521	145	23	1.14	0.24
Speed = 320 rev/min, Feed = 0.4 mm/rev, R = 128 mm/min						
1	3.20	376	107		1.44	0.20
10	3.20	376				
20	3.39	427				
30	3.39	475				
40	3.75	521	126	19	1.23	0.24
Speed = 130 rev/min, Feed = 1.0 mm/rev, R = 130 mm/min						
1	5.79	766	79		2.03	0.19
10	6.16	766				
20	6.53	803				
30	6.53	911				
40	6.72	946	91	12	1.75	0.22

Table 6.2 cont'd

Test 2 Speed = 1660 rev/min, Feed = 0.088 mm/rev, R = 146 mm/min

Hole No.	Torque Nm	Thrust N	Power W	Change in Power W	MRF $\frac{mm^3}{J}$	C
1	1.36	200	236		0.74	0.25
10	1.54	376				
20	1.72	475				
30	1.72	565				
40	1.72	649	298	62	0.59	0.32
Speed = 630 rev/min, Feed = 0.25 mm/rev, R = 158 mm/min						
1	2.46	265	162		1.17	0.22
10	2.65	323				
20	2.83	376				
30	3.02	427				
40	3.30	495	211	49	0.90	0.28
Speed = 530 rev/min, Feed = 0.3 mm/rev, R = 159 mm/min						
1	3.39	265	188		1.02	0.26
10	3.51	323				
20	3.94	427				
30	3.94	475				
40	3.94	521	218	30	0.88	0.30
Speed = 460 rev/min, Feed = 0.35 mm/rev, R = 161 mm/min						
1	4.13	323	198		0.98	0.29
10	4.13	323				
20	4.31	376				
30	4.31	427				
40	4.31	475	207	8	0.94	0.30

Table 6.2 cont'd

Test 3 Speed = 1190 rev/min, Feed = 0.175 mm/rev, R = 208 mm/min

Hole No.	Torque Nm	Thrust N	Power W	Change in Power W	MRF $\frac{mm^3}{J}$	C
1	1.72	160	214		1.19	0.20
10	2.09	376				
20	2.09	521				
30	2.09	689				
40	2.46	728	306	92	0.82	0.28
Speed = 630 rev/min, Feed = 0.35 mm/rev, R = 220 mm/min						
1	3.20	265	211		1.26	0.22
10	3.39	376				
20	3.39	475				
30	3.39	521				
40	3.76	565	248	37	1.07	0.26
Speed = 530 rev/min, Feed = 0.4 mm/rev, R = 212 mm/min						
1	3.39	376	188		1.36	0.24
10	3.39	475				
20	3.57	521				
30	3.57	521				
40	3.57	521	198	10	1.28	0.25
Speed = 286 rev/min, Feed = 0.7 mm/rev, R = 200 mm/min						
1	4.68	803	140		1.72	0.20
10	4.68	840				
20	4.68	840				
30	4.68	840				
40	4.68	840	140	0	1.72	0.20

Table 6.2 cont'd

Test 4 Speed = 1660 rev/min, Feed = 0.175 mm/rev, R = 290 mm/min

Hole No.	Torque Nm	Thrust N	Power W	Change in Power W	MRF $\frac{mm^3}{J}$	C
1	1.54	200	268		1.31	0.19
10	1.91	376				
20	2.09	564				
30	2.09	766				
40	2.09	820	363	95	0.97	0.24
Speed = 1190 rev/min, Feed = 0.25 mm/rev, R = 298 mm/min						
1	2.28	265	284		1.17	0.20
10	2.28	427				
20	2.46	565				
30	2.65	649				
40	2.83	766	352	68	1.02	0.25
Speed = 286 rev/min, Feed = 1.0 mm/rev, R = 286 mm/min						
1	6.16	803	184		1.92	0.20
10	6.16	803				
20	6.16	900				
30	6.16	900				
40	6.16	900	184	0	1.92	0.20
Test 5 Speed = 1190 rev/min, Feed = 0.40 mm/rev, R = 476 mm/min						
1	2.83	323	353		1.62	0.19
10	2.83	427				
20	3.55	565				
30	3.55	649				
40	3.55	76	443	90	1.29	0.23

For R = 441 mm/min and 460 mm/min results unobtainable due to drill jamming in hole.

Table 6.2 cont'd

Test 6 Speed = 1190 rev/min, Feed = 0.088 mm/rev, R = 104 mm/min

Hole No.	Torque Nm	Thrust N	Power W	Change in Power W	MRF $\frac{mm^3}{J}$	C
1	1.35	124	168		0.75	0.25
10	1.72	323				
20	1.91	427				
30	2.09	475				
40	2.09	565	260	92	0.48	0.38
	Speed = 250 rev/min, Feed = 0.40 mm/rev, R = 100 mm/min					
1	3.76	376	98		1.23	0.24
10	3.76	376				
20	3.76	475				
30	3.94	521				
40	4.13	521	108	10	1.12	0.26
	Speed = 140 rev/min, Feed = 0.70 mm/rev, R = 98 mm/min					
1	5.42	607	79		1.49	0.23
10	5.42	689				
20	5.61	766				
30	5.51	766				
40	5.59	803	85	6	1.39	0.25
Test 7	Speed = 1190 rev/min, Feed = 0.30 mm/rev, R = 357 mm/min					
1	2.28	265	284		1.52	0.19
10	2.46	376				
20	2.46	521				
30	2.46	607				
40	2.65	607	330	46	1.30	0.21

Table 6.2 cont'd

Test 7 Speed = 530 rev/min, Feed = 0.7 mm/rev, R = 371 mm/min

Hole No.	Torque Nm	Thrust N	Power W	Change in Power W	MRF $\frac{mm^3}{J}$	C
1	5.49	475	321		1.49	0.23
10	5.79	521				
20	6.16	565				
30	6.16	607				
40	6.35	649	352	31	1.23	0.28
Test 8	Speed = 1660 rev/min, Feed = 0.25 mm/rev, R = 415 mm/min					
1	2.46	323	428		1.17	0.22
10	2.65	376				
20	2.83	521				
30	2.83	565				
40	3.20	689	556	128	0.90	0.28
	Speed = 1190 rev/min, Feed = 0.35 mm/rev, R = 416 mm/min					
1	3.20	376	399		1.26	0.22
10	3.20	376				
20	3.20	475				
30	3.40	607				
40	3.57	649	445	46	1.13	0.25
	Speed = 386 rev/min, Feed = 1.0 mm/rev, R = 386 mm/min					
1	6.16	689	249		1.92	0.20
10	6.16	803				
20	6.16	803				
30	6.16	840				
40	6.35	840	257	8	1.86	0.21

$\overline{C}$ = 0.218 Standard Deviation = 0.027

Table 6.3 "Ra" Values at First and Last Holes

Test 1 $\overline{R}$ = 132 mm/min

Speed rev/min	Feed mm/rev	Penetration Rate mm/min	Hole No. 1 Ra µm	Hole No. 1 Thrust N	Hole No. 40 Ra µm	Hole No. 40 Thrust N	Thrust Difference N
530	0.25	132	3.8	323	13.0	565	242
460	0.30	138	3.5	323	12.7	521	198
320	0.40	128	3.6	376	5.3	521	145
130	1.00	130	3.8	980	3.7	1046	66
		Test 2 $\overline{R}$ = 156 mm/min					
1660	0.088	146	14.0	200	17.5	649	449
630	0.25	158	13.0	265	16.5	495	230
530	0.30	159	13.0	265	15.2	521	256
460	0.35	161	13.4	323	16.1	475	152
		Test 3 $\overline{R}$ = 210 mm/min					
1190	0.175	208	4.6	160	11.7	728	568
630	0.35	220	3.2	265	11.6	565	300
530	0.40	212	2.6	376	10.8	521	145
286	0.70	200	1.4	980	6.2	1046	66
		Test 4 $\overline{R}$ = 294 mm/min					
1660	0.175	290	3.1	200	10.9	820	620
1190	0.25	298	7.9	265	12.7	766	501
286	1.00	286	2.2	980	6.8	1079	99
		Test 6 $\overline{R}$ = 101 mm/min					
1190	0.088	104	16.7	124	15.6	565	441
250	0.40	100	7.4	376	6.3	521	145
140	0.70	98	6.3	803	4.4	850	47

Table 6.3 cont'd

Test 7 $\bar{R}$ = 364 mm/min

Speed rev/min	Feed mm/rev	Penetration Rate mm/min	Hole No. 1 Ra µm	Hole No. 1 Thrust N	Hole No. 40 Ra µm	Hole No. 40 Thrust N	Thrust Difference N
1190	0.30	357	4.2	265	11.8	728	463
530	0.70	371	10.0	475	8.6	649	174
Test 8 $\bar{R}$ = 406 mm/min							
1660	0.25	415	16.5	323	14.3	689	366
1190	0.35	416	11.2	376	19.2	649	273
386	1.00	386	6.0	689	7.5	803	114

Table 6.4 Summary of M.R.F. values

Feed mm/rev	MRF $\frac{mm^3}{J}$	$\overline{MRF}$ $\frac{mm^3}{J}$
0.088	0.74, 0.75	0.75
0.175	1.19, 1.31	1.25
0.25	1.26, 1.17, 1.17, 1.17	1.19
0.30	1.40, 1.02, 1.52	1.31
0.35	1.26, 0.98, 1.26	1.17
0.40	1.44, 1.36, 1.62, 1.23	1.41
0.70	1.72, 1.49, 1.49	1.57
1.00	2.03, 1.92, 1.92	1.96

Table 6.5 Hole Diameters

Nominal Drill Diameter 9.53 mm to BS 328, Part 1,

Tolerance on the drill 0.023 mm

Limits - $\begin{matrix} 0.000 \\ 0.023 \end{matrix}$ mm

Actual hole size is given by: $B + R_g - R_b$

where B is the size of the calibrated plug used,

R_b is the micrometer reading over the plug,

R_g is the micrometer reading over the checking anvils.

B and R_b will be constants, R_g will vary.

For this series of tests unless otherwise stated

$B - R_b = 6.969$ mm.

Test 1 Speed = 530 rev/min, Feed = 0.25 mm/rev, R = 132 mm/min

Hole No.	$B - R_b$ mm	R_g mm	Actual Diameter mm	Change in Dia. mm
1	6.969	2.555	9.524	
10		2.537	9.506	
20		2.515	9.484	
30		2.515	9.484	
40		2.515	9.484	0.04
Speed = 460 rev/min, Feed = 0.30 mm/rev, R = 138 mm/min				
1	6.969	2.537	9.506	
10		2.537	9.506	
20		2.515	9.484	
30		2.515	9.484	
40		2.515	9.484	0.022

Table 6.5 cont'd

Test 1 Speed = 320 rev/min, Feed = 0.40 mm/rev, R = 128 mm/min

Hole No.	$B - R_b$ mm	R_g mm	Actual Diameter mm	Change in Dia. mm
1	6.969	2.555	9.524	
10		2.555	9.524	
20		2.535	9.504	
30		2.535	9.504	
40		2.535	9.504	0.020
Speed = 130 rev/min, Feed = 1.0 mm/rev, R = 130 mm/min				
1	6.969	2.555	9.524	
10		2.546	9.515	
20		2.546	9.515	
30		2.546	9.515	
40		2.546	9.515	0.009

Table 6.5 cont'd

Test 2 Speed = 1660 rev/min, Feed = 0.088 mm/rev, R = 146 mm/min

Hole No.	$B - R_b$ mm	R_g mm	Actual Diameter mm	Change in Dia. mm
1	6.969	2.548	9.517	
10		2.548	9.517	
20		2.548	9.517	
30		2.515	9.484	
40		2.515	9.484	0.033
Speed = 630 rev/min, Feed = 0.25 mm/rev, R = 158 mm/min				
1	6.969	2.530	9.499	
10		2.530	9.499	
20		2.507	9.476	
30		2.507	9.476	
40		2.507	9.476	0.022
Speed = 530 rev/min, Feed = 0.30 mm/rev, R = 159 mm/min				
1	6.969	2.474	9.443	
10		2.474	9.443	
20		2.474	9.443	
30		2.466	9.435	
40		2.466	9.435	0.008
Speed = 460 rev/min, Feed = 0.35 mm/rev, R = 161 mm/min				
1	6.969	2.532	9.501	
10		2.532	9.501	
20		2.532	9.501	
30		2.532	9.501	
40		2.532	9.501	0

Table 6.5 cont'd

Test 3 Speed = 1190 rev/min, Feed = 0.175 mm/rev, R = 208 mm/min

Hole No.	$B - R_b$ mm	R_g mm	Actual Diameter mm	Change in Dia. mm
1	6.969	2.550	9.519	
10		2.550	9.519	
20		2.550	9.519	
30		2.504	9.473	
40		2.504	9.473	0.046
Speed = 630 rev/min, Feed = 0.35 mm/rev, R = 220 mm/min				
1	6.969	2.553	9.522	
10		2.553	9.522	
20		2.535	9.504	
30		2.535	9.504	
40		2.535	9.504	0.018
Speed = 530 rev/min, Feed = 0.40 mm/rev, R = 212 mm/min				
1	6.969	2.550	9.519	
10		2.550	9.519	
20		2.550	9.519	
30		2.543	9.512	
40		2.543	9.512	0.007
Speed = 286 rev/min, Feed = 0.70 mm/rev, R = 200 mm/min				
1	6.969	2.555	9.524	
10		2.555	9.524	
20		2.550	9.519	
30		2.550	9.519	
40		2.550	9.519	0.005

Table 6.5 cont'd

Test 4 Speed = 1660 rev/min, Feed = 0.175 mm/rev, R = 290 mm/min

Hole No.	B - R_b mm	R_g mm	Actual Diameter mm	Change in Dia. mm
1	6.969	2.553	9.522	
10		2.553	9.522	
20		2.535	9.504	
30		2.535	9.504	
40		2.535	9.504	0.018

Speed = 1190 rev/min, Feed = 0.25 mm/rev, R = 298 mm/min

1	6.969	2.553	9.522	
10		2.553		
20		2.553		
30		2.553		
40		2.553	9.522	0

Speed = 286 rev/min, Feed = 1.0 mm/rev, R = 286 mm/min

1	6.969	2.555	9.524	
10		2.555	9.524	
20		2.555	9.524	
30		2.550	9.519	
40		2.550	9.519	0.005

Test 5 Speed = 1190 rev/min, Feed = 0.4 mm/rev, R = 476 mm/min

1	6.969	2.555	9.524	
10		2.555	9.524	
20		2.509	9.478	
30		2.509	9.478	
40		2.509	9.478	0.046

Table 6.5 cont'd

Test 6 Speed = 1190 rev/min, Feed = 0.088 mm/rev, R = 104 mm/min

Hole No.	$B - R_b$ mm	R_g mm	Actual Diameter mm	Change in Dia. mm
1	5.346	4.155	9.501	
10		4.155	9.501	
20		4.140	9.486	
30		4.128	9.474	
40		4.128	9.474	0.027

Speed = 250 rev/min, Feed = 0.40 mm/rev, R = 100 mm/min

1	5.346	4.178	9.524	
10		4.178	9.524	
20		4.163	9.509	
30		4.163	9.509	
40		4.163	9.509	0.015

Speed = 140 rev/min, Feed = 0.70 mm/rev, R = 98 mm/min

1	5.346	4.162	9.508	
10				
20				
30				
40		4.162	9.508	0

Test 7 Speed = 1190 rev/min, Feed = 0.30 mm/rev, R = 357 mm/min

1	5.346	4.171	9.517	
10		4.171	9.517	
20		4.162	9.508	
30		4.162	9.508	
40		4.150	9.496	0.021

Table 6.5 cont'd

Test 7 Speed = 530 rev/min, Feed = 0.70 mm/rev, R = 371 mm/min

Hole No.	B - R_b mm	R_g mm	Actual Diameter mm	Change in Dia. mm
1	5.346	4.135	9.481	
10		4.135	9.481	
20		4.135	9.481	
30		4.128	9.474	
40		4.122	9.468	0.013

Test 8 Speed = 1660 rev/min, Feed = 0.25 mm/rev, R = 415 mm/min

1	5.346	4.087	9.433	
10		4.087	9.433	
20		4.087	9.433	
30		4.074	9.420	
40		4.039	9.385	0.045

Speed = 1190 rev/min, Feed = 0.35 mm/rev, R = 416 mm/min

1	5.346	4.153	9.499	
10		4.153	9.499	
20		4.153	9.499	
30		4.135	9.481	
40		4.135	9.481	0.018

Speed = 386 rev/min, Feed = 1.0 mm/rev, R = 386 mm/min

1	5.346	4.176	9.522	
10		4.176	9.522	
20		4.168	9.514	
30		4.163	9.509	
40		4.163	9.509	0.013

Table 6.6 Slope, Deviation from Straightness and Bore Intrusion

Test 1 Speed = 530 rev/min, Feed = 0.25 mm/rev, R = 132 mm/min

Hole No.	Slope x 10^{-3} Rads				Max. deviation from Straight Line μ m				Intrusion μ m			
	0°	180°	90°	270°	0°	180°	90°	270°	0°	180°	90°	270°
1	-0.8	+1.6	+5.2	-4.4	15	25	15	0	0	30	20	15
10	-2.0	+2.6	+0.8	0	10	7.5	15	2.5	35	35	40	50
20	+2.0	-1.6	+2.4	-2.2	25	30	35	35	40	0	25	65
30	-2.2	+2.6	+1.2	-1.6	20	20	30	15	50	70	130	140
40	+0.2	-0.8	+4.0	-4.0	30	20	35	40	65	10	70	20
	Speed = 460 rev/min, Feed = 0.30 mm/rev, R = 138 mm/min											
1	-2.4	+2.8	+3.2	-1.6	25	0	30	10	0	25	15	0
10	0	+0.8	+0.8	+0.8	25	12	20	5	45	20	0	60
20	+2.6	-2.4	+2.6	-2.0	10	10	20	10	70	40	70	90
30	-4.6	+5.2	-1.6	+2.4	20	30	12	12	40	40	25	30
40	+4.8	-3.2	+1.2	-1.2	18	20	20	25	40	50	20	35
	Speed = 320 rev/min, Feed = 0.40 mm/rev, R = 128 mm/min											
1	+0.4	+0.4	+3.2	-2.4	25	15	20	10	10	10	25	10
10	0	+0.2	0	-0.2	20	20	20	15	22	30	40	0
20	-3.4	+4.2	+0.4	0	10	15	20	20	5	60	30	3
30	0	+1.2	+1.4	0	10	20	18	20	80	25	50	15
40	-2.0	+3.4	0	+0.8	10	10	25	20	40	30	25	35
	Speed = 130 rev/min, Feed = 1.0 mm/rev, R = 130 mm/min											
1	-2.4	+3.2	-3.2	+3.6	50	70	60	70	10	10	0	15
10	+0.6	-0.8	0	-0.6	20	10	20	15	10	0	5	0
20	0	-1.2	+0.8	-1.6	10	30	15	25	5	0	0	0
30	-2.8	+2.8	-1.6	+0.8	15	18	20	20	5	10	15	22
40	+1.6	-2.6	+1.4	-2.0	15	15	15	20	40	20	40	20

Table 6.6 cont'd

Test 2 Speed = 1660 rev/min, Feed = 0.088 mm/rev, R = 146 mm/min

Hole No.	Slope x 10^{-3} Rads				Max. deviation from Straight Line μm				Intrusion μm			
	0°	180°	90°	270°	0°	180°	90°	270°	0°	180°	90°	270°
1	-2.0	+1.8	-6.8	+6.2	30	30	10	25	20	60	60	60
10	+3.6	-4.4	-8.0	+6.4	35	40	20	20	60	95	75	260
20	-3.2	0	-8.0	+6.6	40	70	25	35	110	110	40	20
30	+2.4	-3.2	-6.8	+6.4	60	40	20	35	170	160	50	40
40	-6.0	+6.4	+7.2	-7.2	25	30	20	20	90	180	150	50
	Speed = 630 rev/min, Feed = 0.25 mm/rev, R = 158 mm/min											
1	0	+2.4	+3.6	-2.4	40	30	35	25	10	20	40	30
10	-0.6	+3.6	+6.2	-5.6	10	35	40	20	8	50	50	45
20	-1.6	+4.0	+7.0	-4.8	20	30	20	20	80	20	20	0
30	-1.8	+2.8	+3.6	-2.2	20	25	25	30	50	150	60	40
40	+3.6	-2.4	+1.8	+1.4	15	35	20	25	25	0	25	0
	Speed = 530 rev/min, Feed = 0.30 mm/rev, R = 159 mm/min											
1	-1.6	+2.8	-10.8	+10.4	15	25	20	30	35	20	20	40
10	+0.8	-1.6	-11.2	+9.6	20	20	20	20	25	70	10	40
20	-8.0	+8.8	-1.2	0	20	40	30	35	40	60	40	150
30	+7.6	-8.4	-8.4	+7.2	40	30	25	30	120	220	20	50
40	-8.8	+8.8	-4.0	+2.4	20	30	30	40	30	80	150	120
	Speed = 460 rev/min, Feed = 0.35 mm/rev, R = 161 mm/min											
1	+1.0	+3.6	+5.0	-0.8	35	25	20	20	0	0	25	0
10	-2.6	+4.0	-0.4	+4.4	20	15	30	40	0	30	18	25
20	-12.0	+13.2	-12.0	+12.8	20	20	30	20	40	100	20	80
30	-1.6	-2.4	-2.0	+2.2	50	30	30	30	180	200	60	120
40	-3.2	+7.2	+1.2	-0.8	40	40	30	70	170	120	110	130

Table 6.6 cont'd

Test 3 Speed = 1190 rev/min, Feed = 0.175 mm/rev, R = 208 mm/min

Hole No.	Slope x 10^{-3} Rads				Max. deviation from Straight Line μm				Intrusion μm			
	0°	180°	90°	270°	0°	180°	90°	270°	0°	180°	90°	270°
1	+0.8	+0.8	+1.6	0	20	10	35	20	0	10	25	0
10	-1.2	+1.6	-2.0	+3.0	20	15	15	20	10	18	50	120
20	-3.4	+4.8	-0.2	+1.8	35	35	15	20	65	90	80	25
30	-1.6	+3.0	-2.8	+3.6	35	30	38	33	50	30	30	50
40	-1.6	+2.8	-5.2	+5.0	40	33	50	40	90	170	90	95
Speed = 630 rev/min, Feed = 0.35 mm/rev, R = 220 mm/min												
1	-3.4	+4.0	-1.2	+2.0	10	30	20	15	0	10	0	15
10	-0.2	+0.2	+0.6	0	30	25	20	20	0	30	28	35
20	-1.4	+2.6	+1.2	-1.2	35	28	20	25	40	40	10	20
30	-2.0	+2.2	0	0	18	15	20	15	80	20	40	75
40	-1.8	+4.0	+5.5	-2.0	45	45	43	25	20	90	35	40
Speed = 530 rev/min, Feed = 0.4 mm/rev, R = 212 mm/min												
1	+2.4	-2.4	-1.2	+4.0	10	30	10	5	10	8	10	10
10	+3.2	-1.6	+10.0	-10.0	10	10	20	10	10	30	10	30
20	+2.6	-1.8	-3.2	+4.0	25	30	30	20	10	20	10	5
30	-9.2	+9.2	+13.5	-13.6	30	30	20	30	10	20	20	20
40	-1.2	+3.4	+5.6	-4.0	20	39	25	20	20	55	50	0
Speed = 286 rev/min, Feed = 0.7 mm/rev, R = 200 mm/min												
1	-0.2	+1.8	+1.4	-1.6	20	15	10	15	5	0	5	5
10	-4.8	+5.0	0	0	10	10	5	5	10	10	10	10
20	+0.4	0	-1.2	+1.8	15	20	12	12	10	30	5	20
30	-4.0	+4.0	+3.0	-3.2	20	35	30	15	20	20	20	10
40	-1.0	+2.0	+3.6	-3.6	15	20	20	15	40	0	50	35

Table 6.6 cont'd

Test 4 Speed = 1660 rev/min, Feed = 0.175 mm/rev, R = 290 mm/min

Hole No.	Slope x 10^{-3} Rads 0°	180°	90°	270°	Max. deviation from Straight Line μm 0°	180°	90°	270°	Intrusion μm 0°	180°	90°	270°
1	+5.2	-3.2	-2.4	+4.4	30	20	20	35	30	0	0	20
10	+5.6	-3.5	+0.4	+2.0	30	40	30	25	10	40	10	0
20	-4.2	+4.6	+5.6	-3.8	20	35	25	25	25	85	15	15
30	+4.0	-1.2	+3.4	0	40	20	50	30	10	15	30	0
40	+2.6	0	+2.4	0	20	40	40	25	10	20	10	35
Speed = 1190 rev/min, Feed = 0.25 mm/rev, R = 298 mm/min												
1	-18.8	+18.8	+0.2	-7.2	0	0	80	80	60	0	60	180
10	0	-2.0	-5.0	+5.0	30	28	40	25	50	50	50	30
20	-4.0	+3.4	-0.6	+2.2	20	25	28	20	5	10	30	0
30	+2.4	-2.4	-6.0	+3.6	20	35	25	65	10	15	30	30
40	-1.2	0	+0.8	0	20	30	25	20	80	140	25	45
Speed = 286 rev/min, Feed = 1.00 mm/rev, R = 286 mm/min												
1	-2.4	+1.2	-2.6	+1.6	20	15	55	35	0	0	0	25
10	-2.0	+1.8	+1.2	+0.4	20	15	10	18	0	0	15	0
20	+3.4	-2.8	-2.0	+2.2	10	15	10	10	10	20	20	20
30	+1.2	-1.2	-6.0	+4.2	25	10	10	20	0	25	10	85
40	+2.6	-3.6	-3.0	+2.0	35	20	25	10	10	5	25	35
Test 5 Speed = 1190 rev/min, Feed = 0.40 mm/rev, R = 476 mm/min												
1	+5.4	-3.6	+3.4	-1.2	35	25	80	20	20	60	60	20
10	+6.6	-4.4	+0.6	0	30	40	20	30	10	0	15	25
20	+4.0	-4.0	+6.0	-5.6	35	25	40	18	125	10	35	10
30	-0.8	+0.4	-5.2	+4.6	40	65	25	30	5	90	30	100
40	+3.6	-3.2	+7.2	-7.2	40	20	18	25	90	40	55	18

Table 6.6 cont'd

Test 6 Speed = 1190 rev/min, Feed = 0.088 mm/rev, R = 104 mm/min

Hole No.	Slope x 10^{-3} Rads				Max. deviation from Straight Line μm				Intrusion μm			
	0°	180°	90°	270°	0°	180°	90°	270°	0°	180°	90°	270°
1	+1.4	-1.0	-9.6	+10.8	15	35	20	25	10	145	10	50
10	-7.2	+7.6	-1.2	-1.2	20	40	55	75	280	280	190	220
20	+4.0	-4.0	-6.0	+4.8	40	40	50	80	130	260	110	190
30	+0.8	+1.6	-3.6	+1.2	25	40	40	60	100	340	210	260
40	+8.4	-8.8	-3.2	0	60	20	50	20	300	230	460	290
Speed = 250 rev/min, Feed = 0.40 mm/rev, R = 100 mm/min												
1	-0.8	+0.8	-5.2	+5.6	10	0	0	40	10	30	0	30
10	+0.4	-0.4	-7.2	+7.6	25	20	0	0	20	30	0	40
20	-8.0	+8.0	-1.6	+2.4	10	40	25	20	0	40	30	10
30	+6.0	-6.4	-4.0	+3.2	10	20	20	30	85	20	30	70
40	-4.0	+6.6	-4.8	+7.2	15	20	25	30	20	70	20	20
Speed = 140 rev/min, Feed = 0.70 mm/rev, R = 98mm/min												
1	-4.8	+3.2	-8.0	+8.0	5	5	5	20	20	25	0	70
10	+0.4	-1.6	-8.0	+8.0	20	15	5	20	30	20	0	30
20	+4.4	-4.4	-7.2	+6.4	20	10	5	5	40	20	10	20
30	+4.0	-4.8	-4.8	+4.0	25	10	10	20	40	15	10	40
40	+5.6	-8.0	-6.0	+6.0	25	15	10	10	40	30	0	40
Test 7 Speed = 1190 rev/min, Feed = 0.30 mm/rev, R = 357 mm/min												
1	+7.6	-8.0	+2.4	-2.8	20	30	30	30	50	10	20	30
10	+2.8	-2.4	+5.6	-5.6	40	15	20	40	60	10	50	40
20	-5.8	+6.6	-5.8	+5.6	25	40	30	25	110	75	75	90
30	-1.0	+0.8	+6.4	-7.2	30	25	40	25	55	5	120	130
40	-1.2	+1.0	-9.6	+10.4	20	20	20	20	50	120	100	100

Table 6.6 cont'd

Test 7 Speed = 530 rev/min, Feed = 0.7 mm/rev, R = 371 mm/min

Hole No.	Slope x 10^{-3} Rads				Max. deviation from Straight Line μm				Intrusion μm			
	0°	180°	90°	270°	0°	180°	90°	270°	0°	180°	90°	270°
1	+4.4	-3.6	-9.6	+9.6	30	18	15	30	30	35	20	50
10	-0.8	+2.0	-3.8	+4.8	10	10	40	30	50	50	5	40
20	+8.0	-5.6	-7.2	+8.4	40	20	25	25	20	5	5	50
30	0	+0.6	-3.6	+3.6	10	20	25	10	60	85	15	55
40	+10.2	-10.2	+0.4	+1.2	30	20	30	30	60	80	20	40
Test 8 Speed = 1660 rev/min, Feed = 0.25 mm/rev, R = 415 mm/min												
1	-3.0	+6.0	-6.0	+9.6	10	35	10	40	35	80	30	60
10	+2.4	-1.2	-8.0	+9.6	30	20	30	20	70	70	30	50
20	-9.2	+10.0	+2.4	-1.4	20	30	40	20	0	90	100	50
30	+5.6	-4.4	-2.4	+4.0	70	30	30	40	130	120	50	80
40	+5.6	-4.8	-4.8	+4.8	40	50	40	30	120	45	70	150
Speed = 1190 rev/min, Feed = 0.35 mm/rev, R = 416 mm/min												
1	+3.8	-4.4	-4.0	+3.6	10	25	25	30	25	0	5	10
10	-8.0	+6.4	-1.2	+0.8	30	40	20	15	5	20	10	15
20	-1.6	+2.0	-10.4	+9.6	15	30	30	30	10	10	0	15
30	-10.4	+8.0	-4.8	+5.2	10	25	10	20	5	5	40	90
40	+4.8	-3.6	-10.8	+9.6	30	20	30	30	60	40	30	20
Speed = 386 rev/min, Feed = 1.0 mm/rev, R = 386 mm/min												
1	-0.2	+0.2	-7.0	+7.6	20	20	10	30	40	40	10	30
10	+8.8	-9.2	-4.0	+4.0	20	10	10	15	40	25	20	25
20	0	+0.4	+8.8	-8.0	10	20	20	30	40	60	30	10
30	+9.6	-8.8	-0.4	0	20	30	20	10	20	30	30	30
40	0	+0.8	+8.0	-9.6	5	5	20	15	5	20	30	5

Table 6.7 Computer Results of Roundness

Test 1 Speed = 530 rev/min, Feed = 0.25 mm/rev, R = 132 mm/min

Hole No.	Least Squares Circle µm	Mean Line Average µm
1	13.5	2.0
10	55.0	8.0
20	60.0	10.0
30	68.0	11.0
40	62.0	11.0

Speed = 460 rev/min, Feed = 0.30 mm/rev, R = 138 mm/min

1	14.0	2.0
10	40.0	5.0
20	39.0	7.5
30	56.0	9.0
40	45.0	8.0

Speed = 320 rev/min, Feed = 0.4 mm/rev, R = 128 mm/min

1	13.5	2.0
10	16.0	3.0
20	45.0	7.5
30	35.0	5.0
40	30.0	4.5

Speed = 130 rev/min, Feed = 1.00 mm/rev, R = 130 mm/min

1	29.0	2.5
10	19.5	2.5
20	19.5	2.5
30	24.5	3.5
40	25.0	4.0

Table 6.7 cont'd

Test 2 Speed = 1660 rev/min, Feed = 0.088 mm/rev, R = 146 mm/min

Hole No.	Least Squares Circle μm	Mean Line Average μm
1	71.0	13.0
10	90.0	16.0
20	120.0	20.0
30	120.0	22.0
40	100.0	19.0
Speed = 630 rev/min, Feed = 0.25 mm/rev, R = 158 mm/min		
1	41.0	9.0
10	72.0	13.0
20	76.0	14.0
30	68.0	12.0
40	66.0	12.0
Speed = 530 rev/min, Feed = 0.30 mm/rev, R = 159 mm/min		
1	70.0	12.0
10	83.0	12.5
20	140.0	14.0
30	130.0	15.0
40	80.0	16.0
Speed = 460 rev/min, Feed = 0.35 mm/rev, R = 161 mm/min		
1	56.0	9.0
10	91.0	13.0
20	72.0	15.0
30	84.0	15.0
40	70.0	13.0

Table 6.7 cont'd

Test 3 Speed = 1190 rev/min, Feed = 0.175 mm/rev, R = 208 mm/min

Hole No.	Least Squares Circle μm	Mean Line Average μm
1	40.0	5.0
10	69.0	11.0
20	64.0	13.0
30	75.0	11.0
40	104.0	16.0
Speed = 630 rev/min, Feed = 0.35 mm/rev, R = 220 mm/min		
1	21.0	2.5
10	36.0	5.5
20	51.0	8.0
30	52.0	9.0
40	76.0	12.0
Speed = 530 rev/min, Feed = 0.40 mm/rev, R = 212 mm/min		
1	24.5	4.0
10	28.5	5.0
20	45.0	7.5
30	72.0	12.0
40	62.0	10.0
Speed = 286 rev/min, Feed = 0.70 mm/rev, R = 200 mm/min		
1	14.0	2.75
10	27.0	3.0
20	28.0	4.0
30	26.0	4.5
40	34.0	5.5

Table 6.7 cont'd

Test 4 Speed = 1660 rev/min, Feed = 0.175 mm/rev, R = 290 mm/min

Hole No.	Least Squares Circle μm	Mean Line Average μm
1	26.5	4.5
10	60.0	11.0
20	76.0	13.0
30	78.0	13.0
40	91.0	18.0

Speed = 1190 rev/min, Feed = 0.25 mm/rev, R = 298 mm/min

Hole No.	Least Squares Circle μm	Mean Line Average μm
1	42.5	5.5
10	66.0	10.0
20	57.0	11.0
30	70.0	14.0
40	75.0	12.0

Speed = 286 rev/min, Feed = 1.0 mm/rev, R = 286 mm/min

Hole No.	Least Squares Circle μm	Mean Line Average μm
1	16.0	2.5
10	15.5	3.0
20	24.5	4.0
30	41.0	6.0
40	36.0	6.0

Test 5 Speed = 1190 rev/min, Feed = 0.40 mm/rev, R = 476 mm/min

Hole No.	Least Squares Circle μm	Mean Line Average μm
1	24.0	4.0
10	48.0	8.0
20	54.0	9.0
30	60.0	9.0
40	70.0	10.0

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Table 6.7 cont'd

Test 6 Speed = 1190 rev/min, Feed = 0.088 mm/rev, R = 104 mm/min

Hole No.	Least Squares Circle μm	Mean Line Average μm
1	76.0	12.0
10	82.0	12.0
20	100.0	18.0
30	120.0	20.0
40	122.0	22.0

Speed = 250 rev/min, Feed = 0.40 mm/rev, R = 100 mm/min

1	28.0	5.0
10	50.0	5.0
20	51.0	5.0
30	47.0	8.0
40	54.0	8.0

Speed = 140 rev/min, Feed = 0.7 mm/rev, R = 99 mm/min

1	30.0	5.0
10	30.0	5.0
20	26.0	4.0
30	31.0	5.0
40	25.0	4.0

Test 7 Speed = 1190 rev/min, Feed = 0.30 mm/min, R = 357 mm/min

1	28.0	4.0
10	61.0	11.0
20	61.0	10.5
30	67.0	13.0
40	67.0	11.0

Table 6.7 cont'd

Test 7 Speed = 530 rev/min, Feed = 0.70 mm/rev, R = 371 mm/min

Hole No.	Least Squares Circle μm	Mean Line Average μm
1	50.0	8.0
10	62.0	12.0
20	62.0	12.0
30	77.0	11.0
40	65.0	11.0

Test 8 Speed = 1660 rev/min, Feed = 0.25 mm/rev, R = 415 mm/min

1	72.0	9.0
10	84.0	16.0
20	86.0	13.0
30	86.0	13.0
40	72.0	13.0

Speed = 1190 rev/min, Feed = 0.35 mm/rev, R = 416 mm/min

1	61.0	10.0
10	50.0	10.0
20	59.0	10.0
30	51.0	10.0
40	71.0	14.0

Speed = 386 rev/min, Feed = 1.00 mm/rev, R = 386 mm/min

1	40.0	5.0
10	42.0	8.0
20	52.0	9.0
30	59.0	8.0
40	52.0	8.0

Table 6.8 Height of Burr or Build up at Entry and Exit

The results show the height of the burr, the middle digit being the height difference of the sides of the hole, the left-hand digit in each case being the datum.

Test 1 Speed = 530 rev/min, Feed = 0.25 mm/rev, R = 132 mm/min

Hole No.	Burr Height at Entry μm			Av. Value (Plotted)	Burr Height at Exit μm			Av. Value (Plotted)
1	16	-4	24	20	20	-4	20	20
10	28	-12	20	24	24	12	12	18
20	36	36	44	40	20	20	28	24
30	56	20	20	38	44	-24	24	34
40	32	4	40	36	36	-24	40	38
	Speed = 460 rev/min, Feed = 0.30 mm/rev, R = 138 mm/min							
1	4	-70	20	12	20	40	12	16
10	64	72	12	38	36	4	16	26
20	72	-12	48	60	20	4	20	20
30	36	40	148	92	32	0	36	34
40	80	10	80	80	32	-20	24	26
	Speed = 320 rev/min, Feed = 0.40 mm/rev, R = 128 mm/min							
1	4	-16	0	2	16	14	8	12
10	48	12	24	36	16	-16	14	16
20	130	24	90	110	32	10	24	28
30	84	16	80	80	24	-16	24	24
40	80	16	12	46	32	8	26	28
	Speed = 130 rev/min, Feed = 1.0 mm/rev, R = 130 mm/min							
1	28	-8	40	34	20	-10	0	10
10	68	-8	52	60	16	-10	20	18
20	36	-12	60	48	20	-4	24	22
30	52	-16	28	40	8	-20	8	8
40	16	-16	52	34	28	-16	52	40

Table 6.8 cont'd

Test 2 Speed = 1660 rev/min, Feed = 0.088 mm/rev, R = 146 mm/min

Hole No.	Burr Height at Entry μm			Av. Value (Plotted)	Burr Height at Exit μm			Av. Value (Plotted)
1	28	-56	32	30	52	18	36	44
10	80	20	60	70	28	12	48	38
20	80	10	30	56	58	4	52	56
30	88	-48	64	76	60	12	50	55
40	110	12	64	88	64	20	60	62
	Speed = 630 rev/min, Feed = 0.25 mm/rev, R = 158 mm/min							
1	40	12	8	24	26	6	32	28
10	84	20	88	86	40	-6	40	40
20	100	60	70	84	36	4	40	38
30	100	20	130	116	56	8	36	46
40	100	20	140	120	36	4	40	38
	Speed = 530 rev/min, Feed = 0.3 mm/rev, R = 159 mm/min							
1	14	-36	10	12	36	-20	32	34
10	60	-16	52	56	24	-24	36	30
20	132	16	84	108	34	-4	40	38
30	150	30	90	120	46	-34	58	52
40	74	-20	100	88	52	-24	74	64
	Speed = 460 rev/min, Feed = 0.35 mm/rev, R = 161 mm/min							
1	44	-8	44	44	24	4	16	20
10	76	-12	88	84	26	0	26	26
20	90	10	70	80	32	36	40	36
30	130	-8	84	108	60	12	28	44
40	110	16	56	84	92	60	40	66

Table 6.8 cont'd

Test 3 Speed = 1190 rev/min, Feed = 0.175 mm/rev, R = 208 mm/min

Hole No.	Burr Height at Entry μm			Av. Value (Plotted)	Burr Height at Exit μm			Av. Value (Plotted)
1	4	4	12	8	12	24	12	12
10	36	4	36	36	20	8	16	18
20	60	14	44	50	32	16	16	24
30	88	8	52	70	40	16	44	42
40	100	24	44	72	64	0	52	58
Speed = 630 rev/min, Feed = 0.35 mm/rev, R = 220 mm/min								
1	12	0	60	36	18	16	14	16
10	70	0	32	52	12	8	12	12
20	112	0	84	98	26	12	22	24
30	50	0	90	70	24	12	40	32
40	80	4	110	96	24	24	20	22
Speed = 530 rev/min, Feed = 0.4 mm/rev, R = 212 mm/min								
1	0	-10	24	12	12	-8	16	14
10	20	12	16	18	16	-16	20	18
20	24	-20	20	22	12	-8	24	18
30	28	20	36	32	24	-8	20	22
40	40	12	32	36	28	-8	36	32
Speed = 286 rev/min, Feed = 0.70 mm/rev, R = 200 mm/min								
1	50	80	0	25	8	-14	24	16
10	20	-20	50	35	6	-4	14	10
20	70	50	30	50	8	16	4	6
30	90	-32	120	106	28	0	32	30
40	120	24	90	106	20	-12	16	18

Table 6.8 cont'd

Test 4 Speed = 1660 rev/min, Feed = 0.175 mm/rev, R = 290 mm/min

Hole No.	Burr Height at Entry μm			Av. Value (Plotted)	Burr Height at Exit μm			Av. Value (Plotted)
1	36	-44	24	30	28	-56	20	24
10	28	-20	52	40	12	-40	28	20
20	66	70	64	64	28	-60	56	44
30	30	-100	60	44	64	32	52	58
40	52	-10	24	38	40	60	40	40
Speed = 1190 rev/min, Feed = 0.25 mm/rev, R = 298 mm/min								
1	30	60	20	24	8	40	12	10
10	20	-40	44	32	32	28	32	32
20	36	50	16	26	64	40	36	50
30	60	-50	76	68	60	36	60	60
40	60	50	32	46	44	58	38	40
Speed = 286 rev/min, Feed = 1.0 mm/rev, R = 286 mm/min								
1	60	20	70	65	16	-12	16	16
10	40	12	20	30	12	20	8	10
20	80	8	44	62	36	-16	20	28
30	72	0	100	86	24	-40	36	30
40	100	8	60	80	44	-40	52	48
Test 5 Speed = 1190 rev/min, Feed = 0.4 mm/rev, R = 476 mm/min								
1	12	8	16	14	8	32	12	10
10	40	40	8	24	40	12	20	30
20	56	20	20	38	16	18	18	16
30	52	40	20	36	20	-8	26	24
40	60	4	52	56	40	2	32	36

Table 6.8 cont'd

Test 6 Speed = 1190 rev/min, Feed = 0.088 mm/rev, R = 104 mm/min

Hole No.	Burr Height at Entry μm			Av. Value (Plotted)	Burr Height at Exit μm			Av. Value (Plotted)
1	42	-24	48	44	34	-18	36	35
10	88	24	20	54	48	-40	40	44
20	108	-24	84	96	68	16	60	64
30	150	0	80	116	134	16	70	102
40	100	-20	164	132	150	16	130	140
Speed = 250 rev/min, Feed = 0.4 mm/rev, R = 100 mm/min								
1	8	8	14	12	16	24	14	15
10	40	2	46	44	26	0	28	27
20	94	8	76	84	28	26	14	21
30	90	4	54	72	34	4	16	25
40	160	10	144	152	34	18	24	29
Speed = 140 rev/min, Feed = 0.7 mm/rev, R = 98 mm/min								
1	16	8	34	25	12	-20	16	14
10	42	-14	58	50	32	-32	24	28
20	84	-10	72	78	24	-24	32	28
30	50	-52	90	70	28	-28	36	32
40	144	-20	110	127	46	-28	48	47
Test 7 Speed = 1190 rev/min, Feed = 0.3 mm/rev, R = 357 mm/min								
1	30	4	10	20	24	0	8	16
10	20	-20	24	22	20	-20	20	20
20	20	-24	48	34	40	4	40	40
30	60	-4	64	62	28	-32	40	34
40	60	0	100	80	36	12	48	42

Table 6.8 cont'd

Test 7 Speed = 530 rev/min, Feed = 0.7 mm/rev, R = 371 mm/min

Hole No.	Burr Height at Entry μm			Av. Value (Plotted)	Burr Height at Exit μm			Av. Value (Plotted)
1	32	20	40	36	24	4	28	26
10	36	-8	48	42	28	-4	36	32
20	28	20	24	34	36	-36	28	32
30	50	-20	70	60	20	0	20	20
40	130	0	64	97	32	-52	40	36

Test 8 Speed = 1660 rev/min, Feed = 0.25 mm/rev, R = 415 mm/min

1	40	-20	36	38	32	-32	48	40
10	56	-32	60	58	52	-8	40	46
20	90	22	50	70	60	20	52	56
30	104	20	44	74	68	30	28	48
40	80	20	90	84	50	20	30	40

Speed = 1190 rev/min, Feed = 0.33 mm/rev, R = 416 mm/min

1	32	16	28	30	18	-14	28	23
10	32	-8	36	34	28	-20	28	28
20	54	12	58	56	26	34	20	23
30	58	-12	60	59	50	14	36	43
40	56	10	44	50	44	24	28	36

Speed = 386 rev/min, Feed = 1.0 mm/rev, R = 386 mm/min

1	16	0	32	24	20	-4	8	14
10	40	-20	24	32	16	-12	20	18
20	52	-16	44	48	24	-28	24	24
30	60	-28	28	44	24	-20	20	22
40	70	-8	130	100	44	0	36	40

Table 6.9 Summary of Roundness Values (L.S.C.)

Speed rev/min	Feed mm/rev	Roundness Values μm at Hole No's. 1	10	20	30	40
1190	0.088	72	82	100	120	122
1660	0.088	71	90	120	120	100
1190	0.175	40	69	64	75	104
1660	0.175	26.5	60	76	78	91
530	0.250	13.5	55	60	68	62
630	0.250	41	72	76	68	66
1190	0.250	42.5	66	57	70	75
1660	0.250	72	84	86	86	72
460	0.30	14	40	39	56	45
530	0.30	70	83	140	130	80
1190	0.30	28	61	61	67	67
460	0.35	56	91	72	84	70
630	0.35	21	36	51	52	76
1190	0.35	61	50	59	51	71
250	0.40	28	50	51	47	54
320	0.40	13.5	16	45	35	30
530	0.40	24.5	28.5	45	72	62
1190	0.40	24	48	54	60	70
140	0.70	30	30	26	31	25
286	0.70	14	27	28	26	34
530	0.70	50	62	62	77	65
130	1.0	29	19.5	19.5	24.5	25
286	1.0	16	15.5	24.5	41	36
386	1.0	40	42	52	59	52

Table 6.10 Summary of Change in Hole Diameter and Drill Wear

Speed rev/min	Feed mm/rev	Change in Dia. mm	Drill Wear $mm^2 \times 10^{-2}$
1190	0.088	0.028	3.39
1660	0.088	0.033	4.45
1190	0.175	0.045	1.89
1660	0.175	0.018	2.0
530	0.25	0.040	1.26
630	0.25	0.023	1.97
1190	0.25	0	1.57
1660	0.25	0.048	4.41
460	0.30	0.023	1.18
530	0.30	0.008	1.50
1190	0.30	0.020	1.57
460	0.35	0	1.38
630	0.35	0.018	1.81
1190	0.35	0.018	1.89
250	0.40	0.015	1.69
320	0.40	0.020	0.83
530	0.40	0.008	1.46
1190	0.40		1.93
140	0.70	0	0.83
286	0.70	0.005	0.31
530	0.70	0.013	1.26
130	1.0	0.010	0.63
286	1.0	0.005	0
386	1.0	0.013	1.26

Table 6.11 L.S.C. Values, Change in Diameter, and Drill Wear

Speed rev/min	Feed mm/rev	Change in Dia. mm	Drill Wear $mm^2 \times 10^{-2}$	L.S.C. μm	Range L.S.C. μm
N 1190	0.088	0.028	3.39	100	46
N 1660	0.088	0.033	4.45	100	49
N 1190	0.175	0.046	1.89	70	64
1660	0.175	0.018	2.0	63	65
N 530	0.250	0.040	1.26	52	47
630	0.250	0.023	1.97	65	35
1190	0.250	0	1.57	62	33
N 1660	0.250	0.048	4.41	80	14
460	0.30	0.023	1.18	39	42
N 530	0.30	0.008	1.50	100	70
1190	0.30	0.020	1.57	59	39
460	0.35	0	1.38	75	35
630	0.35	0.018	1.81	47	55
1190	0.35	0.018	1.89	58	21
250	0.40	0.015	1.69	46	26
320	0.40	0.020	0.83	28	32
530	0.40	0.008	1.46	46	48
1190	0.40		1.93	51	46
140	0.70	0	0.83	28	5
286	0.70	0.005	0.31	26	20
530	0.70	0.013	1.26	63	27
130	1.0	0.010	0.63	24	9.5
286	1.0	0.005	0	27	25
386	1.0	0.013	1.26	49	19

- Best results are shown at the higher feed rates.

N - High value at one or more of the variables.

CHAPTER 7.

INFLUENCE OF DRILL GEOMETRY ON HOLE QUALITY

Having obtained optimum values for drill penetration rates the next series of tests was to note any improvement in the operation of the drill and in the finished hole by varying the point and lip clearance angles. A new sheet of material was used for the tests and upon drilling this material entirely new characteristics for both drill and material were displayed. The chip produced was small, approximately 3 mm long and 1 mm wide (Plate 24) and the resulting hole showed discolouration at an early stage in the test. To determine the reason for the difference in chip formation a glass composition test to BS 2782, Part 1, 1970[44] was carried out, and the analysed results are shown in Appendix 1. The results show a glass content of 60.78% by mass for the first sheet and 74.32% by mass for the new sheet. This variation in glass content could have caused the change in chip construction due to the brittle nature of the glass.

A great deal of information was obtained from a material which produces a continuous type chip with no discolouration of the hole. It was decided therefore to carry on with the tests and refer to the sheets used as Sheet 1 and Sheet 2. Sheet 1 was used to determine optimum penetration rates and Sheet 2 was used to determine optimum point and lip clearance angles and the following subsidiary tests; (i) drill relief, (ii) use of a pilot, and (iii) variation in penetration rates to overcome discolouration of the hole.

The optimum point angle tests included increasing the number of holes to be drilled and using a speed feed combination of 1190 rev/min and 0.088 mm/rev respectively. This speed and feed combination enabled an accelerated wear test to be carried out and by using a larger number of holes complete breakdown of the drill might be experienced.

7.1 Results of Tests for Optimum Point Angle

A series of drill point angles from 100° - 140° were used and the torque and thrust values were noted with the wear on the drill being measured at hole numbers 30, 60 and 90, the results are shown in Tables 7.1 and 7.1a.

When the results are compared it can be seen that there is very little difference in the values from each of the tests. Lake, Appl and Bert[45] commented on the inconsistency of results obtained from glass reinforced plastic materials and hence a further series of tests was carried out. The results were compared using the Mann-Whitney U test and showed no significant difference between the two sets of values for torque and thrust. The wear values of the drills used in the two tests were compared using the $2\sqrt{N}$ test for association. The results again showed no significant difference in the wear values of the drills used. A two way F test was carried out on the values of the last hole drilled in both tests for torque, thrust and wear. The result was no significant difference in the values or tests at an α value of 0.02 (Appendix 5).

Figs. 7.1 and 7.2 show the torque and thrust values plotted against hole numbers respectively for the appropriate point angles used in the tests and on each graph the hole number which shows the start of discolouration of the hole is indicated. The 130° point angle shows marginally better results for the number of holes drilled before discolouration and for this reason was used in all the subsequent tests. In all the tests carried out discolouration of the hole occurs when a torque value of 2.61 Nm is reached. It would appear that for these conditions the torque value of 2.61 Nm is the value that the material can accept before the heat which is generated at the cutting point is transferred from the drill to the material resulting in discolouration of the hole. The value of 2.61 Nm before discolouration only occurs with a speed of 1190 rev/min and a feed of 0.088 mm/rev. When the speed feed combination is changed much higher torque values are experienced.

7.1.1 Double Point Angle Drill

Many twist drill manufacturers recommend a double point angle drill when brittle materials such as cast iron are to be drilled. For this reason a 118° - 130° double point angle was ground on drills of 9.53 mm and 12.7 mm nominal diameters and various drill speed and feed combinations were carried out. The torque and thrust values obtained for the 9.53 mm diameter drill were greater than those experienced in the previous tests. With a speed of 1660 rev/min and a feed of 0.088 mm/rev discolouration of the hole was experienced at an early stage in the test. However by using the same drill and increasing the feed rate to 0.15 mm/rev the discolouration of the hole was removed but a ring appeared on the material at the exit side of the hole. Plate 25 shows the ring and its formation is discussed in a later section.

Various speed and feed combinations were used with a 12.7 mm diameter drill to determine if the same hole conditions were experienced as in previous tests. It was again found that by increasing the feed rate the discolouration of the hole was removed but the ring appeared again on the material at the exit side of the hole.

7.2 Optimum Lip Clearance Angle

The tests to determine the optimum lip clearance angle were carried out using a drill with a 130° nominal point angle and a speed feed combination of 1190 rev/min and 0.088 mm/rev over a range of lip clearance angles from 8° to $18\frac{1}{2}$°. Thirty holes were drilled for each drill lip clearance angle and the torque and thrust values noted (Table 7.2) and plotted against hole number (Figs. 7.3 and 7.4). The drill wear was obtained by measuring the drill corner wear only and also by the analytical method described in Chapter 3.

The graph of drill wear against lip clearance angle shows a minimum wear value with a lip clearance angle of 13° while the greatest number of holes drilled before discolouration of the hole occurs with a lip clearance angle of 9°. The number of holes drilled before discolouration is shown in Fig. 7.6 for the corresponding lip clearance angle.

The increase in lip clearance produces only a small change in torque for angles between 8^o and 16^o while the thrust forces decrease with increase in lip clearance angle. It has been found that the same conditions apply when alloy steels are drilled with various lip clearance angles[46], torque values remain reasonably constant irrespective of any change in drill parameters with a constant penetration rate until drill wear becomes excessive. Chapter 3 describes the effects of clearance angles and considers the lip clearance angle on the drill to be equivalent to the front clearance angle on a single point cutting tool. With small clearance angles rubbing may occur, thus increasing the radial cutting force when turning and the thrust force when drilling.

The results obtained from these series of tests clearly show that when drilling at a speed feed combination of 1190 rev/min and 0.088 mm/rev discolouration of the hole takes place after a small number of holes have been drilled and as in previous tests when the torque developed at the drill cutting zone is 2.61 Nm. The main cause of the discolouration is the high glass content which produces a small chip which cannot carry the heat away from the cutting zone. This effect has previously been discussed in Chapter 3. It has been noticed from all the tests carried out that after a relatively small number of holes the chip tended to burn and remain in the flute of the drill resulting in discolouration of the hole. During the examination of the drills for wear it was found that the drill flute showed an oxide film where the chip fused in the drill flute and that the distance of the film from the point of the drill increased as the point angle increased for drills which had been used to determine optimum point angle.

It was decided to relieve the drill body land for a particular distance from the drill point as shown in Fig. 7.7 in an attempt to study the influence of this relief on the drilling parameters and to determine the optimum amount of relief and the position of the start of the relief from the drill point.

7.2.1 Drill Relief

The drill relief for the first test was obtained by means of an off-hand grinder and the amount removed from the diameter of the drill body was approximately 0.5 mm. The preliminary test results obtained using this drill were encouraging in as much as the number of holes drilled before discolouration was greatly increased. Consequently further drills were prepared with a nominal point angle of 130° and a nominal lip clearance angle of 13° together with a range of cylindrically ground reliefs from 0.1 - 0.5 mm off the diameter of the drill. The speed and feed combination was again 1190 rev/min and 0.088 mm/rev respectively. The best results were obtained from the drill with the highest relief value, as it would appear that this material tends to compress onto the body of the drill. This is clearly shown by the brightness of the land on the blackened drill body where rubbing between the wall of the hole and the drill takes place. The results have been tabulated and are shown in Table 7.3 and torque and thrust values against hole number have been plotted and are shown in Figs. 7.8 and 7.9 respectively with the number of holes drilled before discolouration shown on each graph.

7.2.2 Optimum Distance from Drill Point to the start of the Relief

A range of distances were used for the start of the relief from the drill point, 9.5 - 19 mm, while both the drill specification and speed feed combination were the same as in the previous test. The relief used was the best value obtained i.e. 0.5 mm off the diameter. The drill test results were again tabulated and are shown in Table 7.4, torque and thrust values are plotted against hole number, Figs. 7.10 and 7.11, and the number of holes drilled before discolouration was again indicated on each graph.

It can be seen that the best results with respect to the number of holes drilled before discolouration occurs with a drill relief of 0.5 mm off the diameter when the relief starts 9.53 mm from the drill point. The distance of 9.53 mm was the minimum distance which could be allowed for the centre cap to be held on the drill point when the drill was supported on the tailstock centre of a cylindrical grinder. Relieving the drill body eliminates rubbing of the drill and workpiece. Because of the greater thrust forces encountered with this type of material the material tends to compress onto the drill causing the rubbing action. The distance that the relief starts from the point of the drill gives the maximum body length of the drill before the rubbing is again initiated.

7.3 Variation in Penetration Rate

A number of tests were carried out at different penetration rates and it was again found that greater discolouration of the hole occurred at the lower feed rates. When the feed was increased the discolouration of the hole decreased but due to the higher thrust values experienced a ring appears around the hole at the exit side. The size of the ring was proportional to the feed rate used, decreasing the feed rate decreases the size of the ring but increases the discolouration of the hole.

It is a common practice in many workshops to support the plastic material on a board of wood or similar substance to overcome delamination around the periphery of the hole when the drill breaks through. The introduction of a support was not applied during any of the tests carried out since it was considered that the hole in the table of the drill dynamometer was of such a size as to allow the passage of a 9.53 mm diameter drill through the material being drilled and into the table but leaving an area of table large enough to support the material without delamination occurring.

The hole in the dynamometer table was increased to allow the passage of a 12.7 mm diameter drill thus giving maximum table support to the sheet being drilled. The test piece drilled with a 12.7 mm diameter drill again produced a ring at the exit side of the sheet after drilling a number of holes. This clearly shows that the ring which appears on the exit side of the material was not due to lack of support when the smaller diameter drill was used. Another possibility was that the sheet was not flat on the table. Before drilling and after clamping the workpiece, a feeler gauge was applied to the area between the mating surfaces and if the feeler gauge could be moved under the sheet re-clamping was carried out.

The ring is produced by internal cracking of the resin below the hard surface skin of the material. Plates 26, 26a and 27 show the side of the hole and the top of the hole i.e. at the skin surface respectively.

The black area is dye which has penetrated through the cracks at the surface and the side of the hole into the cavity caused by the crack. The depth of the ring into the sheet from the work carried out ranges between 0.25 - 0.5 mm. The delamination or ring can be prevented by removing the top skin on the exit side prior to drilling. Removal of the skin was carried out and then a drilling operation performed to substantiate this statement.

7.4 Use of a Pilot Hole

The work carried out in the previous sections of this chapter was to determine the optimum drilling conditions needed to overcome the discolouration of the hole at an early stage in the drilling process without producing any detrimental effects such as the ring around the exit, i.e. delamination. Some success was achieved with the aid of the relieved drill and it was necessary to determine whether the discolouration could be removed by a final sizing operation i.e. by using a pilot hole. 24 holes were drilled using a 9.53 mm nominal diameter drill with a 130° point angle and 13° lip clearance angle with a speed feed combination of 1190 rev/min and 0.088 mm/rev. The holes produced were then increased in diameter with the aid of a 12.7 mm nominal diameter drill with the same point and lip clearance angles as those produced on the 9.53 mm diameter drill.

Table 7.5 shows the torque and thrust values for the 24 holes drilled with the aid of the pilot and 4 further holes drilled without the pilot hole. The torque values obtained for the 4 holes drilled without the pilot hole was the same as the values obtained for the last 4 holes with the pilot. The thrust values however increased by 75% when the pilot hole is not used.

Fig. 7.12 shows the position of the drill in the material at a particular instant in time during the drilling operation and also includes the points of wear on the drill. The wear profile magnified 100X is shown in Fig. 7.13, which shows the expected drill corner wear and also wear on the primary cutting edge of the drill, where the edges make contact with the pre-drilled hole. This is a clear indication of the abrasive nature of this type of high glass content reinforced plastic.

Variations of speed and feed were again introduced as part of the test programme using the same 12.7 mm diameter drill. It was again found that a low feed rate produces discolouration of the hole, while increasing the feed rate overcomes discolouration but introduces delamination at the exit side of the hole.

7.5 Summary of Results

It can be stated that Glass Reinforced Plastic sheet which contains a lower glass composition by mass and produces chips of a continuous nature when drilled with a High Speed Steel twist drill should produce no problems as long as the parameters chosen for the drilling process allow the twist drill to remain sharp for as long as possible.

Sheets of G.R.P. which contain a higher glass composition by mass cannot be treated in the same manner as the lower glass composition sheets because of the small discontinuous type chip formed during the drilling operation. Bogdanov[42] in his research on the turning of plastics states that certain types of G.R.P. cannot be successfully machined using

High Speed Steel tool bits. It is possible that Sheet 2 is material of this category. However the present work has highlighted two methods which can be adopted to drill the higher glass content sheet using a High Speed Steel twist drill, i.e. by relieving the land on the drill periphery and by increasing the feed rate.

Both methods have their limitations; in the case of the first method the life of the H.S.S. drill is limited due to the small length of actual drill edge behind the point which allow only a limited number of times the drill can be re-sharpened. Secondly the amount of feed rate increase cannot be of the same order as those used when previous tests were carried out on Sheet 1 because of the size of ring produced around the hole at the exit side of the hole. If it is possible to remove the outer skin at the exit prior to drilling then this ring i.e. delamination, would be eliminated.

Table 7.1 Thrust, Torque, and Wear Values for Various Drill Point Angles

Test 1 Speed = 1190 rev/min, Feed = 0.088 mm/min

	100°			110°			118°			130°			140°		
Hole No.	T Nm	V_f N	Wear mm^2x10^{-2}	T Nm	V_f N	Wear mm^2x10^{-2}	T Nm	V_f N	Wear mm^2x10^{-2}	T Nm	V_f N	Wear mm^2x10^{-2}	T Nm	V_f N	Wear mm^2x10^{-2}
1	2.08	194.7	0	2.08	194.7	0	2.58	253.5	0	1.81	280	0	2.58	353	0
15	2.58	398		2.58	499		2.83	480		2.08	518		2.58	675	
30	2.61	554.4	5.55	2.58	640.9	5.81	3.07	590	5.81	2.58	721	5.94	2.83	791	4.52
45	2.83	657		2.83	737		3.54	721		3.07	752		3.54	898	
60	3.07	752.4	13.40	3.07	897.8	13.16	3.54	856	11.74	3.07	812	12.00	3.54	1006	11.42
75	3.30	898		3.30	1006		3.54	953		3.30	925		3.54	1031	
90	3.79	1156.6	22.80	3.54	1204	23.10	3.75	1157	22.90	3.75	952	21.48	3.97	1082	21.94

Table 7.1a Thrust, Torque, and Wear Values for Various Drill Point Angles

Test 2 Speed = 1190 rev/min, Feed = 0.088 mm/min

1	2.08	195	0	2.08	195	0	2.58	254	0	1.81	280	0	2.58	353	0
15	2.34	398		2.34	499		2.58	398		2.08	480		2.58	590	
30	2.58	554.4	5.94	2.58	554	5.81	2.58	480	5.16	2.58	590	5.16	2.58	657	4.17
45	2.58	812		2.58	690		2.58	624		2.83	721			870	
60	3.30	925	15.10	3.07	812	12.26	3.07	783	10.71	3.07	812	12.32	3.30	1006	11.90
75	3.30	1082		3.30	952		3.30	812		3.30	883			1031	
90	3.54	1228	21.94	3.54	1157	18.06	3.54	1050	20.00	3.75	925	20.65	3.94	1082	20.65

Table 7.2 Thrust, Torque and Wear Values for various Lip Clearance Angles

Speed = 1190 rev/min, Feed = 0.088 mm/min

8°					9°				
Hole No.	V_f N	T Nm	Wear $mm^2 \times 10^{-2}$ Est.	Corr.	Hole No.	V_f N	T Nm	Wear $mm^2 \times 10^{-2}$ Est.	Corr.
1	370	1.82			1	265	1.51		
5	470	2.09			5	470	2.09		
10	600	2.09			10	565	2.09		
15	720	2.09			15	760	2.09		
20	770	2.09			20	840	2.34		
25	920	2.35			25	910	2.34		
30	940	2.61	47.17	54.17	30	940	2.61	50.60	54.68

10°					11½°				
Hole No.	V_f N	T Nm	Wear Est.	Corr.	Hole No.	V_f N	T Nm	Wear Est.	Corr.
1	260	2.09			1	230	2.09		
5	370	2.09			5	430	2.09		
10	520	2.34			10	550	2.34		
15	610	2.34			15	610	2.34		
20	650	2.61			20	700	2.34		
25	730	2.61			25	750	2.61		
30	800	2.61	54.61	57.56	30	800	2.61	41.97	41.46

N.B. Est. = Estimated Value
Corr. = Corrected Value

Table 7.2 cont'd

Speed = 1190 rev/min, Feed = 0.0888 mm/min

13°					16°				
Hole No.	V_f N	T Nm	Wear $mm^2 \times 10^{-2}$		Hole No.	V_f N	T Nm	Wear $mm^2 \times 10^{-2}$	
1	200	2.09			1	260	2.09		
5	370	2.34			5	370	2.09		
10	520	2.34			10	500	2.34		
15	600	2.34			15	580	2.34		
20	690	2.61			20	670	2.61		
25	730	2.61	Est.	Corr.	25	710	2.61	Est.	Corr.
30	800	2.61	41.97	38.31	30	760	2.61	66.69	62.91

17°					18½°				
1	260	2.11			1	260	2.34		
5	430	2.11			5	370	2.34		
10	500	2.11			10	475	2.61		
15	570	2.34			15	500	2.61		
20	650	2.61			20	560	2.61		
25	700	2.61	Est.	Corr.	25	610	2.61	Est.	Corr.
30	770	2.85	73.07	71.50	30	650	3.09	66.46	59.13

N.B. Est. = Estimated Value
Corr. = Corrected Value

Table 7.3 Thrust and Torque Values for Relieved Drills

Speed = 1190 rev/min, Feed = 0.088 mm/rev

Amount of Relief 0.1 mm

Hole No.	V_f N	T Nm
1	260	1.52
15	510	2.08
30	720	2.60
35	770	2.72

Amount of Relief 0.15 mm

Hole No.	V_f N	T Nm
1	280	1.56
15	520	2.32
30	690	2.66
35	730	2.84

Amount of Relief 0.38 mm

Hole No.	V_f N	T Nm
1	320	0.90
15	600	1.82
30	910	2.36
45	1040	2.61
60	1140	2.86
75	1180	2.86
90	1200	3.08

Table 7.3 cont'd

Speed = 1190 rev/min, Feed = 0.088 mm/rev

Amount of Relief 0.5 mm

Hole No.	V_f N	T Nm
1	290	1.22
15	520	1.82
30	650	2.08
45	700	2.32
60	770	2.32
75	880	2.61
90	920	2.61

Hand Relief 0.5 mm

1	290	1.22
15	560	2.08
30	650	2.08
45	680	2.32
60	730	2.46
75	800	2.61
90	920	2.61

Table 7.4 Thrust and Torque Values for Relieved Drills with Varying Point Start Distances

Amount of Relief 0.5 mm

Distance from Point 18.75 mm

Hole No.	V_f N	T Nm
1	250	1.82
10	470	2.08
15	570	2.34
20	650	2.62

Distance from Point 15.63 mm

Hole No.	V_f N	T Nm
1	250	0.9
15	600	2.08
30	810	2.08
45	870	2.60
60	900	2.60
75	970	3.08
90	1170	3.08

Distance from Point 12.5 mm

1	320	1.24
15	610	2.10
30	860	2.34
45	980	2.34
60	1070	2.62
75	1200	3.08
90	1300	3.56

Distance from Point 9.53 mm

1	250	1.54
15	510	1.54
30	760	2.10
45	980	2.10
60	1170	2.10
75	1210	2.56
90	1290	2.62

Table 7.5 Thrust and Torque Values with and without Pilot

with Pilot

Hole No.	V_f N	T Nm
2	200	2.60
20	803	4.44
24	803	4.44

without Pilot

Hole No.	V_f N	T Nm
1	607	3.10
25	1440	4.44
28	1498	4.44

CHAPTER 8.

CONCLUSIONS

The information obtained from the tests must be seen to be applicable to two different materials. For this reason the conclusions reached are given with respect to Sheet 1 and Sheet 2.

Sheet 1

(1) Chips produced from this material by the drilling operation are of a continuous nature.

(2) Thrust or vertical force increases with feed rate increase.

(3) Torque increases with decrease in speed.

(4) Torque may be estimated from the equation

$$T = 0.22\ D^{1.5}\ F^{0.7} \quad (\mathrm{Nm}).$$

(5) Material Removal Factor "M.R.F." may be estimated from the equation

$$\mathrm{M.R.F.} = \frac{D^{0.5}\ F^{0.3}}{1.76} \quad (\mathrm{mm^3/J})$$

(6) Material Removal Factor is greatest when higher feed rates are applied (0.7 - 1 mm/rev).

(7) Power consumed at the drill point is least when the lowest speed highest feed combination is used for a given penetration rate.

(8) Change in power consumed is least when the lowest speed highest feed combination is used for a given penetration rate.

(9) Least drill wear is experienced when lower speed higher feed combinations of a given penetration rate are applied.

(10) Roundness values are improved when higher feed rates are applied (0.7 - 1 mm/rev).

(11) Surface finish "Ra" values show little change in value over the test range of holes drilled when higher feed rates are applied (0.7 - 1 mm/rev).

(12) Change in hole size is least when higher feed rates (0.7 - 1 mm/rev) are applied.

(13) Burr or build up is less at the exit side of the hole than at the entry side.

(14) Delamination around the hole both at exit and entry occurs with low feed rates (0.088 mm/rev).

(15) Intrusion of material in the bore is greater at the exit side of the hole than at entry.

Sheet 2

(1) Chips produced from this material by the drilling operation are small and discontinuous.

(2) Varying the point angle has little effect on the torque, vertical force, or drill wear, when a low feed rate is used (0.088 mm/rev).

(3) Discolouration of the hole occurs early in the drilling operation when using H.S.S. twist drills with a penetration rate combination of 1190 rev/min and 0.088 mm/rev.

(4) Discolouration of the hole occurs when a torque value of 2.61 Nm is reached with a speed of 1190 rev/min and a feed of 0.088 mm/rev.

(5) Increase in lip clearance angle from 8° - 16° produces only a small change in torque while the thrust decreases with an increase in lip clearance angle.

(6) Increase in feed decreases discolouration but increases the area of delamination.

(7) Discolouration is decreased by relief of the drill along its body diameter.

(8) From the conditions chosen the best results are obtained when the drill relief is 0.5 mm off the diameter.

(9) From the conditions chosen the best results are obtained when the drill relief commences 9.53 mm from the point when a 9.53 mm diameter drill is used.

(10) Discolouration still occurs when an initial pilot hole is used.

(11) Vertical force or thrust is decreased but the torque remains the same when a pilot hole is used.

From the above conclusions it is possible to state that if the material produces a continuous chip when drilled H.S.S. drills are quite satisfactory for the operation as long as a high feed rate is used. When a small discontinuous chip is produced, re-designing the drill by "backing off" or increasing the time between re-grinds by using carbide tipped drills may be the answer.

CHAPTER 9.

FURTHER WORK

(i) It has been found from the work carried out during this project that "backing off" a standard drill along the drill body tends to reduce discolouration of the hole when closely woven glass fabric is used as the reinforcement. For this reason further work could be carried out using a drill of the type known as a spade drill, or a re-designed standard drill to include (a) the "backing off" effect, and (b) the use of carbide tipped cutting edges to further reduce wear at the drill corners.

(ii) Delamination of the sheet has been shown to occur when feed rates are increased. Further work could be carried out to compare the effects other than the asthetic when the top skin of the sheet is removed.

(iii) It has been found that an increase in the value of the thrust force on the drill results in less drill wear and an improvement in the surface finish of the hole. This effect of compressing the sheet in the direction of its thickness with the aid of a hydraulic tail stock could be used when turning this type of material. It has been found when turning the material with a knife type turning tool, when the cutting action is perpendicular to the laminates, that the material delaminates and forms an umbrella effect around the turning tool.

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APPENDICES

APPENDIX 1.

Results of Glass Analysis

(BS 2782, Part 1, 1970[44])

Sheet No.	Thickness (cm)	% Glass by Mass	Glass Mass/unit area
1	2.73	60.78	3.18
2	2.46	74.32	3.55

Mass of each constituent/cm^2

Sheet 1 - Glass by mass 60.78%, Resin by mass 39.22%

$$\text{mass/cm}^3 = 0.6078 \times 2.55 + 0.3922 \times 1.25$$
$$= 1.55 + 0.49$$

where 2.55 and 1.25 are the specific gravities of the glass and resin constituents respectively,

$$\text{mass/cm}^2 = 1.55 \times 2.73 + 0.49 \times 2.73$$
$$= 4.23\text{g} + 1.34\text{g}$$
$$= \underline{5.57\text{g}}$$

Sheet 2 - Glass by mass 74.32%, Resin by mass 25.68%

$$\text{mass/cm}^3 = 0.7432 \times 2.55 + 0.2568 \times 1.25$$
$$= 1.895 + 0.32$$
$$\text{mass/cm}^2 = 1.895 \times 2.46 + 0.32 \times 2.46$$
$$= 4.66\text{g} + 0.79\text{g}$$
$$= \underline{5.45\text{g}}$$

$$\%\ \text{difference in mass/cm}^2 = \frac{5.57 - 5.45}{5.57} \times 100$$

Therefore Sheet 1 is approximately 2% greater in mass than Sheet 2.

To compare measured glass mass/unit area with the calculated glass mass/cm^2

% difference measured value

$$= \frac{3.55 - 3.18}{3.55} \times 100 = 10\%$$

% difference calculated value

$$= \frac{4.66 - 4.23}{4.66} \times 100 = 9\%$$

Thus the glass content/unit area is higher in Sheet 2 than in Sheet 1. If it is assumed that the thickness of the fibre is the same for both weaves then the weave of the reinforcement in Sheet 2 must be closer than that in Sheet 1. This is shown to be the case from Plate 1

% Resin content/cm^2 - Sheet 1 = 1.34g

% Resin content/cm^2 - Sheet 2 = 0.79g

then the % difference is given by

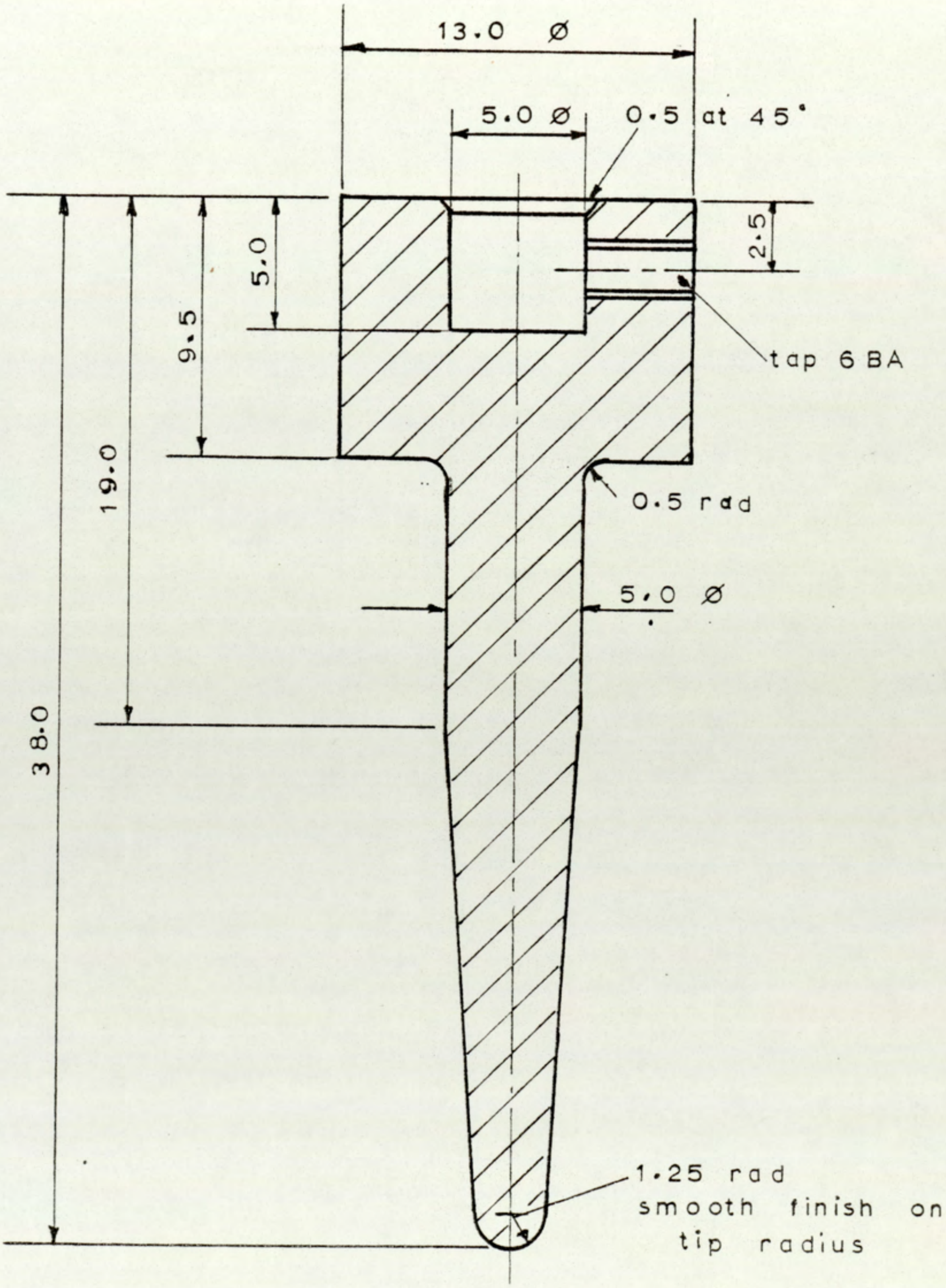
$$\frac{1.34 - 0.790}{1.34} \times 100 = 41\%$$

hence Sheet 1 contains 41% more resin/cm^2 than Sheet 2.

The great difference in resin content provides a good indication as to why it is possible to produce a continuous chip from Sheet 1 and not from Sheet 2. The glass fibres of the fabric in Sheet 1 are a greater distance apart than those in Sheet 2 when constructed in the matrix. Thus as the drill cuts further through the material the greater the amount of ductile material i.e. the resin is produced. The resin produces the chip embedded with the brittle glass particles from the reinforcement. In the case of Sheet 2 the fabric layers being closer together produce a structure which contains less of the ductile resin thus when drilled form chips which contain more of the brittle glass fabric with a result that the chip is small and discontinuous.

The variation in glass and resin content further substantiates the discussion in Chapter 6 regarding drill wear formation and also gives an indication as to why the ring which appears at the exit side of Sheet 2 material increases in size with increase in feed but bore discolouration is lessened. The ring is produced by the higher thrust forces required to overcome the resistance set up by the finer woven fabric reinforcement. When the feed is decreased the drill stays longer in the hole and heat is generated by friction between the primary cutting edges of the drill and the increased area of glass fabric with which the drill is in contact. The increased glass percentage coupled with the decrease in resin content results in a small chip. This chip is not large enough to carry away heat from the cutting zone so the drill and workpiece become hot resulting in discolouration of the hole, and wear and oxidisation of the drill point cone and flute occurs.

APPENDIX 2.



PROBE TIP

Mat'l SILVER STEEL

All units in millimetres

Drg Nº 1

APPENDIX 2.

APPENDIX 3.

Calibration of the Drill Dynamometer

Torque

Y lbf ft	X deflection	Log Y	Log X
1	2	0	0.3010
2	4.5	0.3010	0.6532
3	8	0.4771	0.9031
4	11	0.6020	1.0414
5	15	0.6990	1.1761
6	19	0.7782	1.2788
7	23	0.8457	1.3617
8	26	0.9031	1.4149

$$\text{Torque (Nm)} = 0.9\, X^{0.767}$$

Vertical Force - Thrust

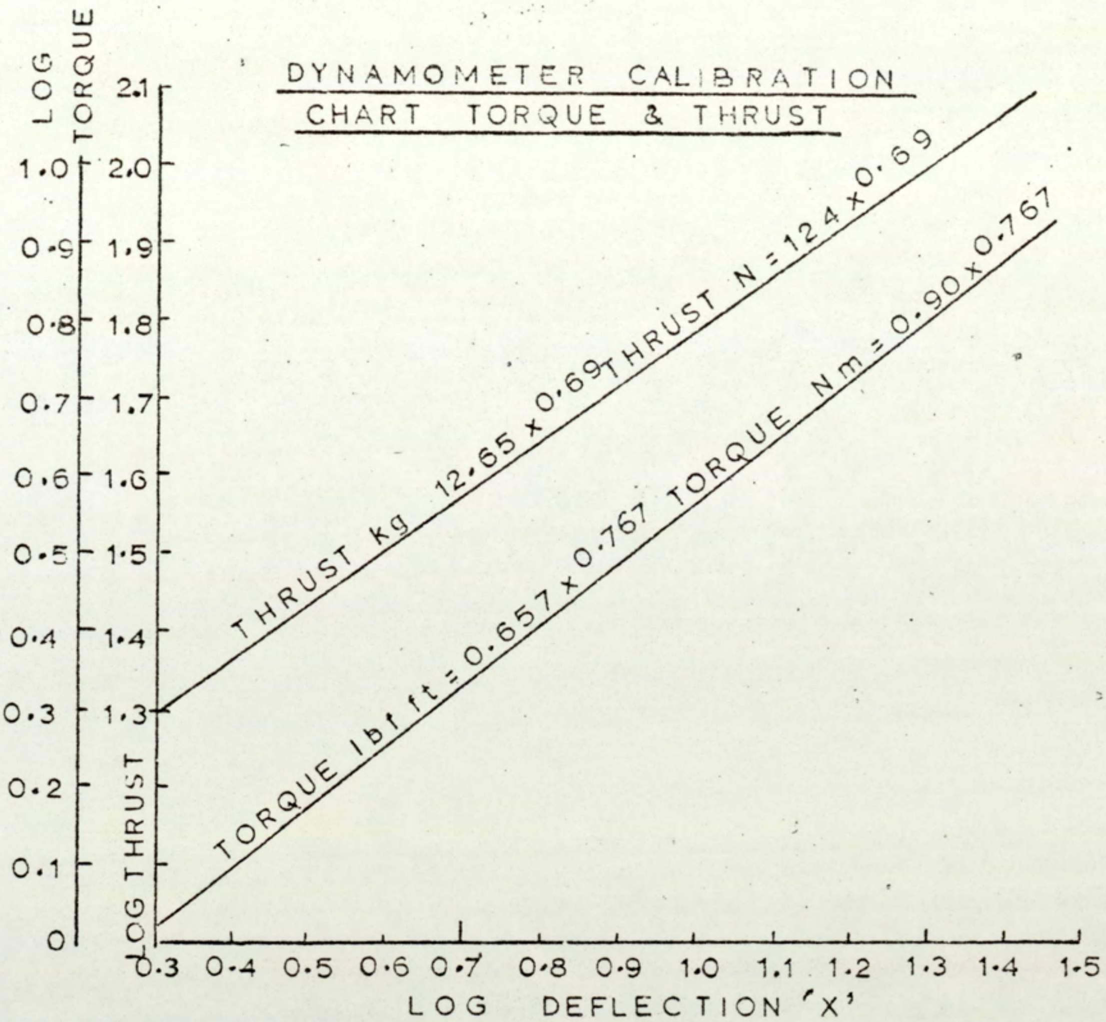
Y kg	X deflection	Log Y	Log X
20	2.0	1.3010	0.3010
40	5.5	1.6021	0.7404
60	10	1.7782	1.0000
80	15	1.9031	1.1761
100	20	2.0000	1.3010
120	26	2.0792	1.4149

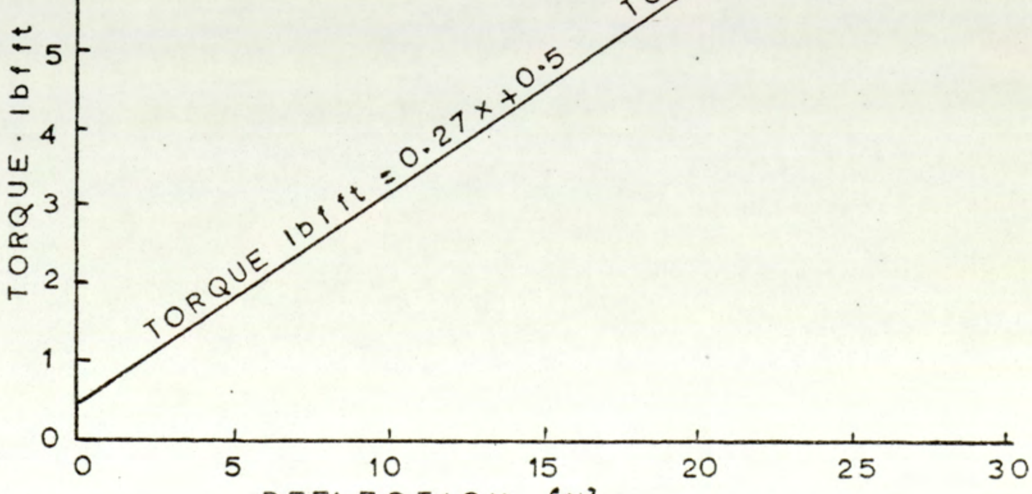
$$\text{Thrust (N)} = 124\, X^{0.69}$$

The TALYMIN 4-10 RECORDER was serviced and it was found necessary to re-calibrate the dynamometer for the torque values only. The following are the revised values:-

Y lbf ft	X deflection
1	2
2	6
3	$9\frac{1}{2}$
4	13
5	$16\frac{1}{2}$
6	$20\frac{1}{2}$
7	24
8	28

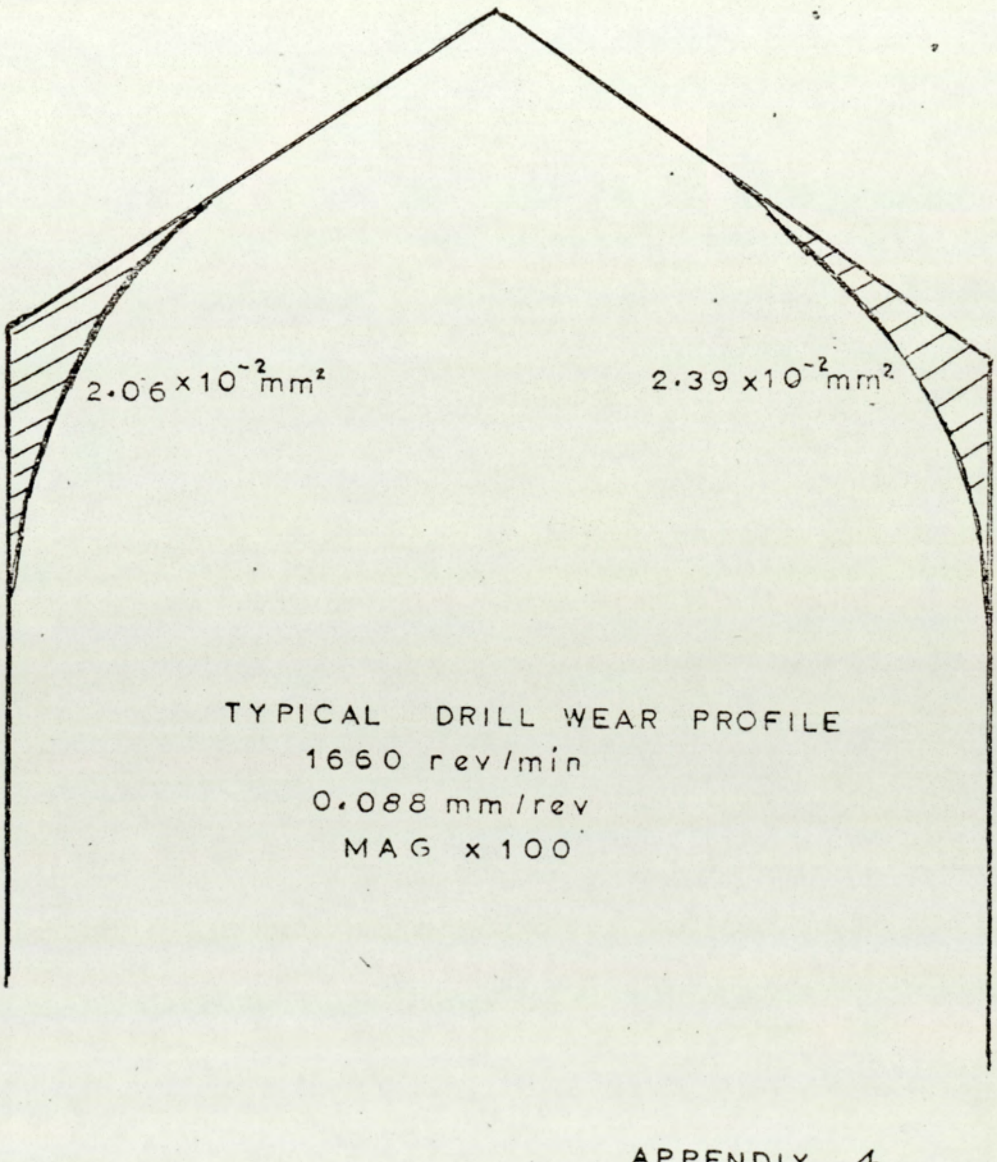
$$\text{Torque (Nm)} = 0.37\, X + 0.68$$


DYNAMOMETER CALIBRATION
CHART TORQUE & THRUST
LOG TORQUE
LOG THRUST
LOG DEFLECTION 'X'
THRUST kg 12.65 x 0.69 THRUST N = 124 x 0.69
TORQUE lbf ft = 0.657 x 0.767 TORQUE Nm = 0.90 x 0.767
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
2.1 2.0 1.9 1.8 1.7 1.6 1.5 1.4 1.3
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5


REVISED TORQUE CHART
TORQUE · lbf ft
DEFLECTION 'X'
TORQUE lbf ft = 0.27 x + 0.5 TORQUE Nm = 0.37x + 0.68
8 7 6 5 4 3 2 1 0
0 5 10 15 20 25 30

APPENDIX 3

APPENDIX 4.



TYPICAL DRILL WEAR PROFILE
1660 rev/min
0.088 mm/rev
MAG x 100

APPENDIX 4.

APPENDIX 5.

Correlation values and levels of significance for various pairings

Degrees of Freedom = 23 - 2 = 21 (Chapter 6)

Pairing	Spearman Correlation r_{RHO}	Level of Significance
Drill Wear and Range of Roundness (L.S.C. values)	0.44	0.05 (5%)
Change in Dia. and Range of L.S.C.	0.34	0.10 (10%)
Change in Dia. and Drill Wear	0.58	0.01 (1%)
M.R.F. and Feed	0.80	0.001 (0.1%)
Feed and Surface Roughness Ra	-0.805	0.001 (0.1%)

Statistical Tests to determine the difference between (i) Test Results and (ii) Tests 1 and 2 (Chapter 7)

Mann-Whitney U-Test

The Mann-Whitney U-Test is designed to test differences between location parameters of two independent samples.

Let θ_1 and θ_2 be location parameters for Test 1 and Test 2 of Tables 7.1 and 7.1a respectively.

Null hypothesis (H_0): $\theta_1 = \theta_2$

Alternate hypothesis (H_1): $\theta_1 \neq \theta_2$

Significance level α, 0.10 two tail test.

Critical region: when $n_1 = n_2 = 5$ the critical region is given by:-

$$U_1 \leqslant 4 < 21 \leqslant U_2$$

where
$$U_1 = n^2 + \frac{n(n-1)}{2} - R_1$$

$$U_2 = n^2 + \frac{n(n-1)}{2} - R_2$$

n = sample size,

R_1 = sum of ranked values, Test 1,

R_2 = sum of ranked values, Test 2.

Kruskal-Wallis One-way Analysis of Variance by Ranks

The Mann-Whitney U-test of difference between two groups may be extended to situations where more than two groups are involved. The extensions are proposed by Kruskal and Wallis[49].

Suppose that there are K experimental groups with N_1 readings in the first N_2 in the second N_k in the last,

where $N_1 + N_2 + \ldots\ldots\ldots + N_k = N$.

The N values are pooled and ranked from 1 to N then rank totals are found for each group (R_j), the statistic H is calculated from:

$$H = \frac{12}{N(N+1)}\left(\sum_{j=1}^{K} \frac{R_j^2}{N_j}\right) - 3(N+1)$$

the distribution of H is approximately given by (Chi^2)χ^2 with K - 1 degrees of freedom.

Reject H_0 when calculated $H > \chi^2$.

F Test

To determine whether or not two variances differ significantly from one another reference is made to a distribution called the F distribution and named after R. A. Fisher the statistician who first described it. Given independent samples of two populations it is usual to base tests of equality on the ratio S_1^2/S_2^2 or S_2^2/S_1^2 where S_1 and S_2 are the two sample standard deviations.

Assuming that the population from which the two samples were obtained have roughly the shape of a normal distribution, it can be shown that the sampling distribution of such a ratio (appropriately called a variance ratio) is a continuous distribution called the F distribution. This distribution depends upon the sample sizes n_1 and n_2 or better still the two parameters $n_1 - 1$ and $n_2 - 1$ referred to as the respective degrees of freedom. The decision concerning the equality of the two population standard deviations σ_1 and σ_2 is based on the statistic

$$F = \frac{S_1^2}{S_2^2} \text{ or } \frac{S_2^2}{S_1^2} \text{ whichever is the larger.}$$

With this statistic the null hypothesis is $\sigma_1 = \sigma_2$ and the alternative hypothesis $\sigma_1 \neq \sigma_2$ is accepted when the observed value of F exceeds $F_{\frac{\alpha}{2}}$, where α, is the level of significance.

Comparison of Tests 1 and 2 from Tables 7.1 and 7.1a

Mann Whitney U-Test

Two tail test $\alpha_1 = 0.10$.

Accept H_0 no significant difference when $4 < U_2 < U_1 < 21$.

Thrust Force

100° Point Angle $U_2 = 8\frac{1}{2}$ $U_1 = 16\frac{1}{2}$ Accept

Torque

100° " " $U_2 = 13$ $U_1 = 12$ "

Thrust Force

110° Point Angle $U_2 = 15$ $U_1 = 10$ Accept

Torque

110° " " $U_2 = 13\frac{1}{2}$ $U_1 = 11\frac{1}{2}$ "

Thrust Force

118° Point Angle $U_2 = 15$ $U_1 = 10$ Accept

Torque

118° " " $U_2 = 21$ $U_1 = 4$ Reject

Thrust Force

130° Point Angle 3 samples - Kruskal Wallace

$H = 1.685$ $d_f = 2$ $\alpha_1 = 0.05$

$1.685 < 5.99$ Accept null hypothesis

Torque

130° Point Angle 3 samples - Kruskal Wallace

$H = 0.635$ $d_f = 2$ $\alpha_1 = 0.05$

$0.635 < 5.99$ Accept null hypothesis

Thrust Force

140° Point Angle $U_2 = 13\frac{1}{2}$ $U_1 = 11\frac{1}{2}$ Accept

Torque

140° " " $U_2 = 18\frac{1}{2}$ $U_1 = 6\frac{1}{2}$ "

F Test - Two Way Classification

To determine whether there is (i) a difference between drill wear and (ii) a difference between Test 1 and Test 2 of Tables 7.1 and 7.1a.

Drill Point Angle	100	110	118	130	140
Drill Wear Test 1	22.80	23.10	22.9	21.48	21.94
Drill Wear Test 2	21.94	18.06	20.0	20.65	20.65

Mean 21.35, K = 2, n = 5

Difference between mean

1	1.45	1.75	1.55	0.13	0.59	5.47
2	0.59	-3.29	-1.35	-0.70	-0.70	-5.45
Total	2.04	-1.54	0.20	-0.57	-0.11	-0.02

Drill Wear $\dfrac{2.04^2 + (-1.54)^2 + 0.20^2 + (-0.57)^2 + (-0.11)^2}{2} - \dfrac{(-0.02)^2}{10}$

$= \dfrac{4.1616 + 2.3716 + 0.04 + 0.3249 + 0.0121}{2} - 0.00004$

$= \underline{3.45506}$

Tests $= \dfrac{5.47^2 + (-5.45)^2}{5} - 0.00004$

$= \dfrac{29.9209 + 29.7025}{5}$

$= \underline{11.92464}$

Totals $= 1.45^2 + 1.75^2 + 1.55^2 + 0.13^2 + 0.59^2$

$+ 0.59^2 + (-3.29)^2 (-1.35)^2 + (-0.70)^2 + (-0.70)^2$

$= 2.1025 + 3.0625 + 2.4025 + 0.0169 + 0.3481$

$+0.3481 + 10.8241 + 1.8225 + 0.49 + 0.49$

$= 21.9072$

Source	Sum of Squares	d_f	Mean Square	F Ratio
Drill Wear	3.45506	4	0.863665	$\dfrac{0.863765}{2.98116} = 0.28974$
Test	11.92464	1	11.92464	$\dfrac{11.92464}{2.98116} = 4$
Error	6.5275	4	2.98116	
Total	21.9072	9		

$F_{0.01}$ 4/4 = 16   0.2897 < 16   No significant difference between wear values.

$F_{0.01}$ 1/4 = 21.02   4 < 21.02   No significant difference between tests.

To determine whether there is (i) a difference between Torque values and (ii) a difference between Test 1 and Test 2 of Tables 7.1 and 7.1a.

Drill Point Angle	100	110	118	130	140
Torque - Test 1	3.79	3.54	3.75	3.75	3.97
Torque - Test 2	3.54	3.54	3.54	3.75	3.94

Source	Sum of Squares	d_f	Mean Square	F Ratio
Torque Value	0.19354	4	0.0484	6.96
Test	0.02401	1	0.02401	3.454
Error	0.02774	4	0.00695	
Total	0.24529	9	—	

$F_{0.01}$ 4/4 = 16   6.96 < 16   No significant difference between Torque values.

$F_{0.01}$ 1/4 = 21.2   3.454 < 21.2   No significant difference between tests.

To determine whether there is (i) a difference between Thrust values (V_f) and (ii) a difference between Test 1 and Test 2 of Tables 7.1 and 7.1a.

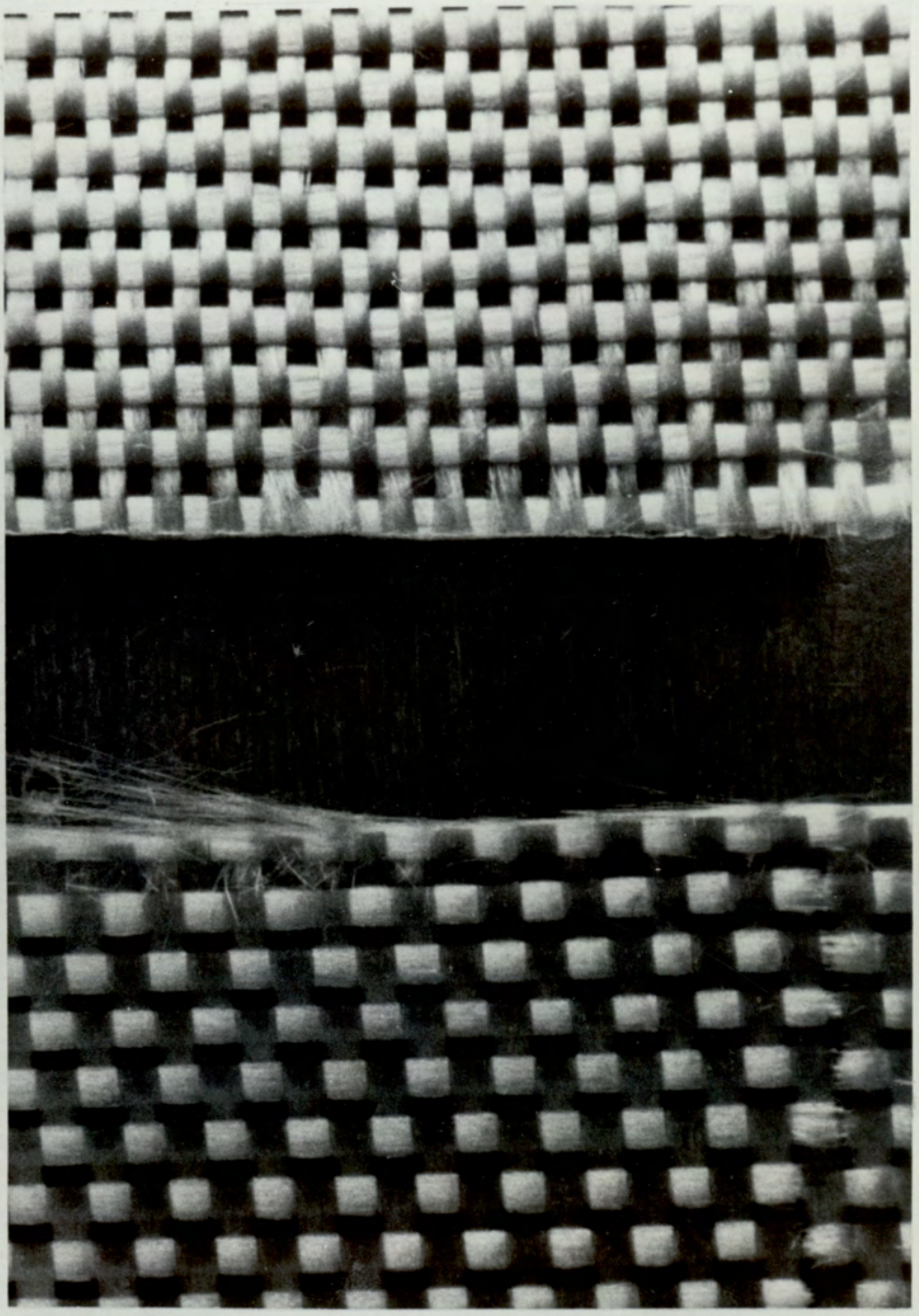
Drill Point Angle	100	110	118	130	140
Thrust - Test 1	1157	1204	1157	952	1082
Thrust - Test 2	1228	1157	1050	925	1082

Source	Sum of Squares	d_f	Mean Square	F Ratio
Thrust	82906	4	20727	9.9
Test	1210	1	1210	0.583
Error	8306	4	2075	
Total	92422			

$F_{0.01}$ 4/4 = 16   9.9 < 16   No significant difference between values.

$F_{0.01}$ 1/4 = 0.583   0.583 < 21.2   No significant difference between tests.

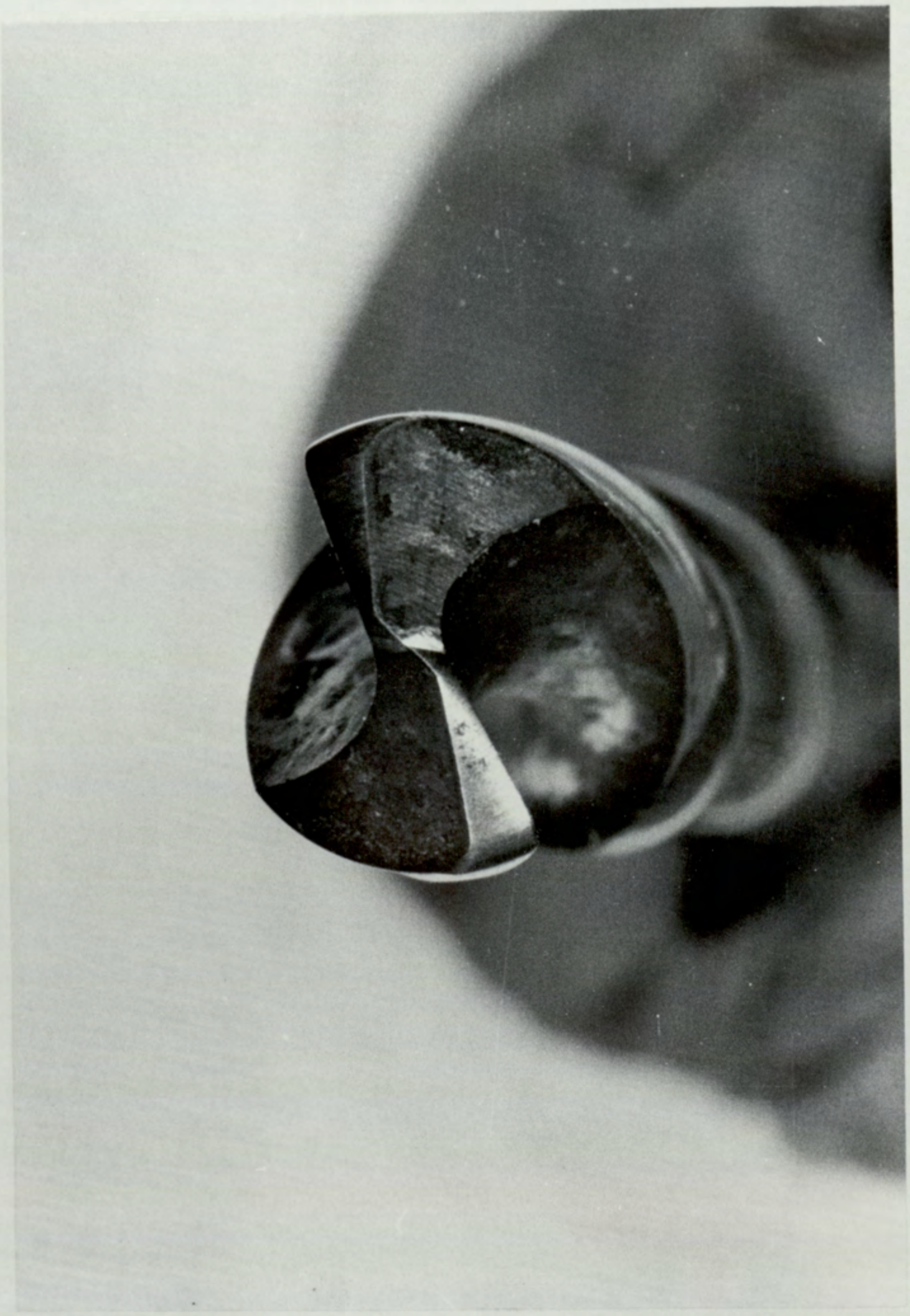
Sample from sheet N° 1



Sample from sheet N° 2

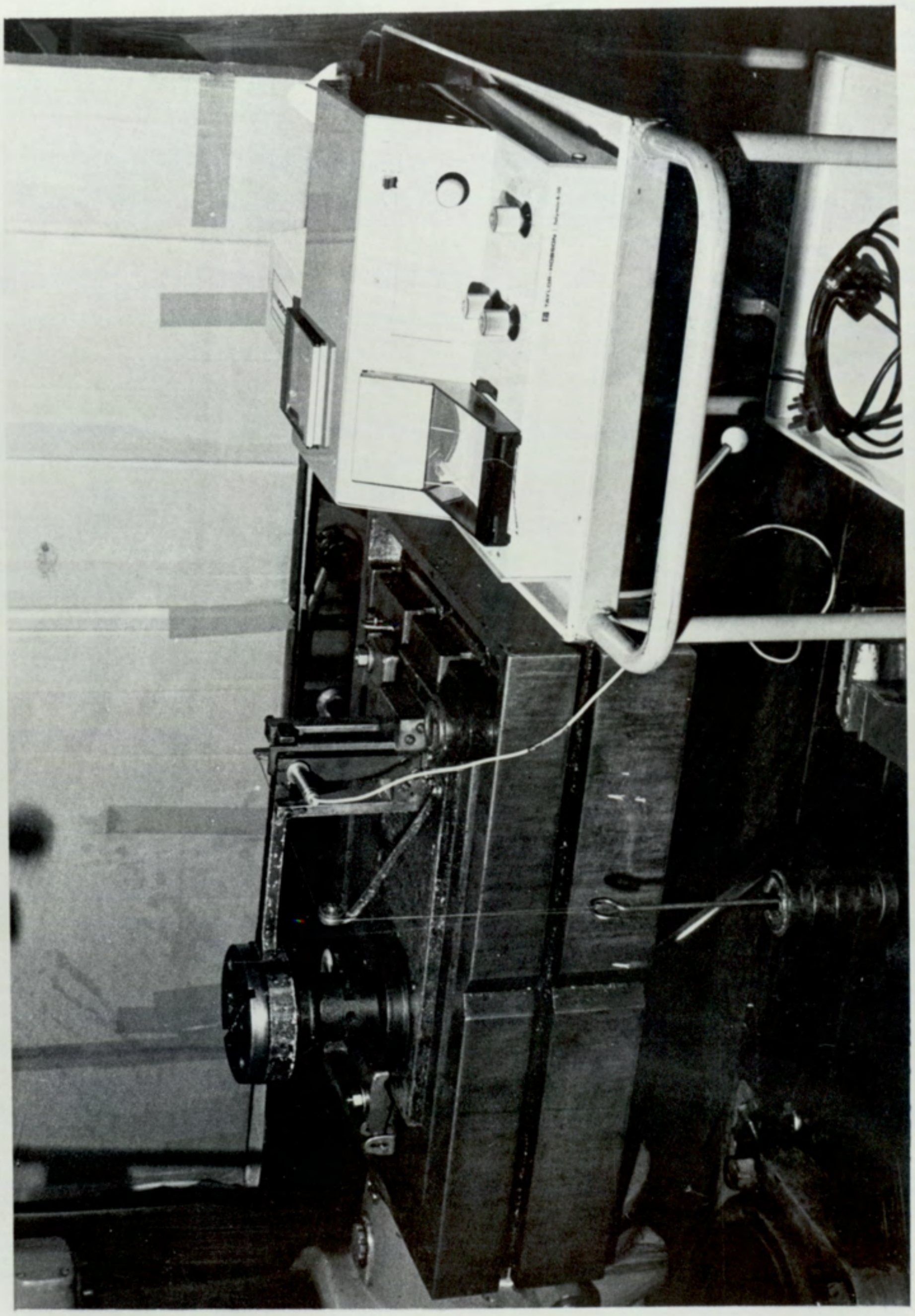
GLASS FABRIC

Plate N° 1



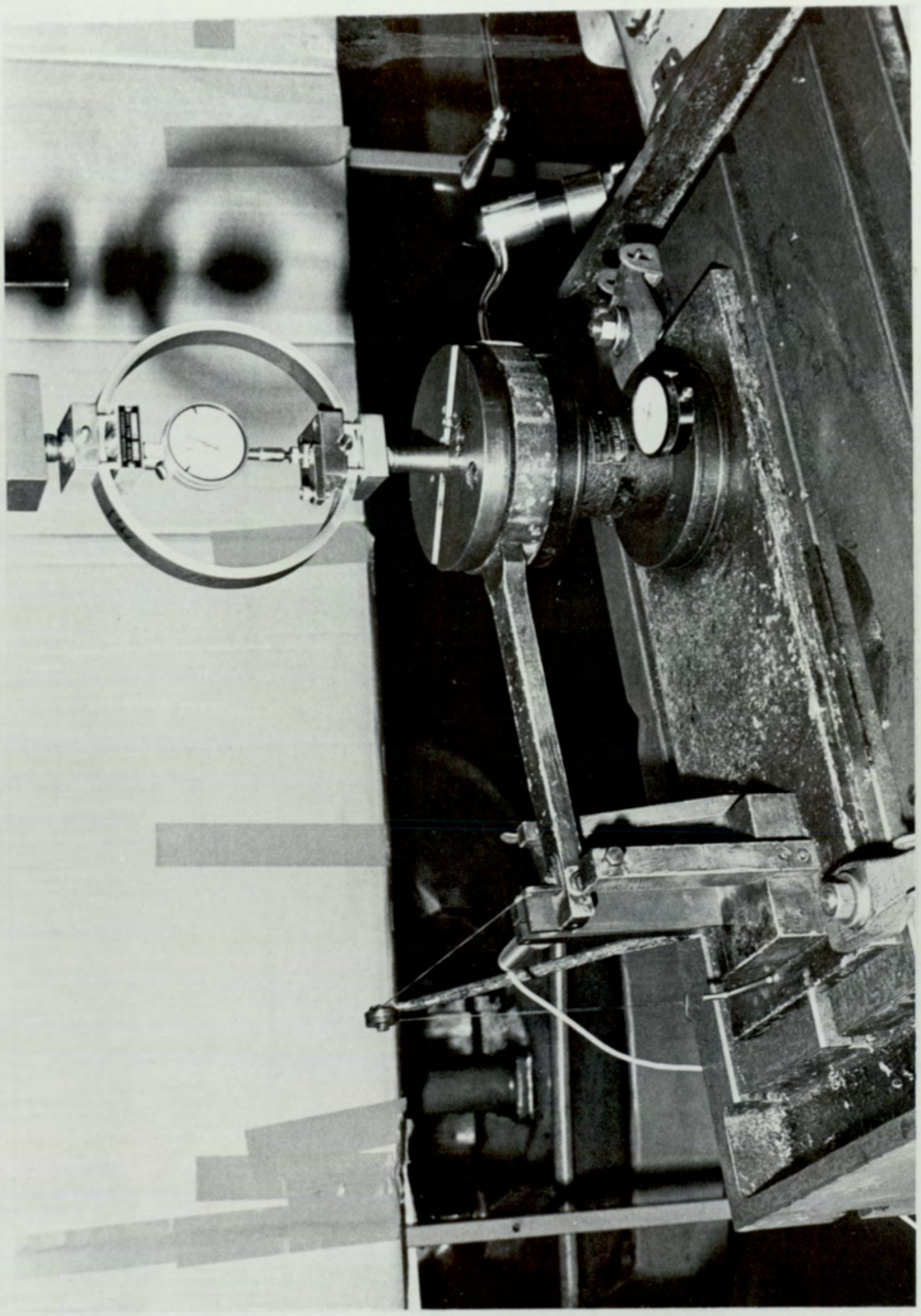
DRILL WEAR

Plate Nº 2



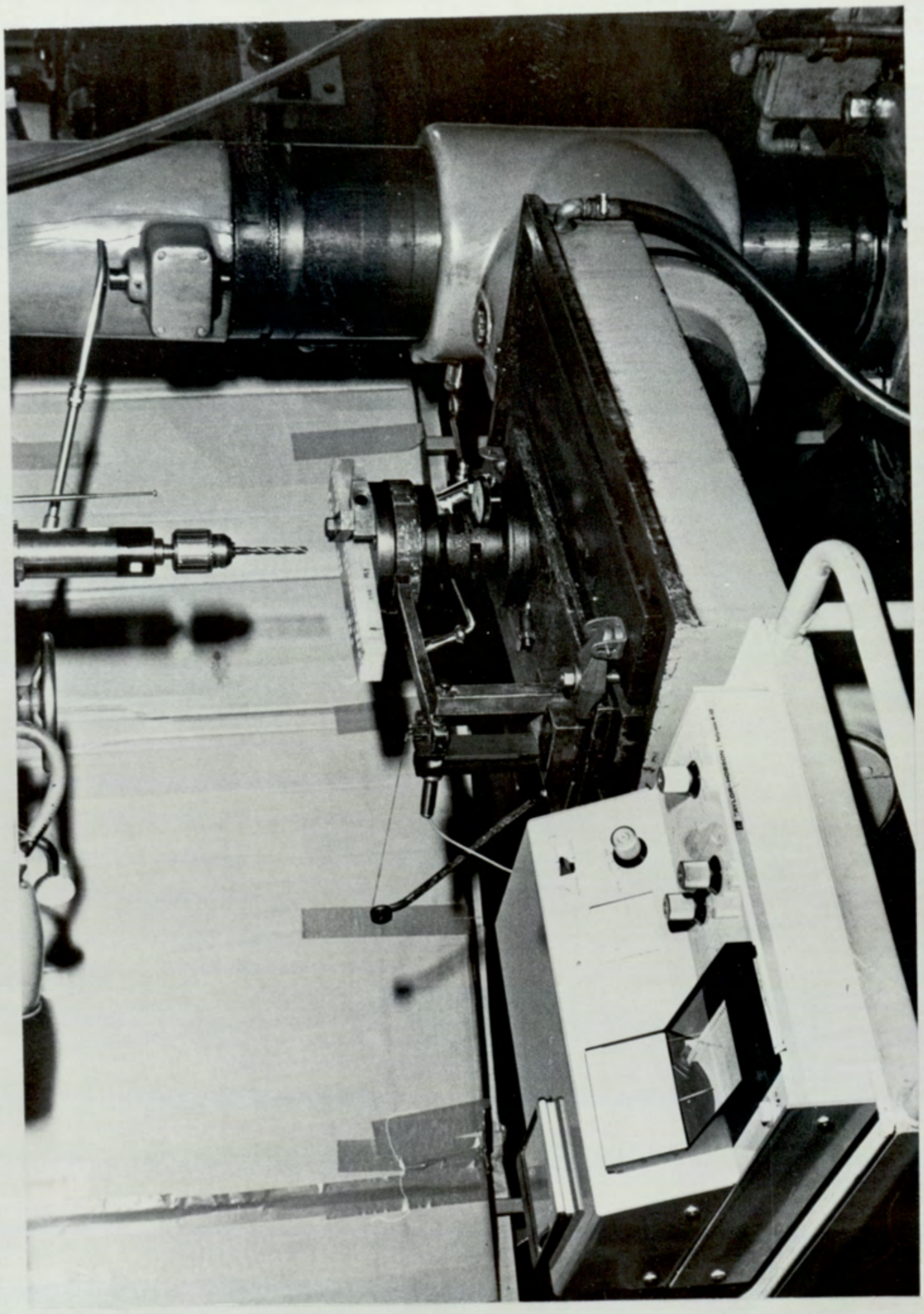
DYNAMOMETER CALIBRATION TORQUE

Plate N° 3



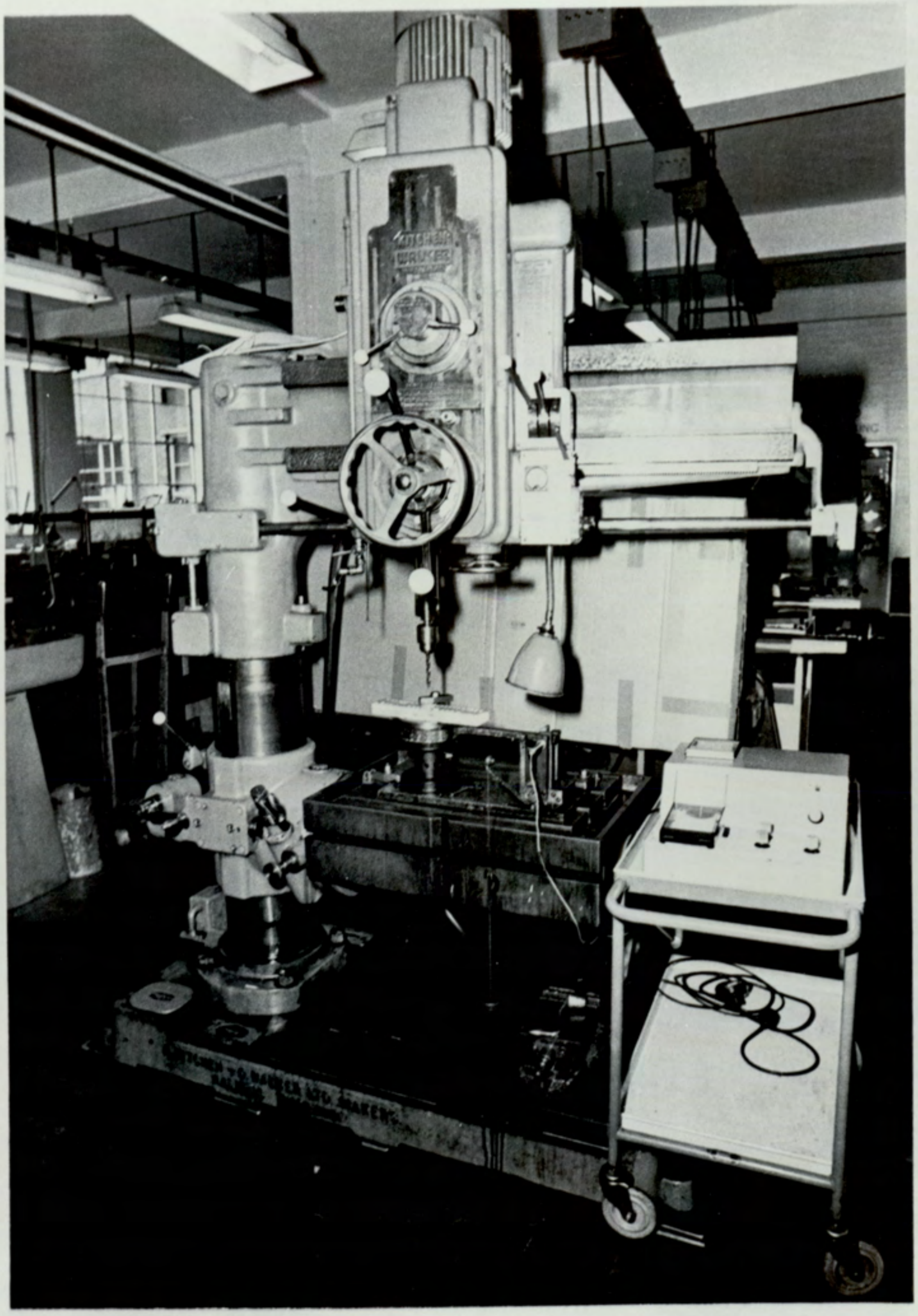
DYNAMOMETER CALIBRATION THRUST

Plate N°4



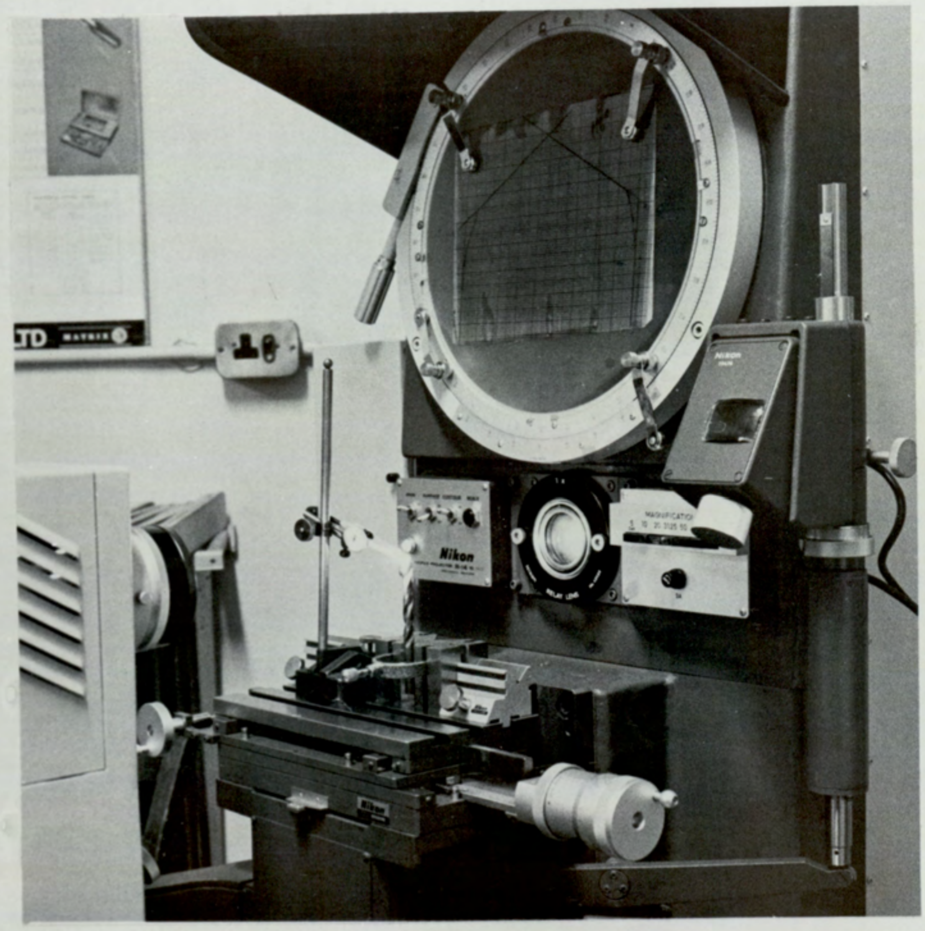
SET UP FOR DRILLING OPERATION

Plate N° 5



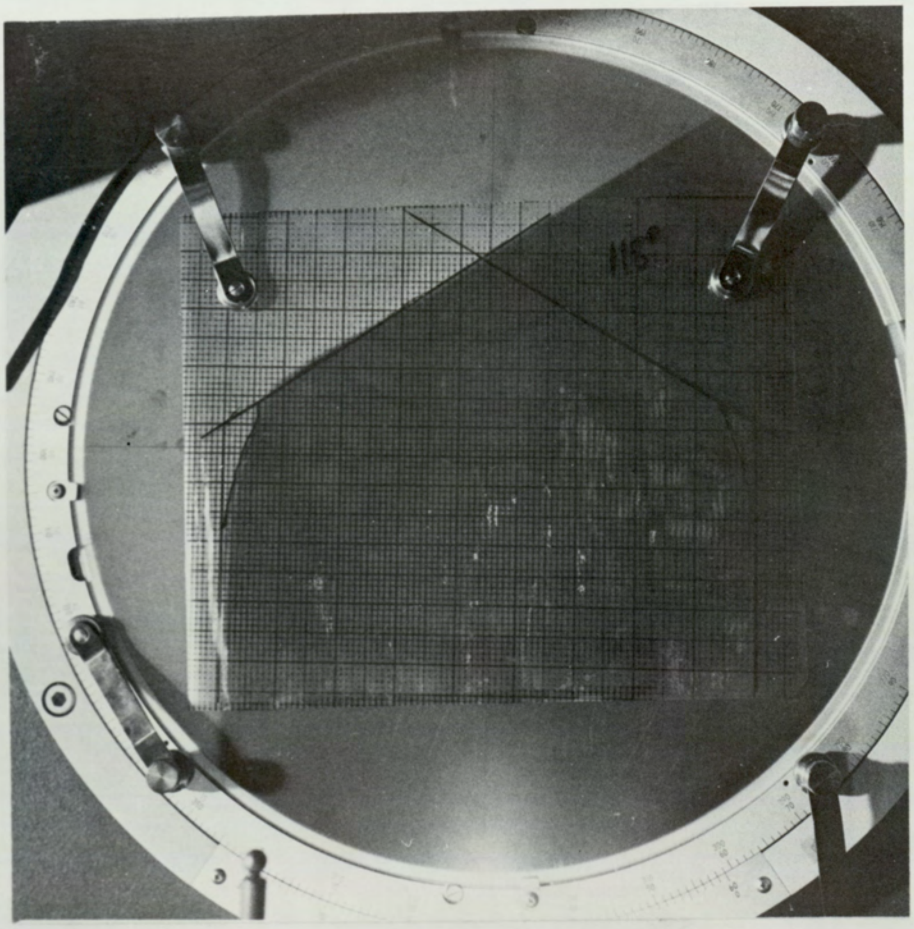
RADIAL DRILL USED FOR TEST

Plate N° 6



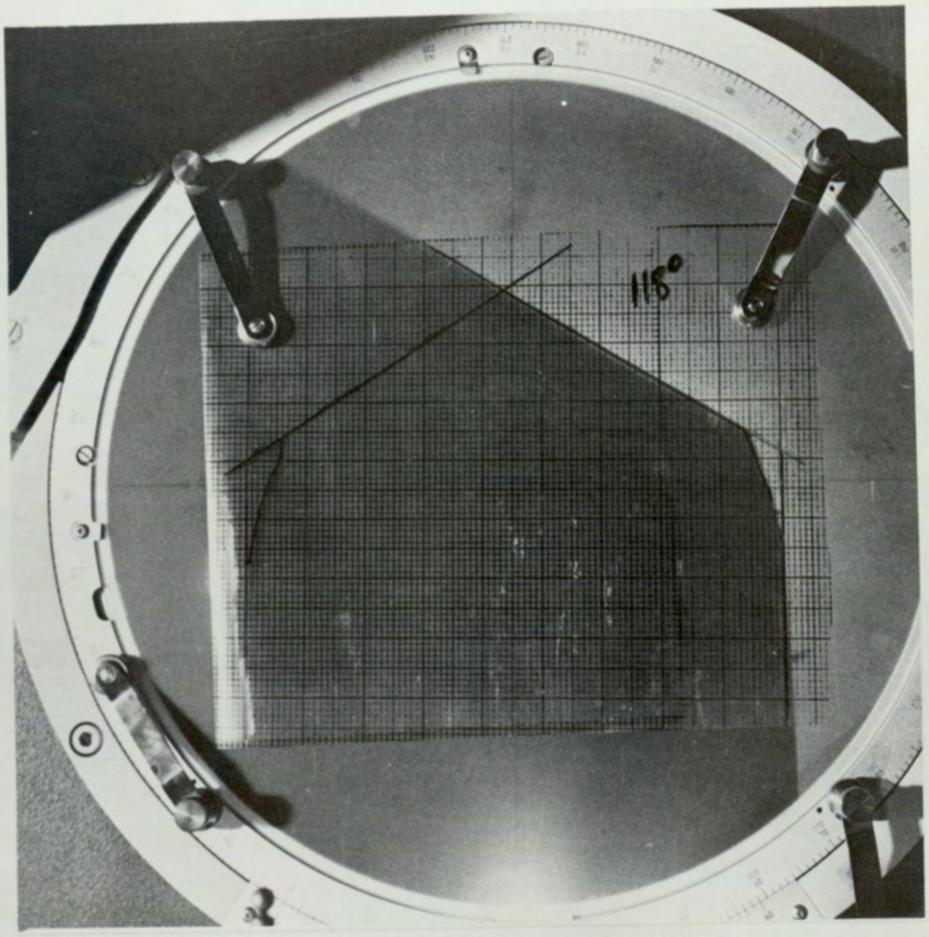
DETERMINATION OF DRILL POINT ANGLE

Plate N° 7



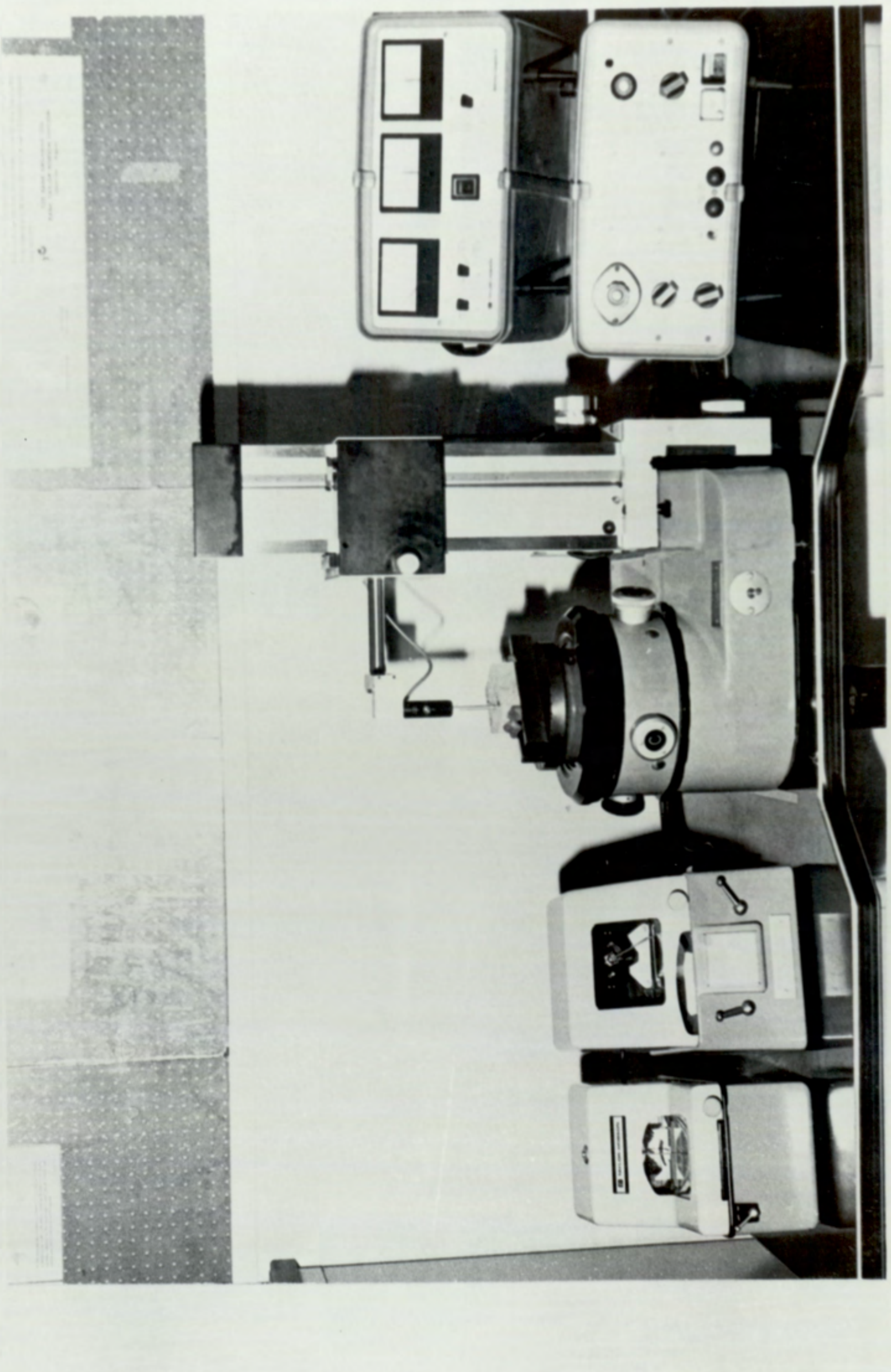
PROJECTED CORNER WEAR

Plate N° 8



PROJECTED CORNER WEAR
OPPOSITE CORNER

Plate N° 9

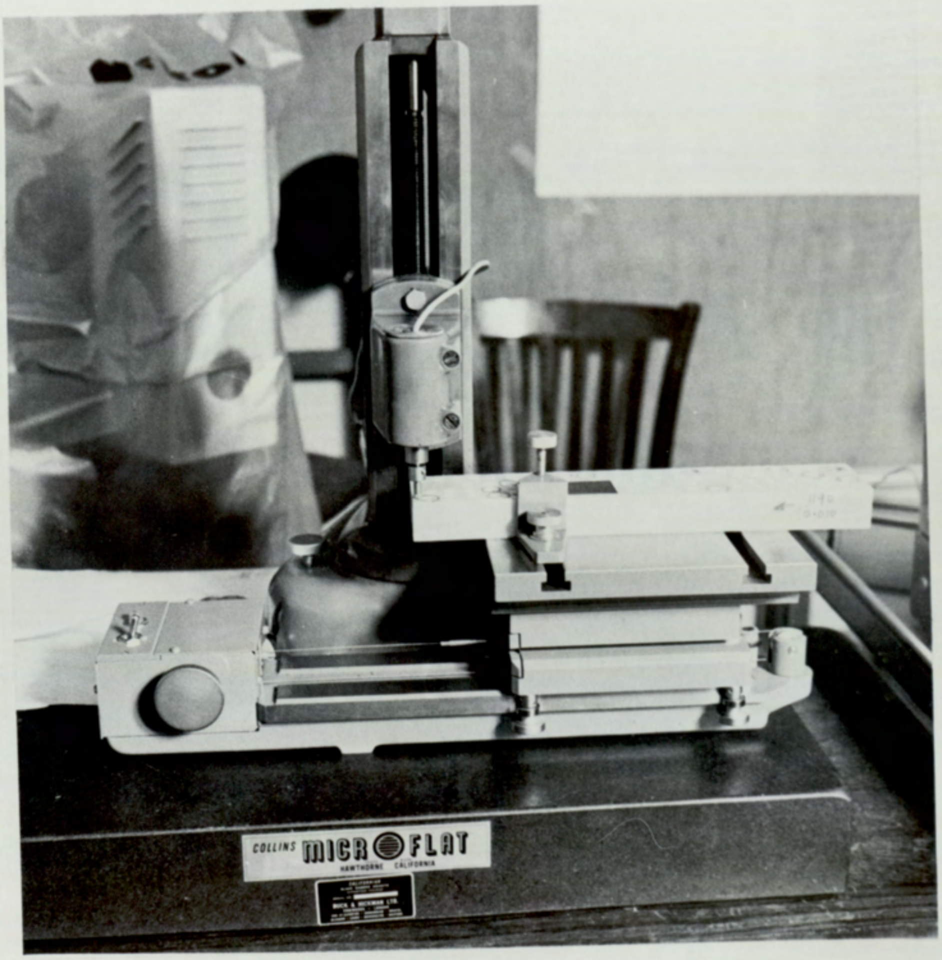


CHECKING ROUNDNESS OR STRAIGHTNESS OF THE HOLE

Plate N°10

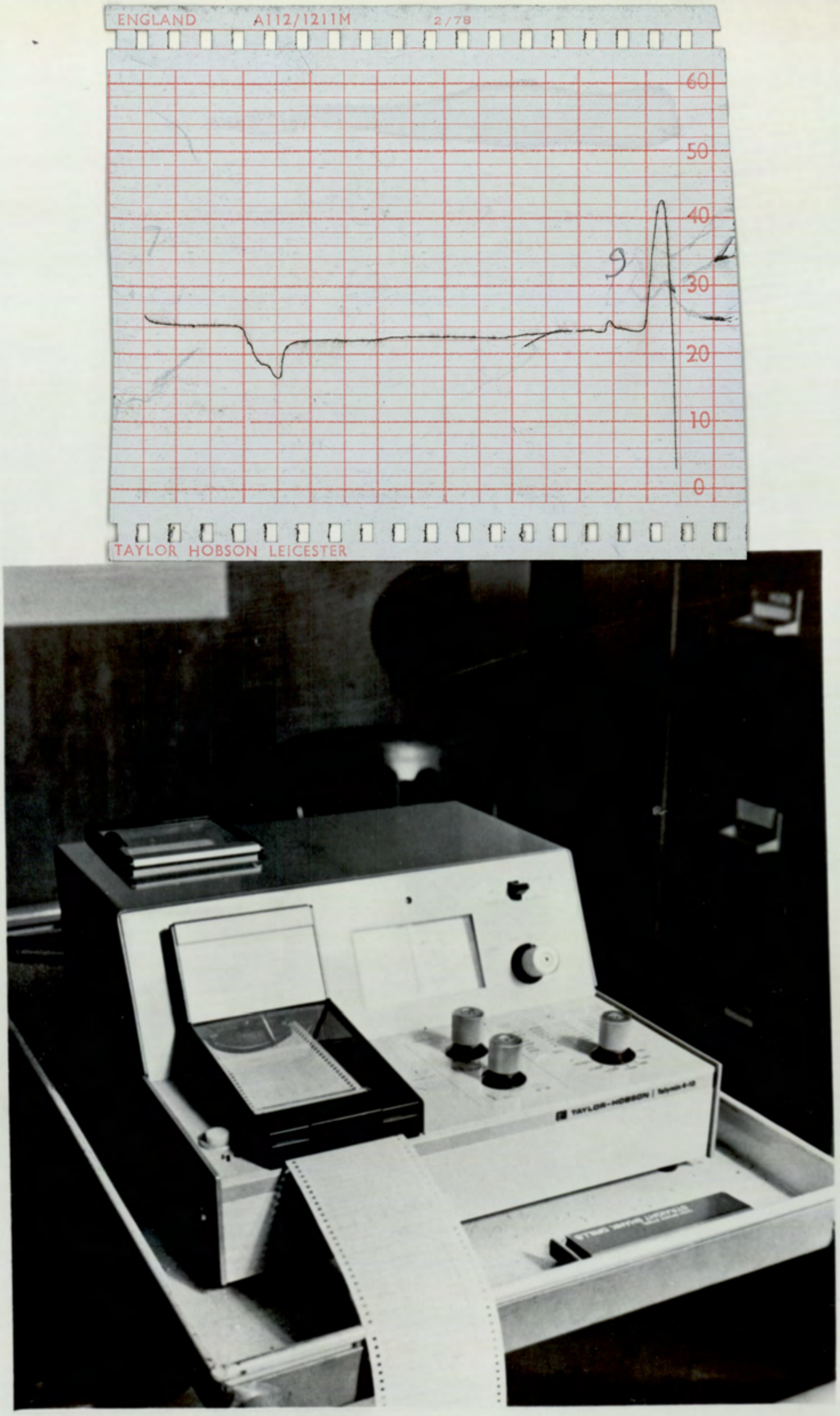
DETERMINATION OF BURR BUILD UP

Plate N°11



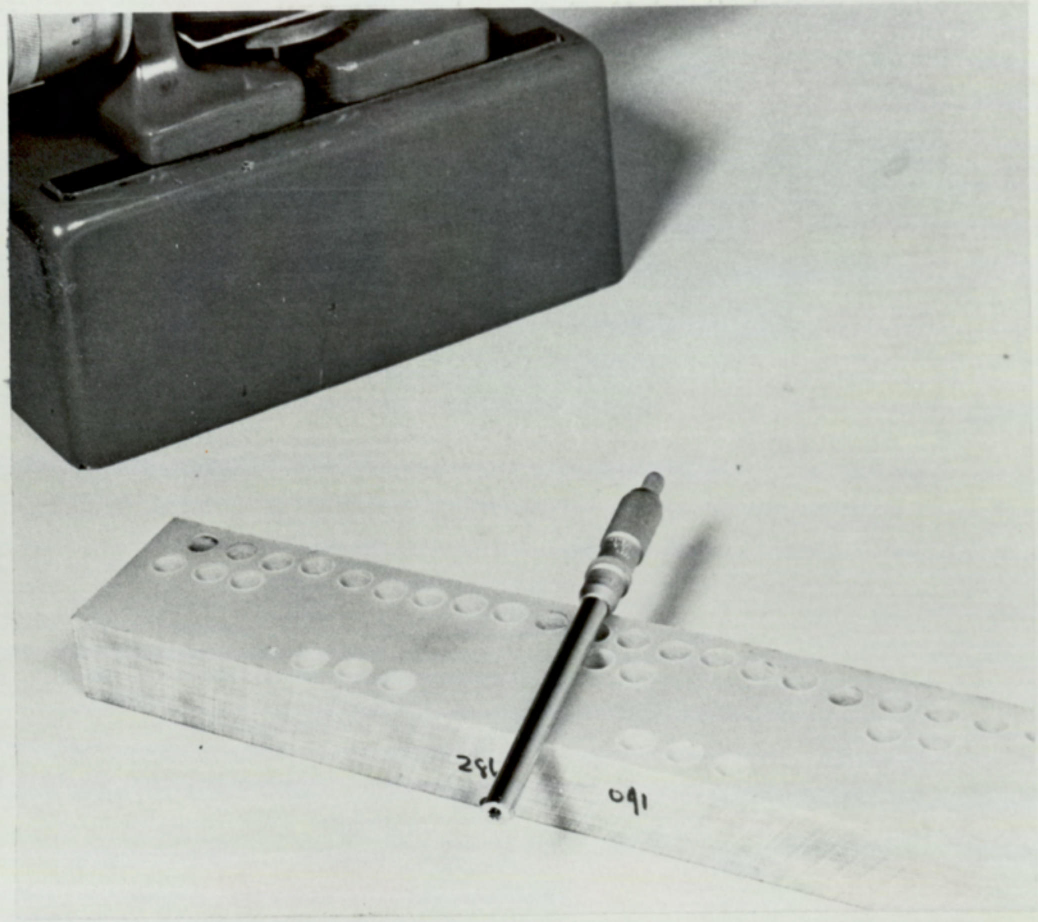
DETERMINATION OF BURR BUILD UP

Plate N°12



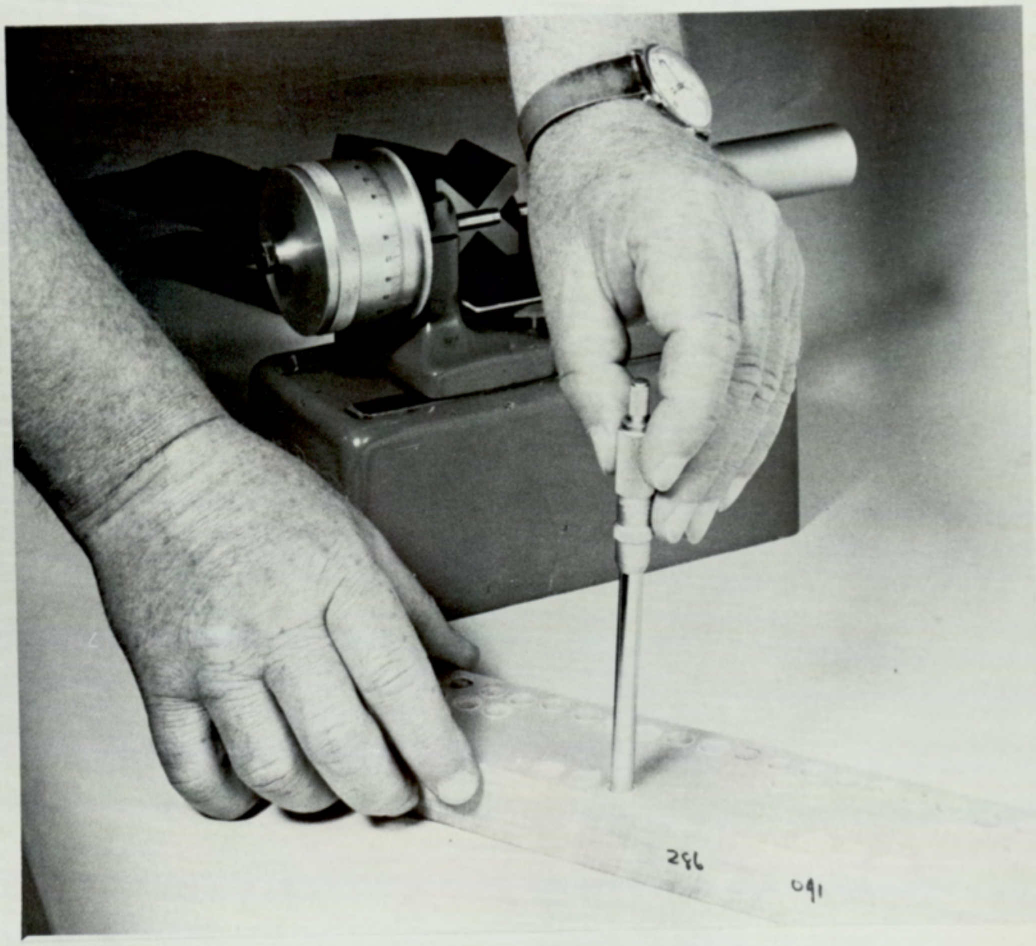
TALYMIN 4-10 RECORDER
WITH TYPICAL TRACE PATTERN

Plate No 13



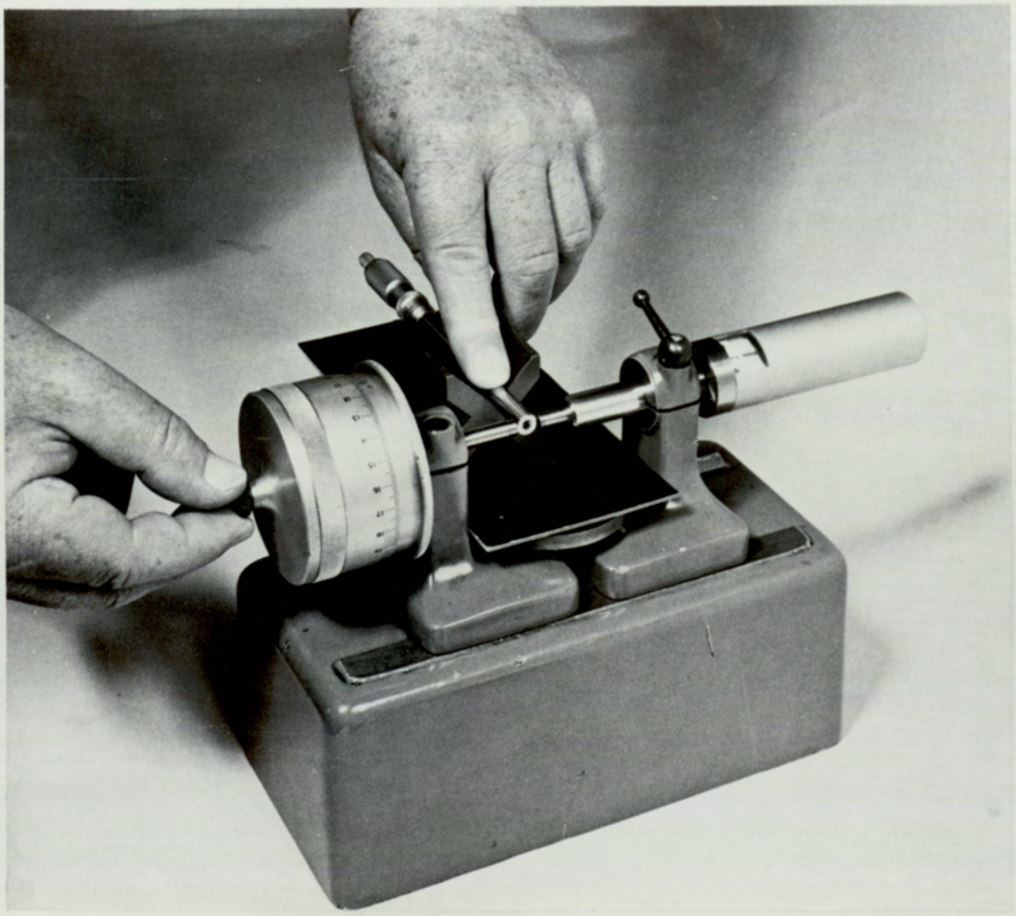
DETERMINATION OF HOLE DIAMETER

Plate N° 14



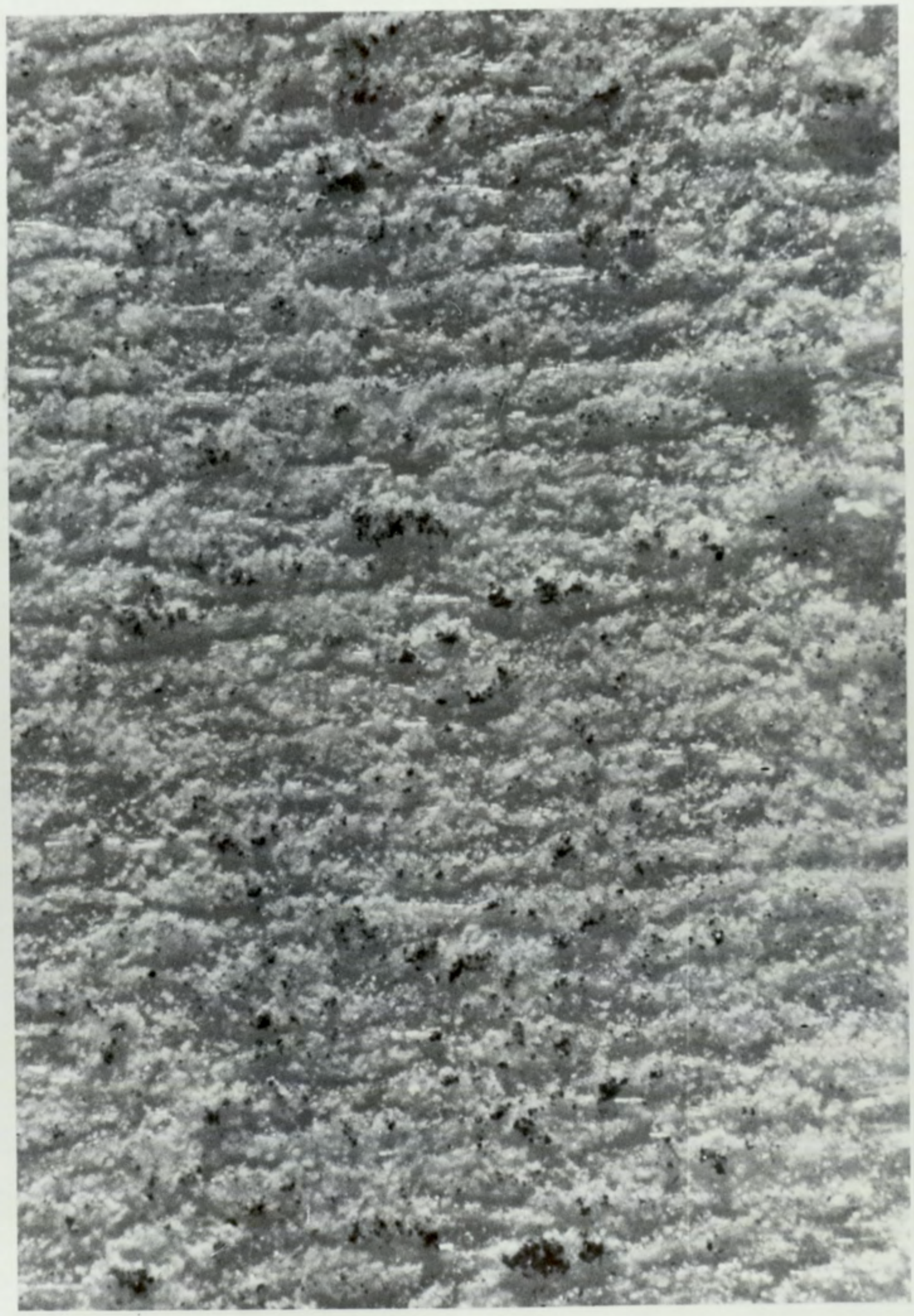
DETERMINATION OF HOLE DIAMETER

Plate N° 15



DETERMINATION OF HOLE DIAMETER

Plate N° 16



MATERIAL SURFACE AS CUT
BY HORIZONTAL BANDSAW

Plate N° 17

BORE SURFACE AS DRILLED
530 rev/min 0·25mm/rev

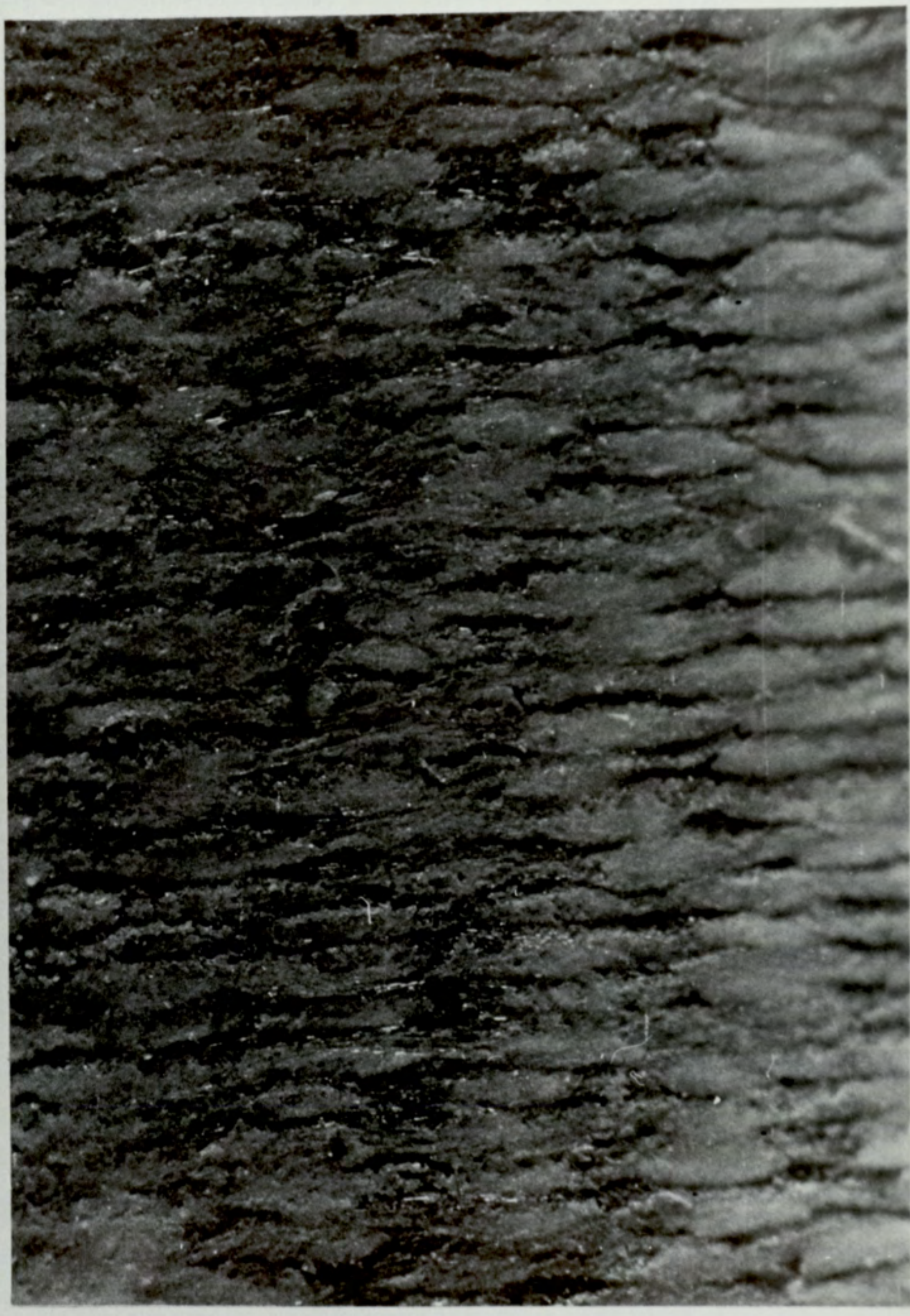
Plate N° 18

BORE SURFACE AS DRILLED
460 rev/min 0·30 mm/rev

Plate Nº 19

BORE SURFACE AS DRILLED
320 rev/min 0·40 mm/rev

Plate N° 20



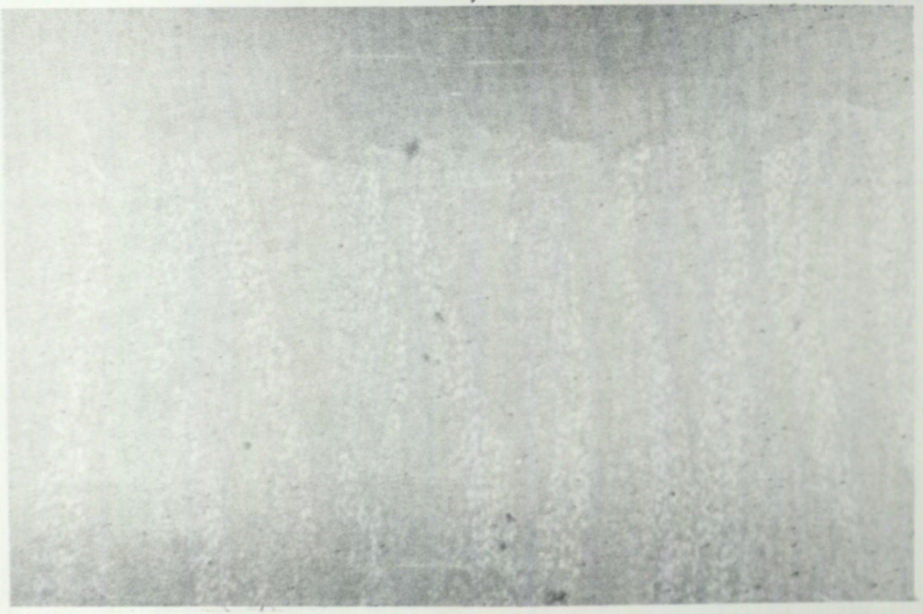
BORE SURFACE AS DRILLED
130 rev/min 1·0 mm/rev

Plate N° 21

EDGE OF HOLE

DIRECTION OF CUTTING

EDGE OF HOLE



SIDE OF HOLE ×50

1190 rev/min 0·088 mm/rev

Showing rougher surface

Plate N°18 a

SIDE OF HOLE ×50

386 rev/min 1·0 mm/rev

Showing smoother more compacted surface

Plate N° 21 a

BURR WITH DELAMINATION EXIT OF DRILL
1190 rev/min 0.088 mm/rev

Plate N° 22

BURR WITH DELAMINATION ENTRY OF DRILL

1190 rev/min 0.088 mm/rev

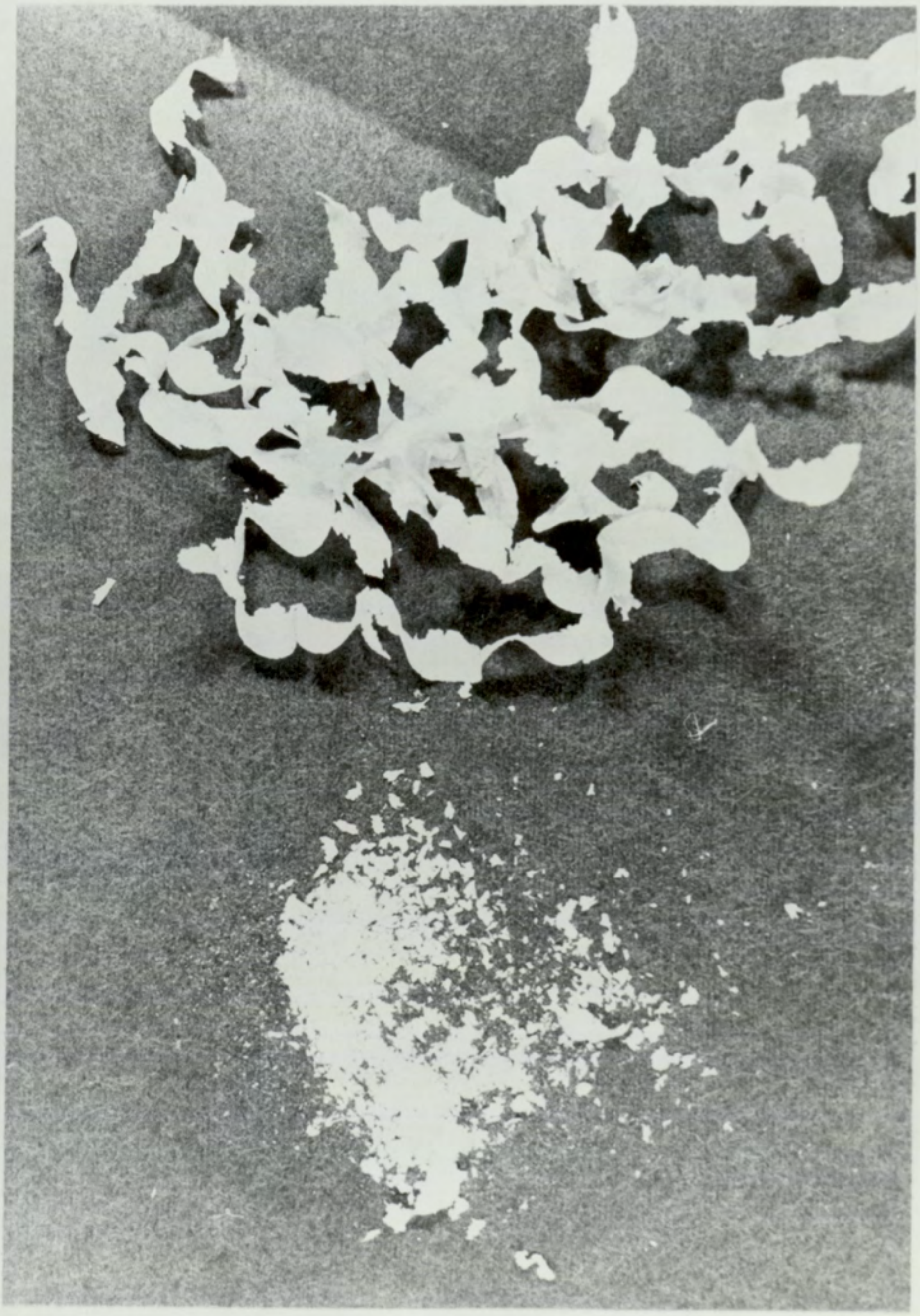
Plate N° 22 a

BURR WITHOUT DELAMINATION EXIT OF DRILL
386 rev/min 1·0 mm/rev

Plate N° 23

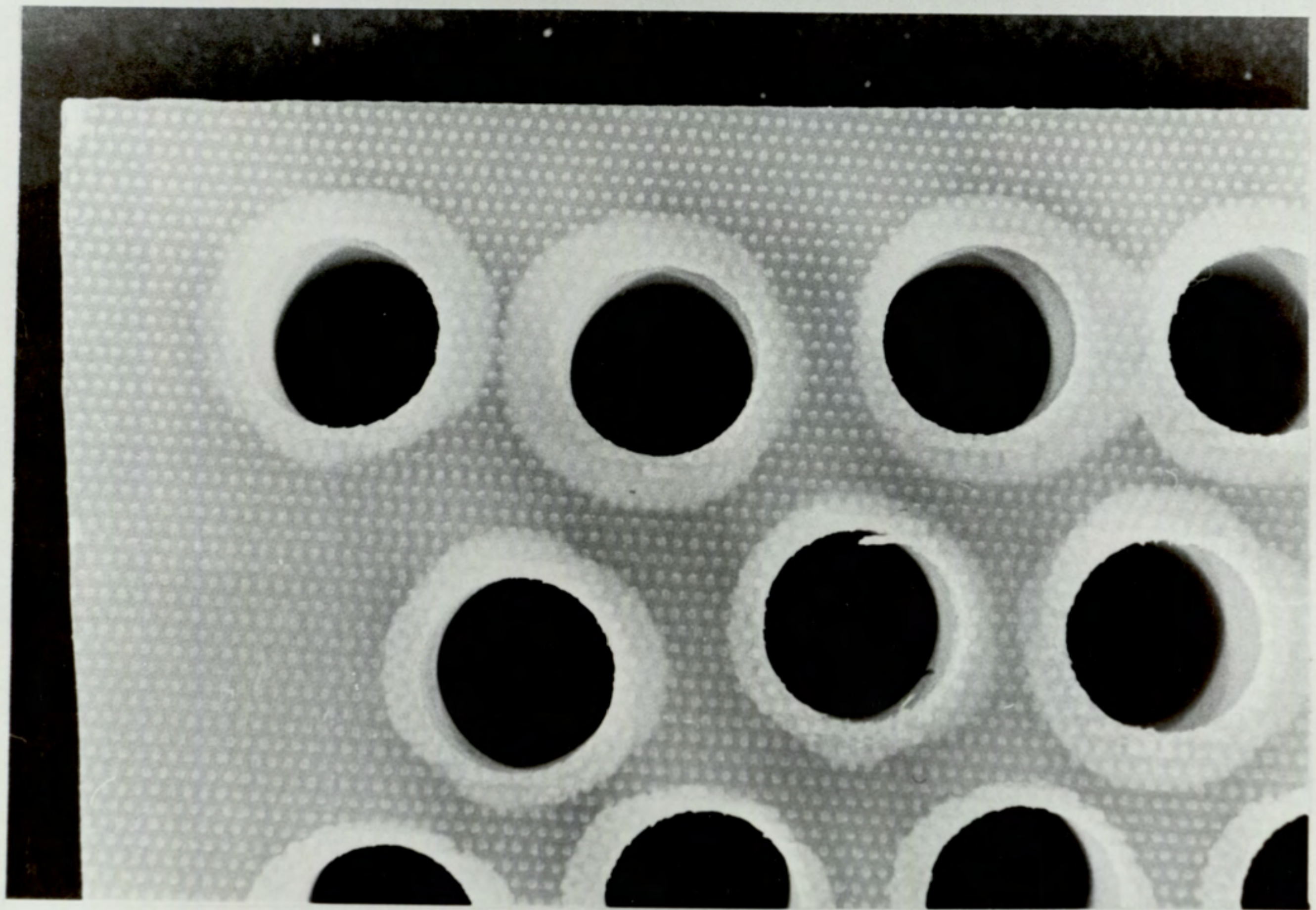
BURR WITHOUT DELAMINATION ENTRY SIDE OF DRILL
386 rev/min 1.0 mm/rev

Plate N°23 a



COMPARISON OF CHIPS PRODUCED

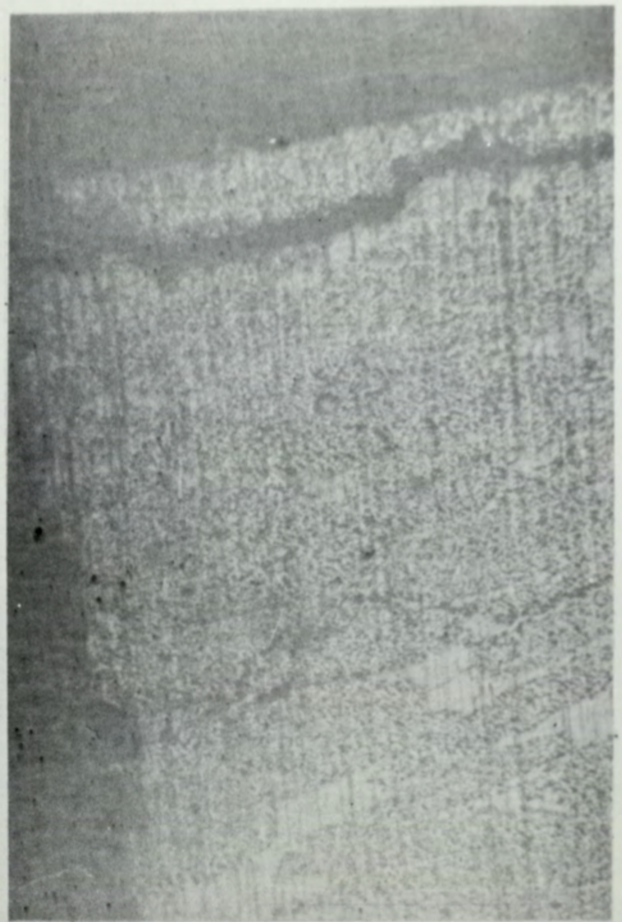
Plate N° 24



DELAMINATION RINGS EXIT SIDE OF HOLE
1660 rev/min 0·15 mm/rev

Plate N° 25

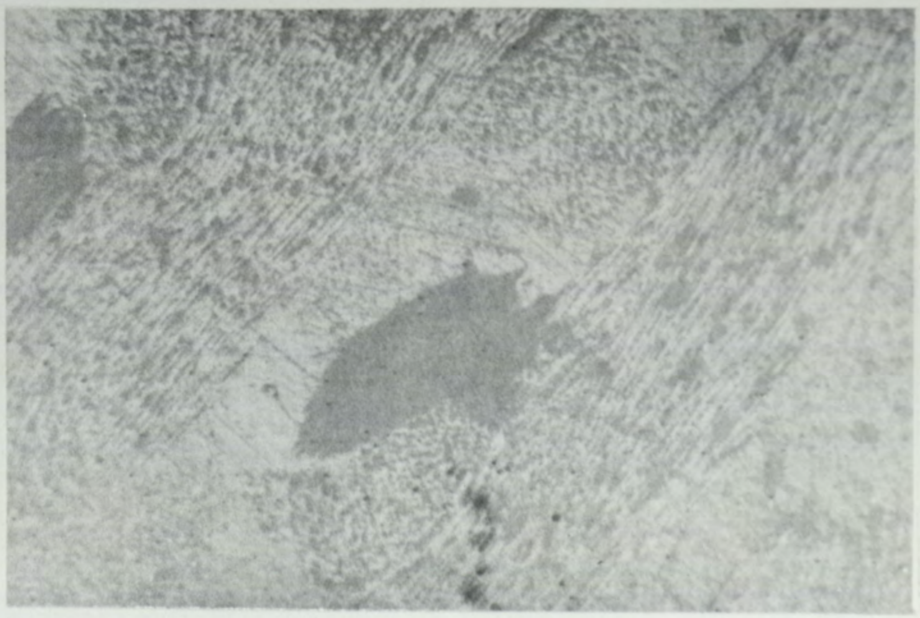
Crack →



x 50

TOP & SIDE OF HOLE SHOWING INK IMPREGNATED CRACK

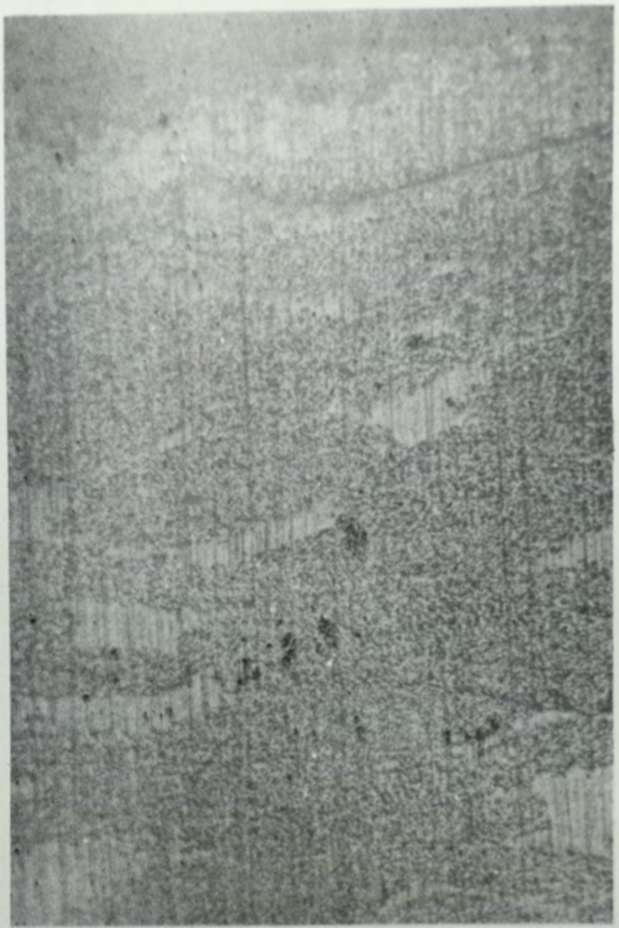
Plate No 26



SHOWING SURFACE AWAY FROM THE HOLE

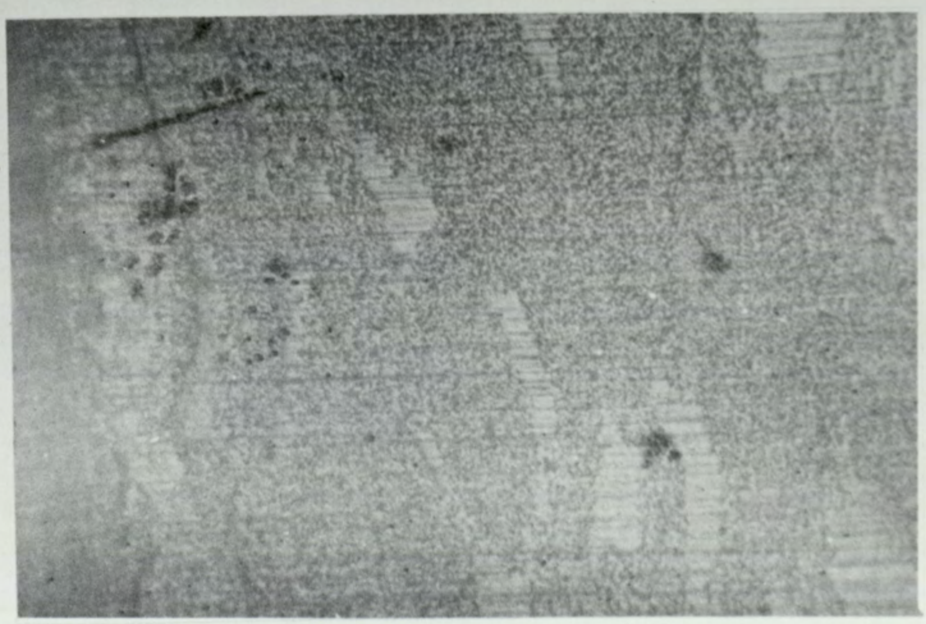
x 50

Plate No 26 a



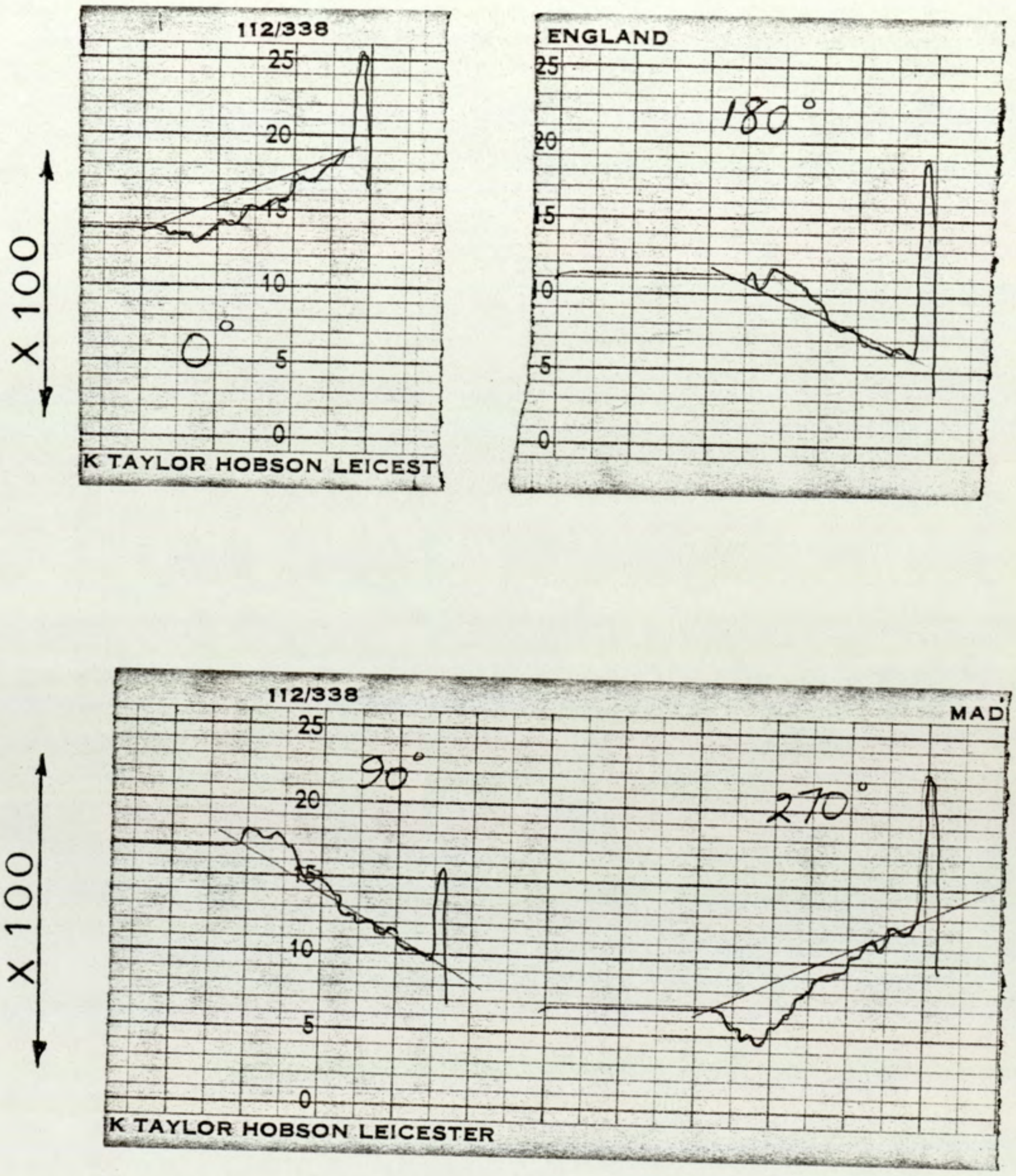
x 50

SHOWING SURFACE CRACK IN SKIN CLOSE TO THE HOLE Plate N°27



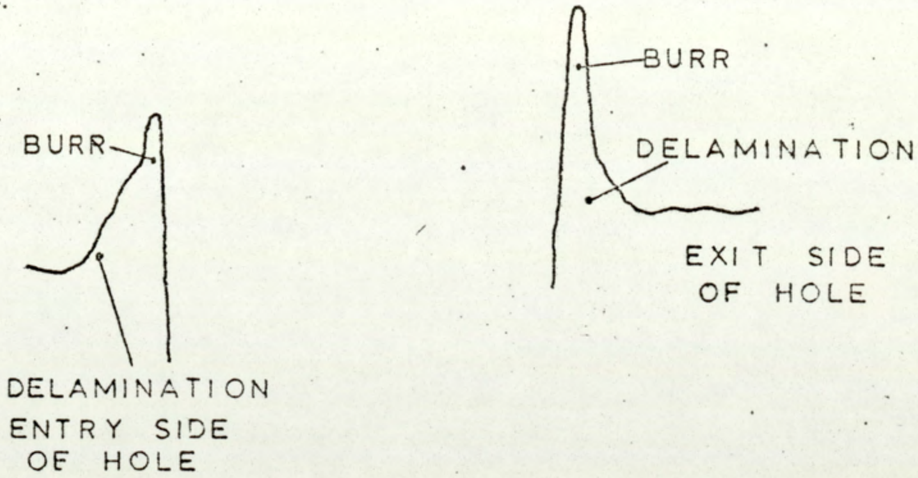
x 50

Plate N°27 a



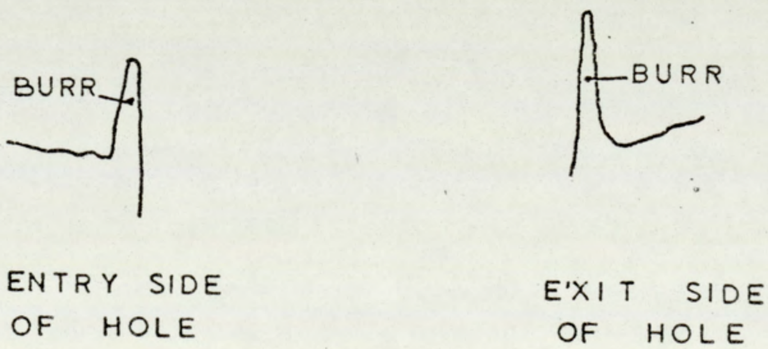
1190 rev / min   0·088 mm / rev

INTRUSION   TRACE N° 1



HOLE NUMBER 40 1190 rev/min 0·088 mm/rev
MAG x 200 TRACE N° 2

BURR WITH DELAMINATION



HOLE NUMBER 40 386 rev/min 1·0 mm/rev
MAG x 200 TRACE N° 2A

BURR WITHOUT DELAMINATION

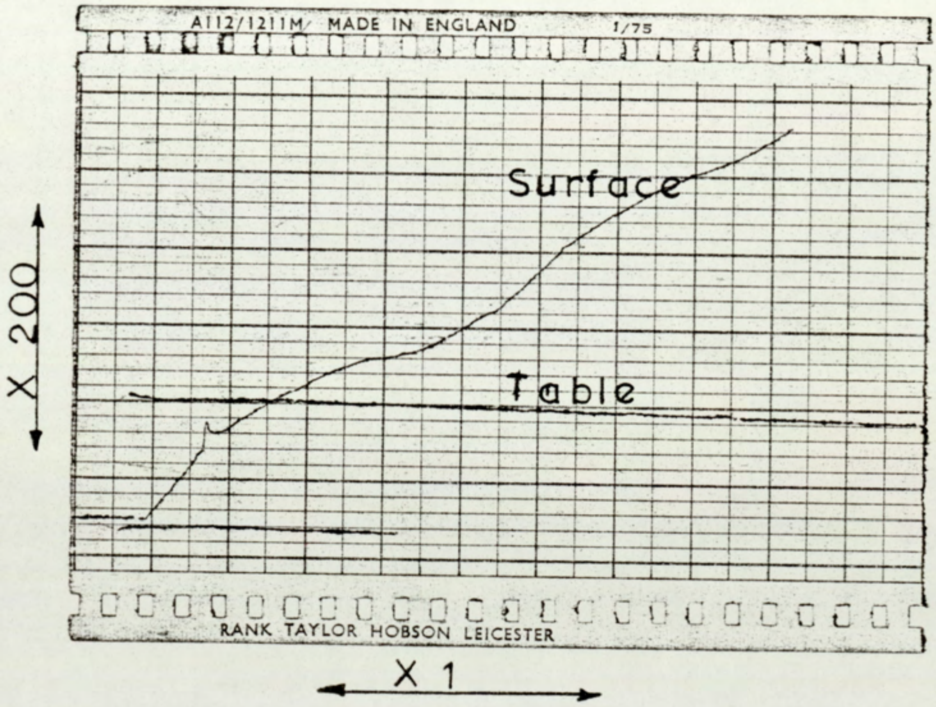
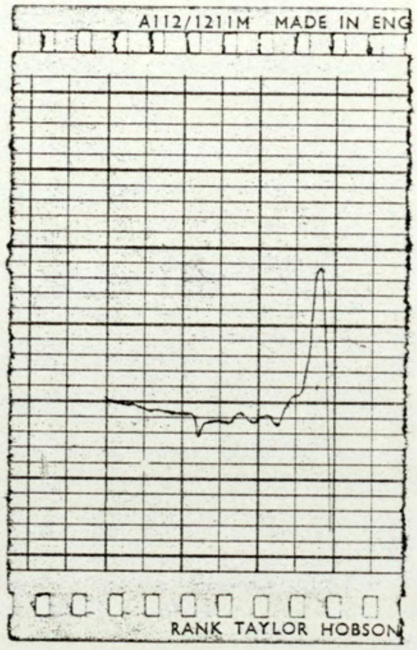
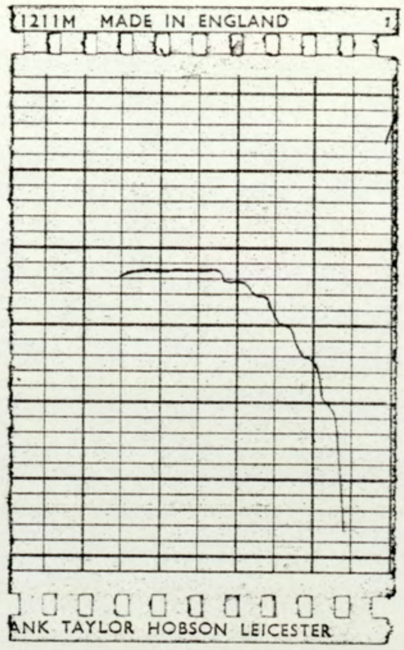


TABLE & SURFACE FLATNESS

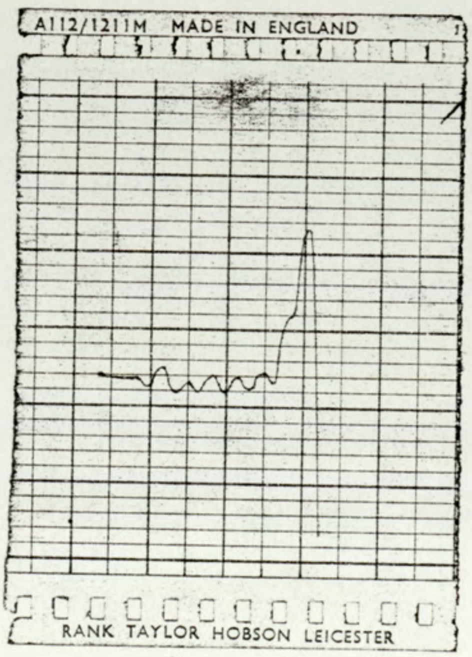
TRACE N° 3



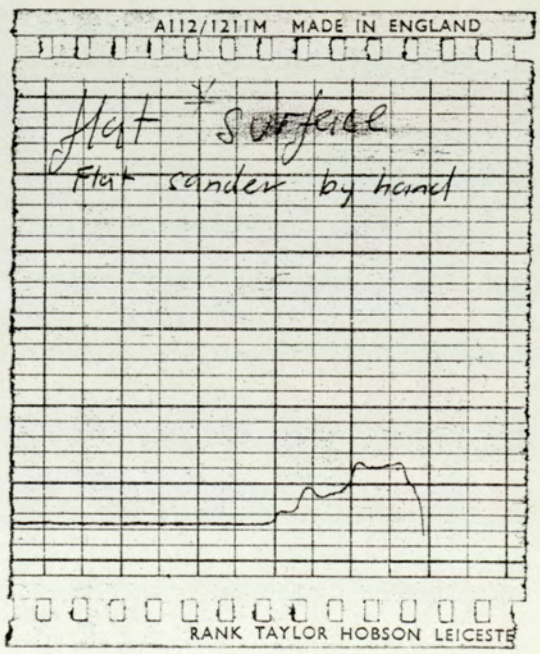
Drilled condition



After linishing with rose bit



Drilled condition

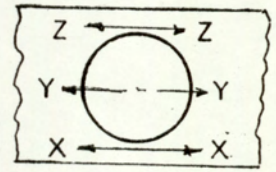


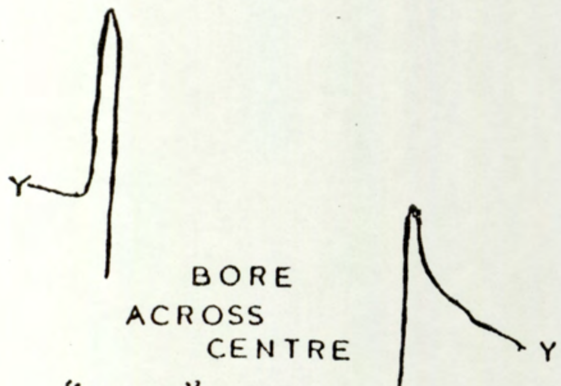
After linishing with sander

BURR before and after attempted removal

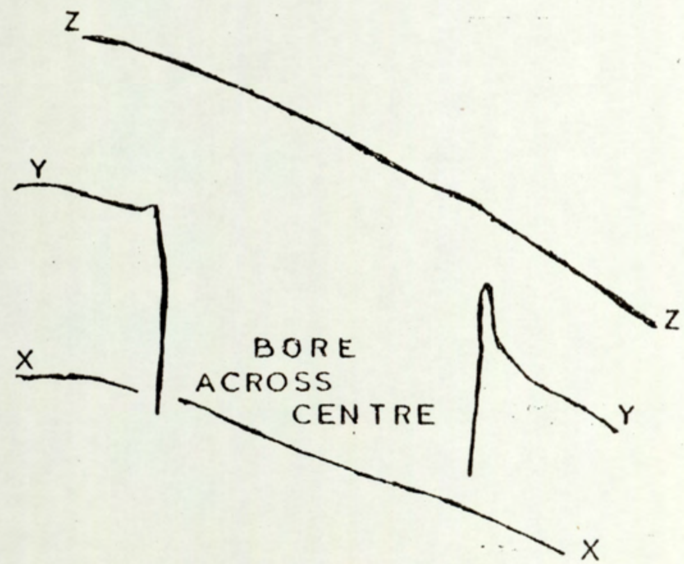
TRACE N° 4

Z-Z SURFACE SHAPE ABOVE HOLE CENTRE AT Y-Y
Y-Y SURFACE SHAPE ACROSS HOLE CENTRE
'X-X SURFACE SHAPE BELOW HOLE CENTRE AT Y-Y
MAG x500



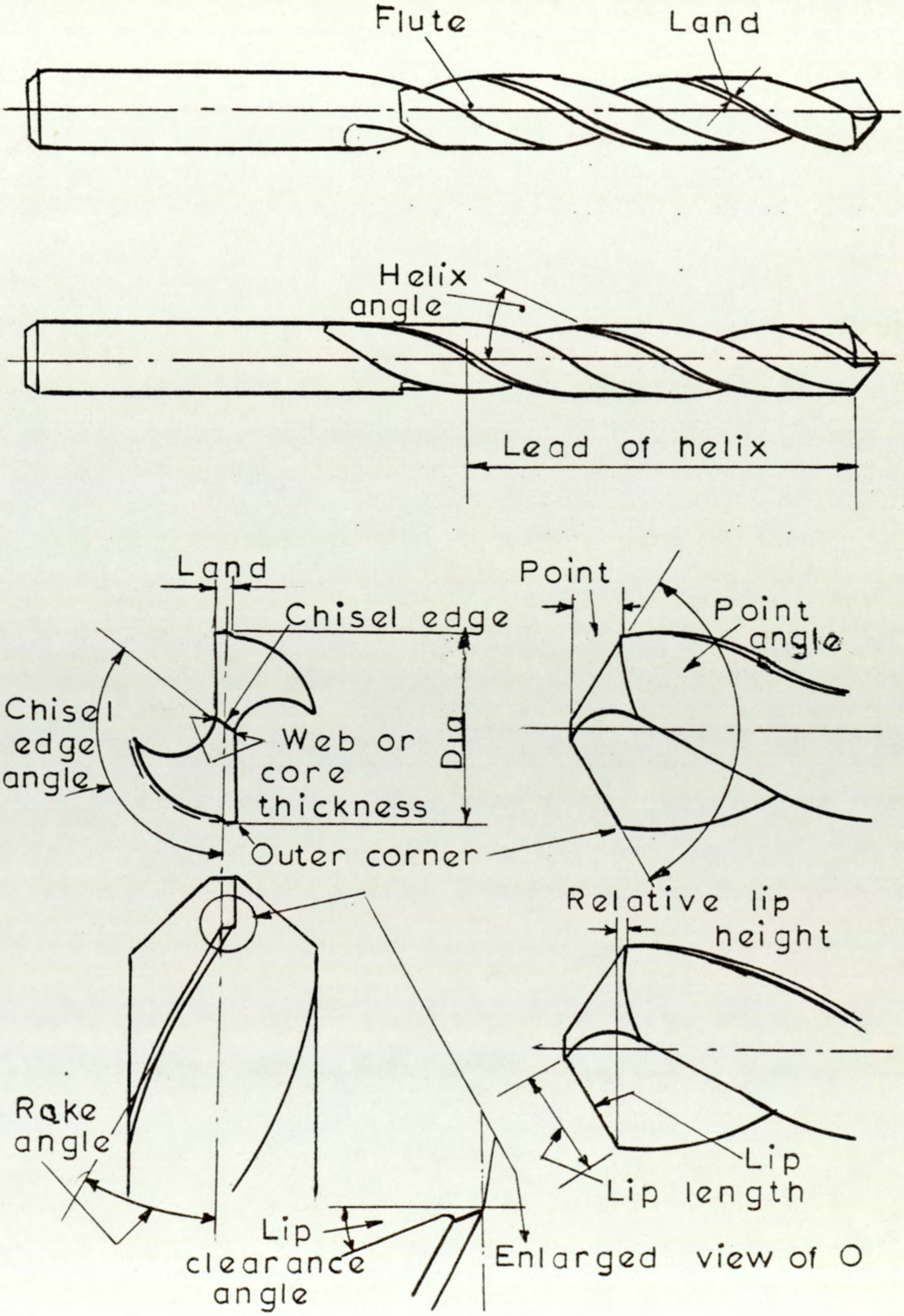


"BURR" AS DRILLED



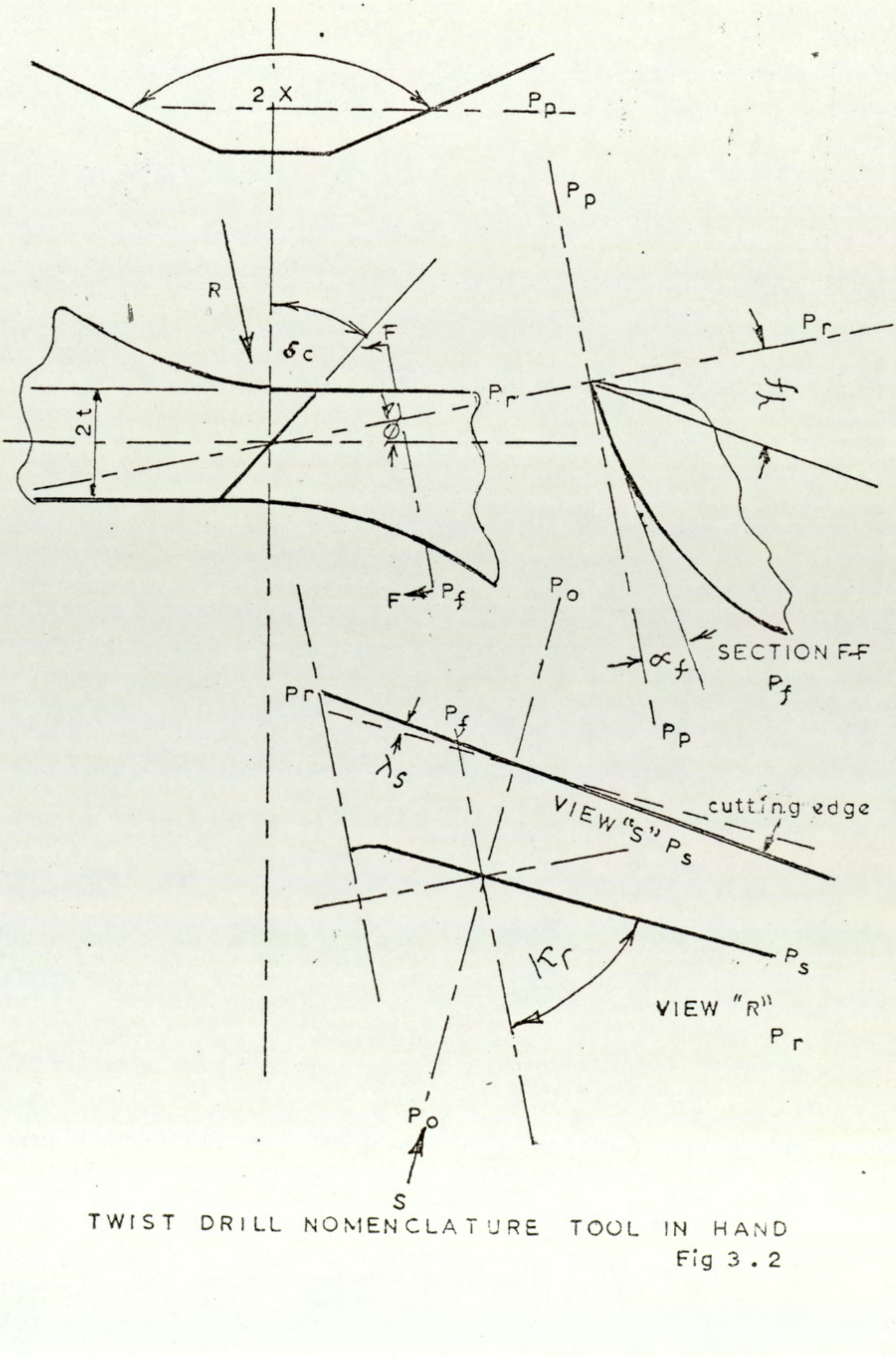
BURR REMAINING
AFTER REMOVAL ATTEMPT
WITH DRILL BIT

TRACE N° 5

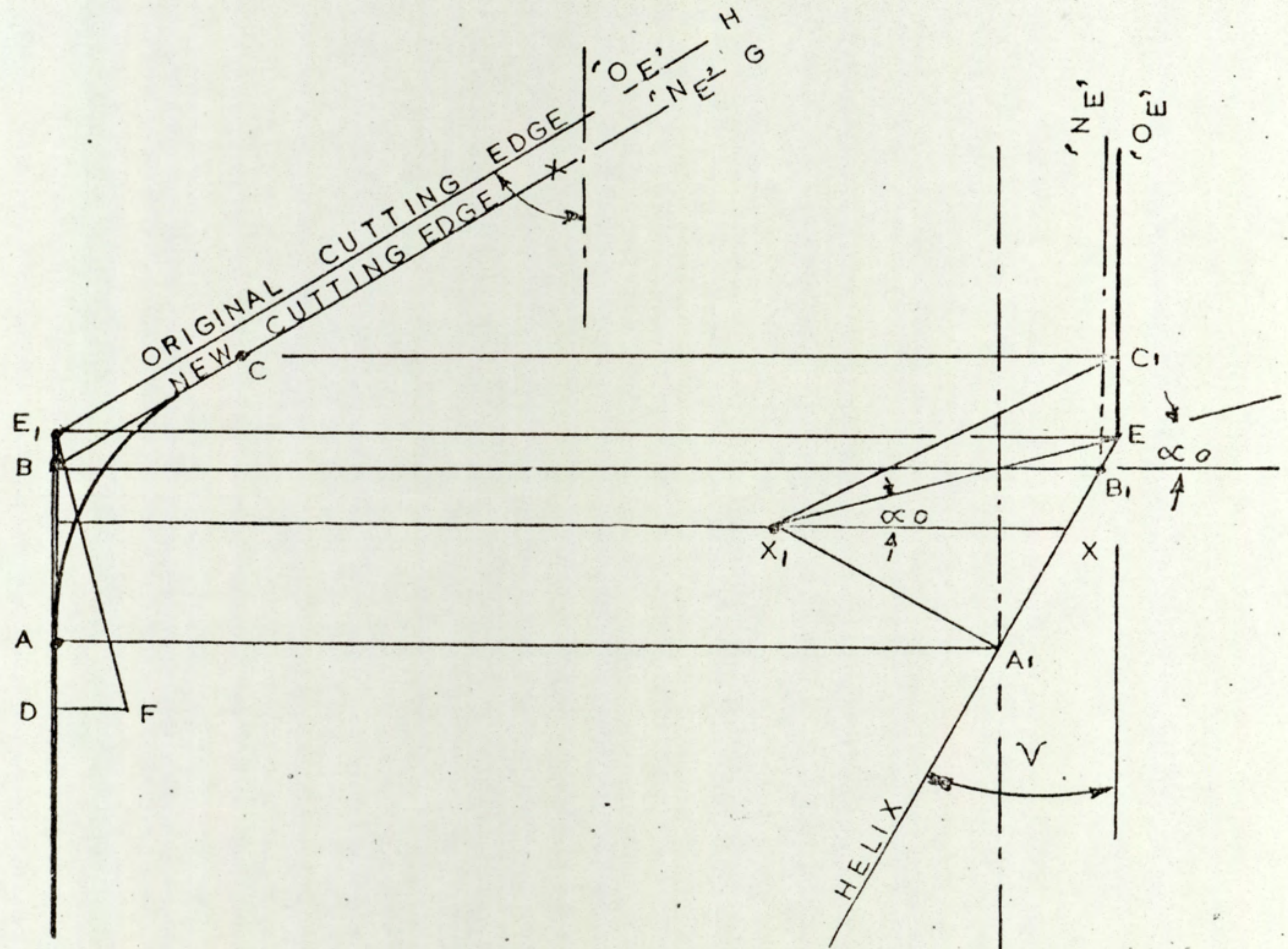


TWIST DRILL NOMENCLATURE

Fig 3.1



TWIST DRILL NOMENCLATURE TOOL IN HAND
Fig 3.2



ANALYTICAL METHOD OF DETERMINING DRILL WEAR

Fig 3.3

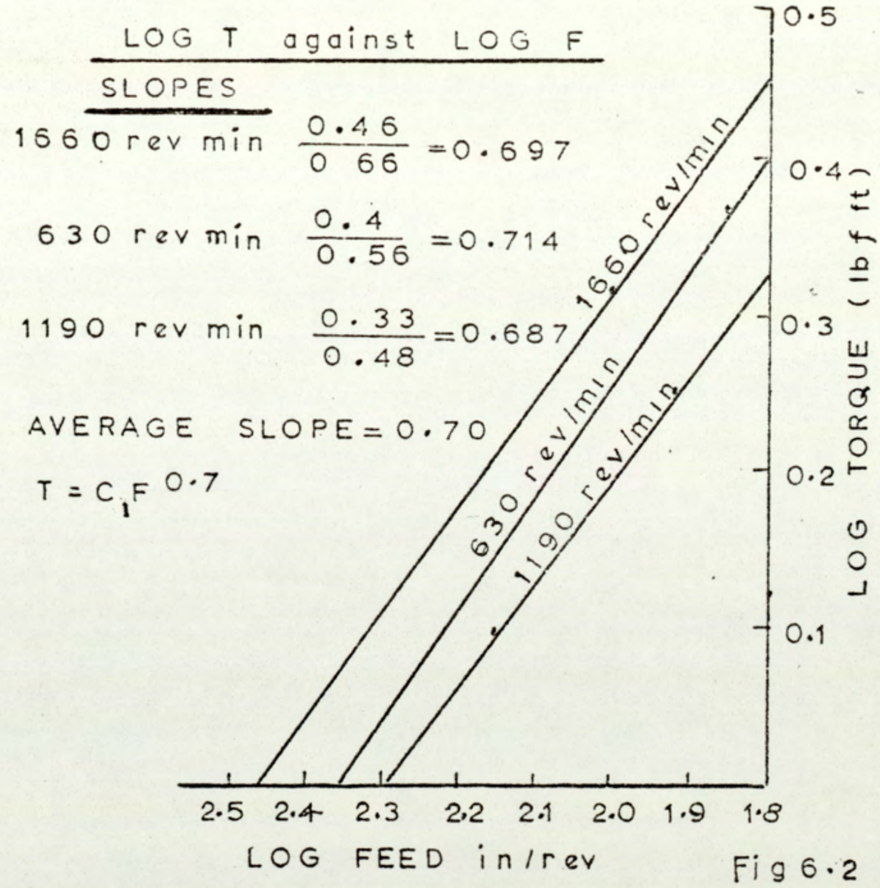

LOG T against LOG F
SLOPES
1660 rev min $\frac{0.46}{0.66} = 0.697$
630 rev min $\frac{0.4}{0.56} = 0.714$
1190 rev min $\frac{0.33}{0.48} = 0.687$
AVERAGE SLOPE = 0.70
$T = C_1 F^{0.7}$
1660 rev/min
630 rev/min
1190 rev/min
LOG TORQUE (lbf ft)
0·5
0·4
0·3
0·2
0·1
2·5 2·4 2·3 2·2 2·1 2·0 1·9 1·8
LOG FEED in/rev

Fig 6·2

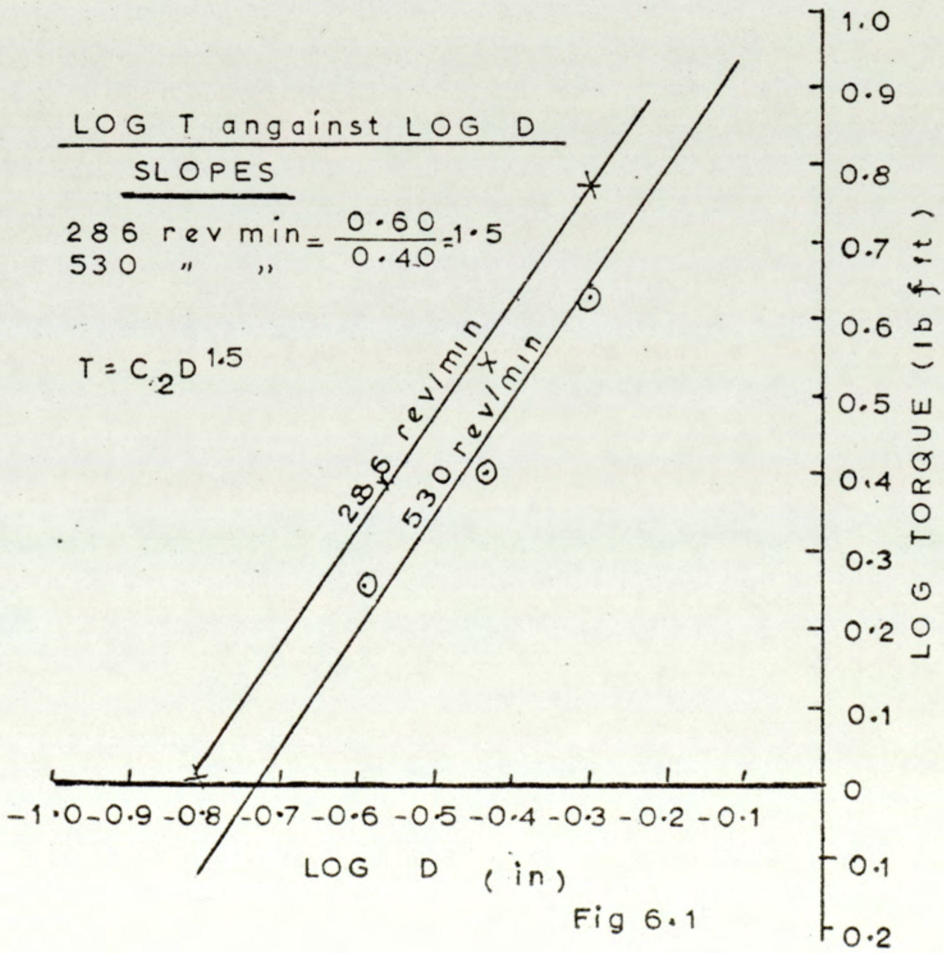

LOG T angainst LOG D
SLOPES
286 rev min $= \frac{0.60}{0.40} = 1.5$
530 " "
$T = C_2 D^{1.5}$
286 rev/min
530 rev/min
LOG TORQUE (lbf ft)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
−1·0 −0·9 −0·8 −0·7 −0·6 −0·5 −0·4 −0·3 −0·2 −0·1
LOG D (in)

Fig 6·1

POWER CONSUMED HOLE NUMBER 40
AGAINST DRILL WEAR

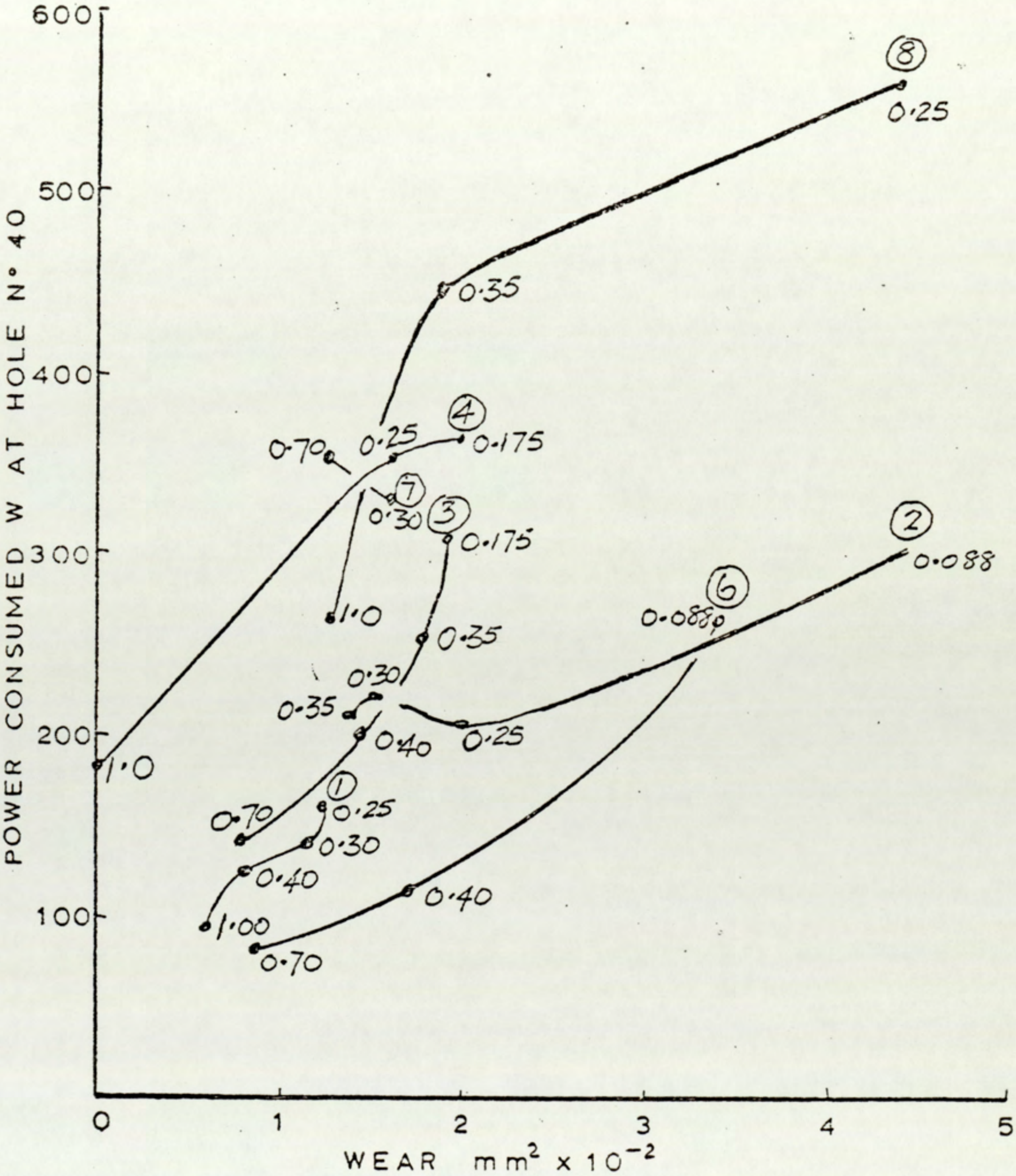


Fig 6.3

⑧ DENOTES TEST NUMBER
0·25 DENOTES FEED RATE mm/rev

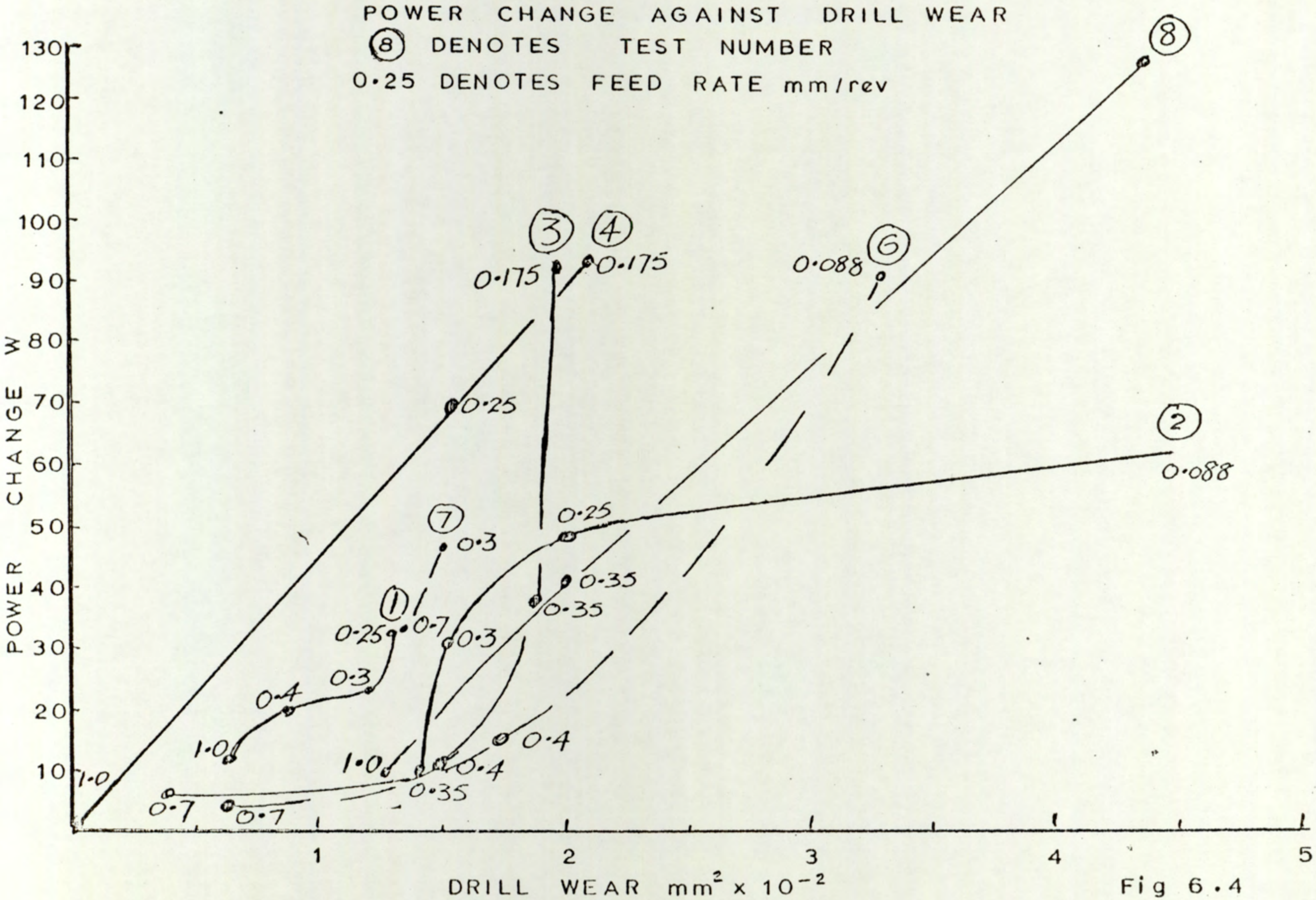

POWER CHANGE AGAINST DRILL WEAR
8 DENOTES TEST NUMBER
0·25 DENOTES FEED RATE mm/rev
POWER CHANGE W
DRILL WEAR mm² x 10⁻²
130
120
110
100
90
80
70
60
50
40
30
20
10
1
2
3
4
5
8
3
4
6
7
1
2
0·175
0·175
0·088
0·25
0·088
0·25
0·3
0·35
0·35
0·7
0·25
0·3
0·3
0·4
1·0
1·0
0·4
0·4
1·0
0·35
0·7
0·7

Fig 6.4

SCHEMATIC IMPRESSION OF INTRUSION

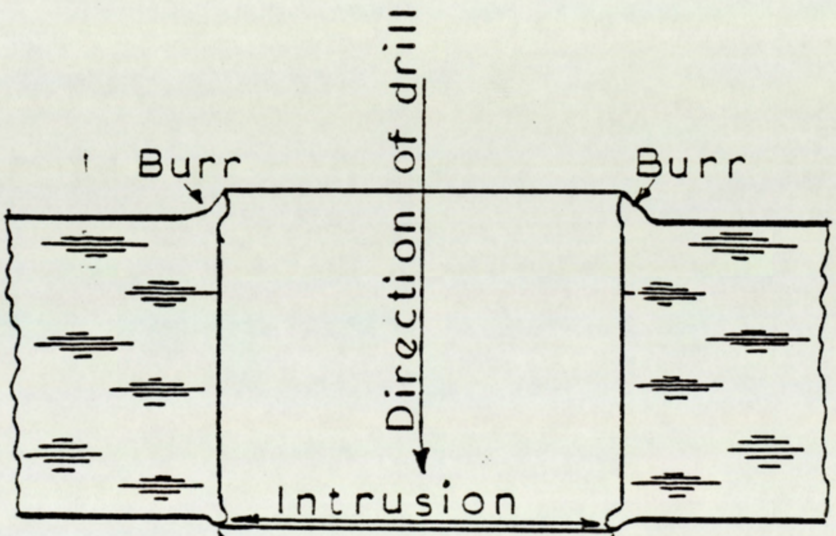


Fig 6.5

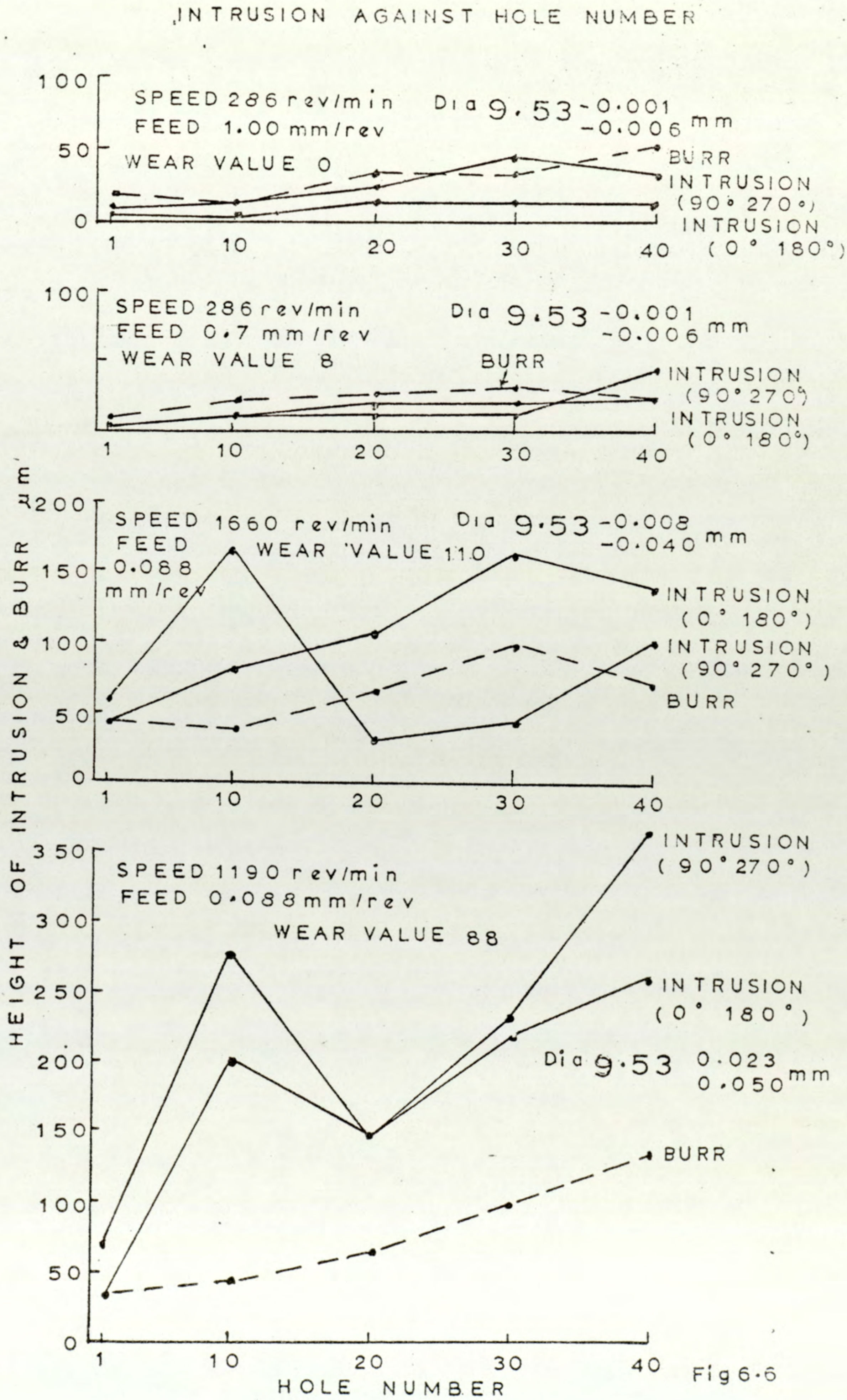

INTRUSION AGAINST HOLE NUMBER
SPEED 286 rev/min
FEED 1.00 mm/rev
WEAR VALUE 0
Dia 9.53 -0.001 -0.006 mm
BURR
INTRUSION (90° 270°)
INTRUSION (0° 180°)
SPEED 286 rev/min
FEED 0.7 mm/rev
WEAR VALUE 8
Dia 9.53 -0.001 -0.006 mm
BURR
INTRUSION (90° 270°)
INTRUSION (0° 180°)
SPEED 1660 rev/min
FEED 0.088 mm/rev
WEAR VALUE 110
Dia 9.53 -0.008 -0.040 mm
INTRUSION (0° 180°)
INTRUSION (90° 270°)
BURR
HEIGHT OF INTRUSION & BURR μm
SPEED 1190 rev/min
FEED 0.088 mm/rev
WEAR VALUE 88
INTRUSION (90° 270°)
INTRUSION (0° 180°)
Dia 9.53 0.023 0.050 mm
BURR
HOLE NUMBER

Fig 6.6

"BURR" HEIGHT AT ENTRY & EXIT

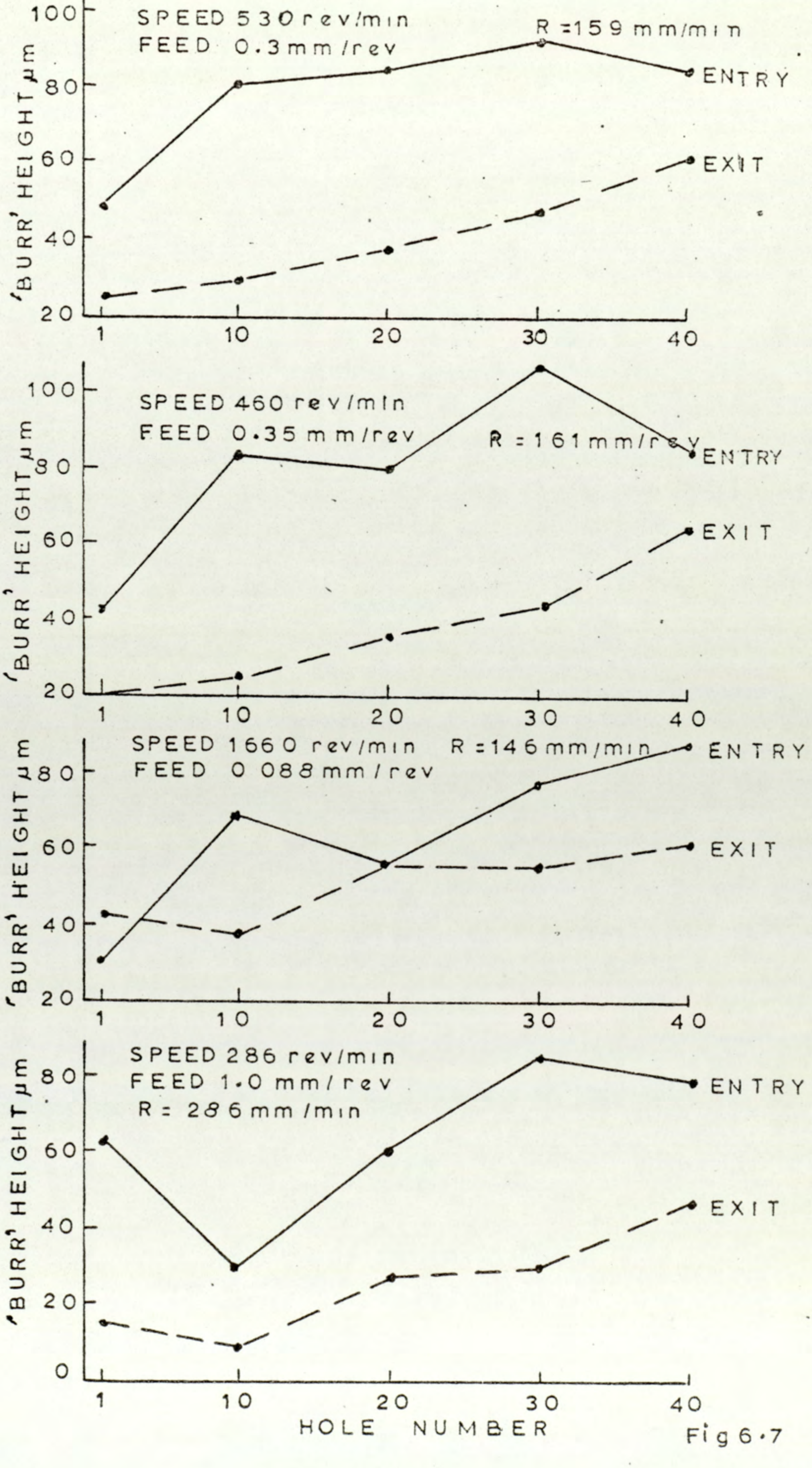
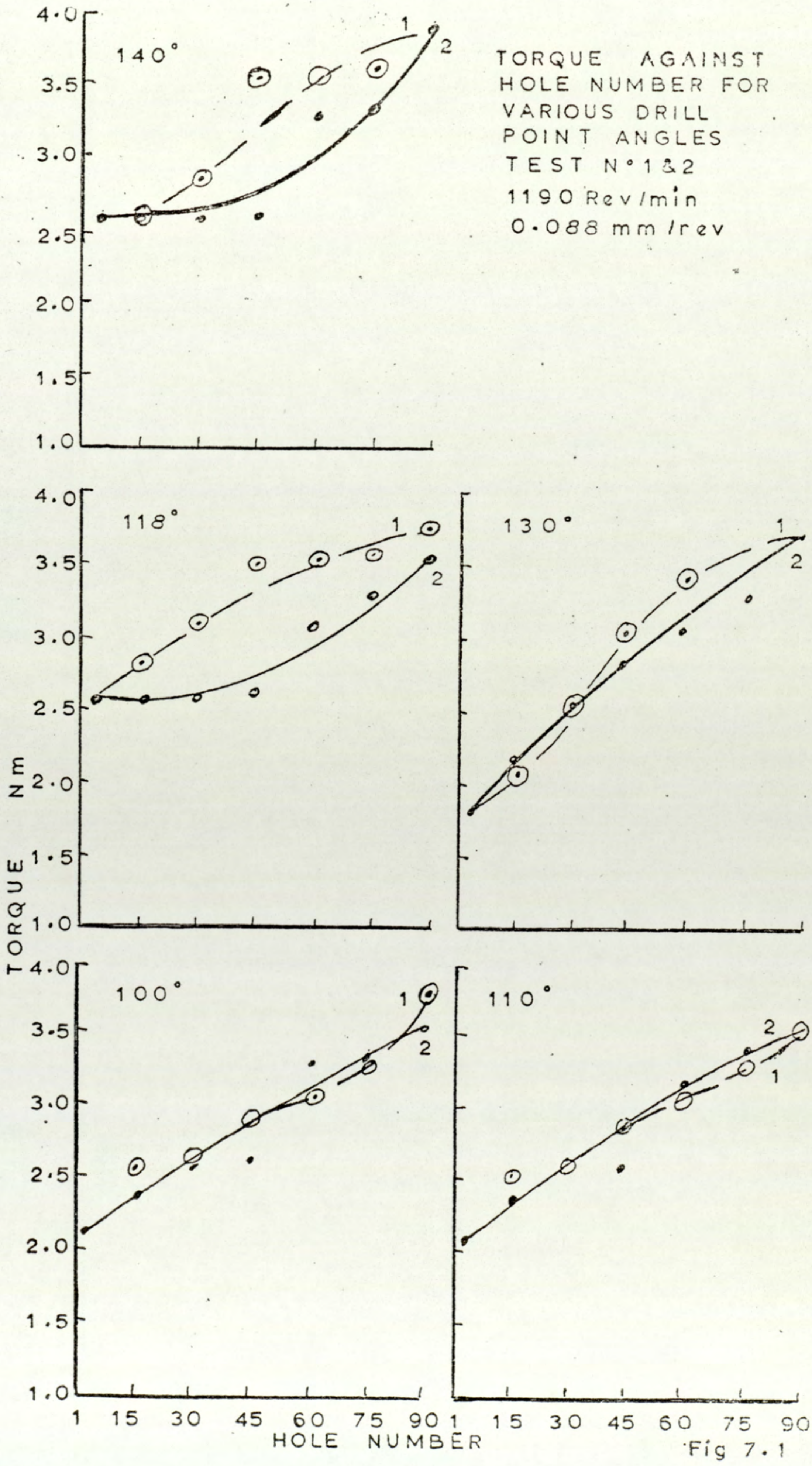
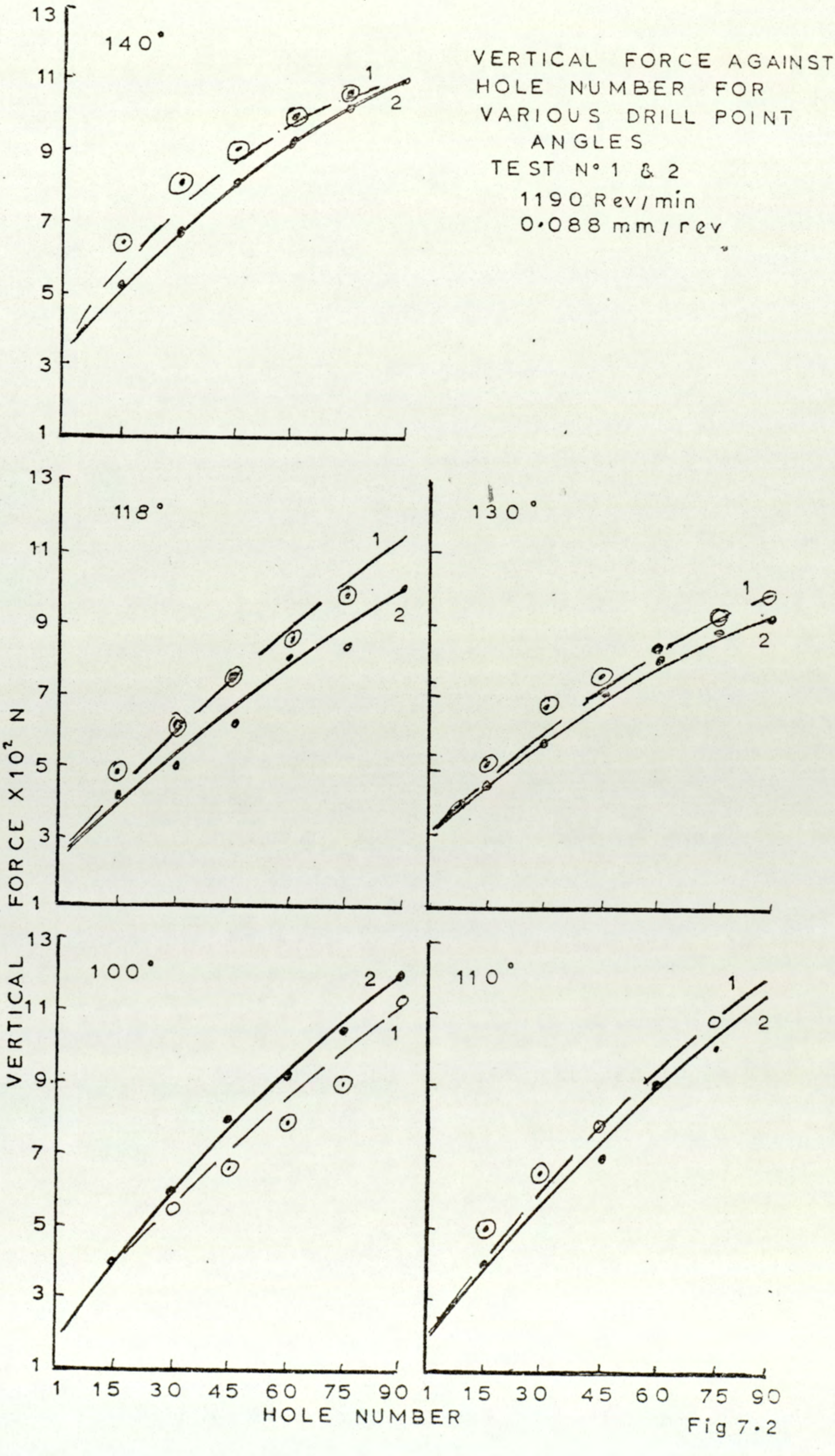


Fig 6.7



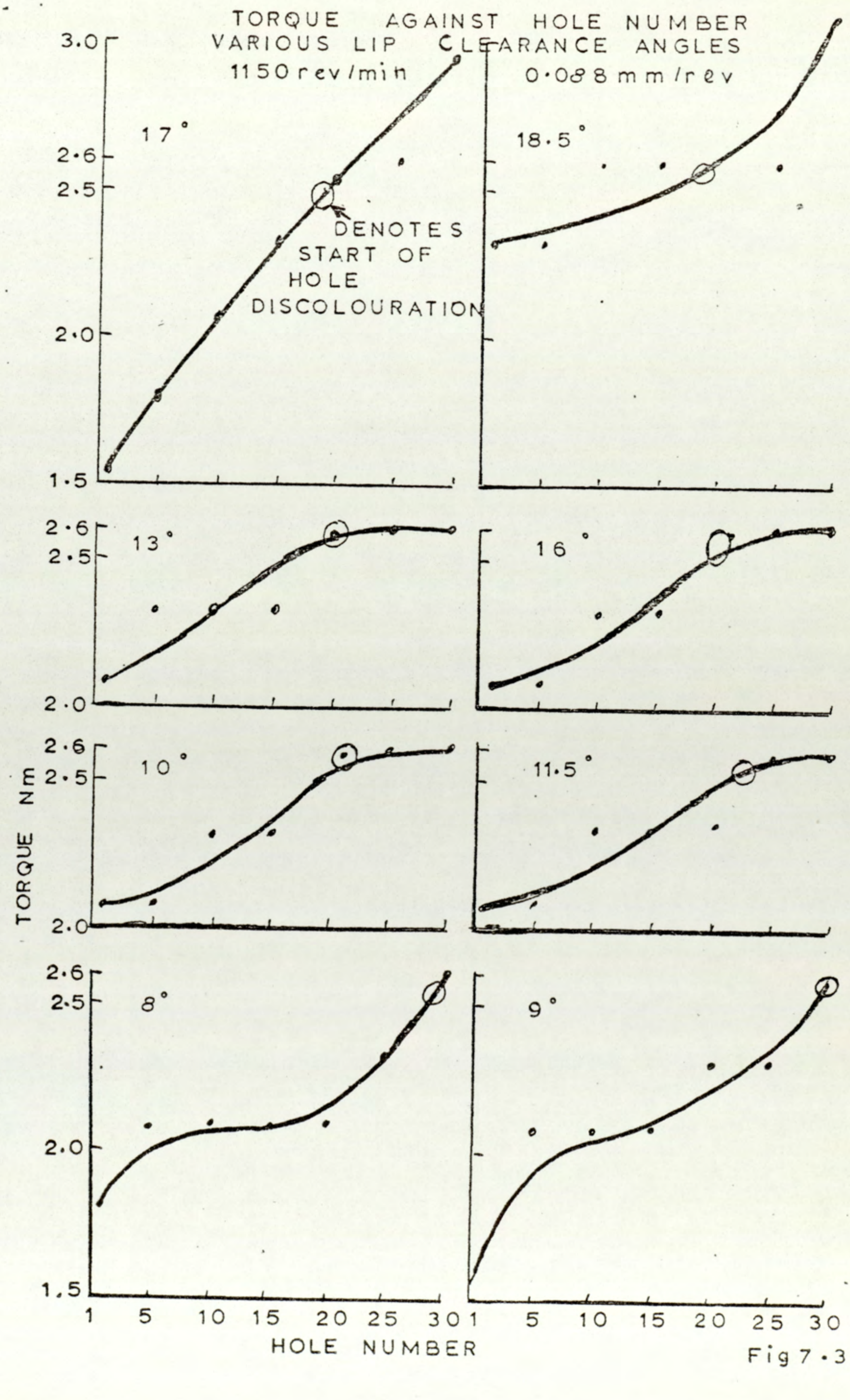
TORQUE AGAINST HOLE NUMBER FOR VARIOUS DRILL POINT ANGLES
TEST N°1&2
1190 Rev/min
0·088 mm/rev
140°
118°
130°
100°
110°
1
2
TORQUE Nm
HOLE NUMBER
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1
15
30
45
60
75
90

Fig 7.1



VERTICAL FORCE AGAINST HOLE NUMBER FOR VARIOUS DRILL POINT ANGLES
TEST N° 1 & 2
1190 Rev/min
0·088 mm/rev
140°
118°
130°
100°
110°
VERTICAL FORCE X10² N
HOLE NUMBER
1 15 30 45 60 75 90
1 3 5 7 9 11 13
1
2

Fig 7·2



TORQUE AGAINST HOLE NUMBER
VARIOUS LIP CLEARANCE ANGLES
1150 rev/min
0·088 mm/rev
17°
18·5°
DENOTES START OF HOLE DISCOLOURATION
13°
16°
10°
11·5°
8°
9°
TORQUE Nm
3.0
2·6
2·5
2·0
1·5
1 5 10 15 20 25 30
HOLE NUMBER

Fig 7·3

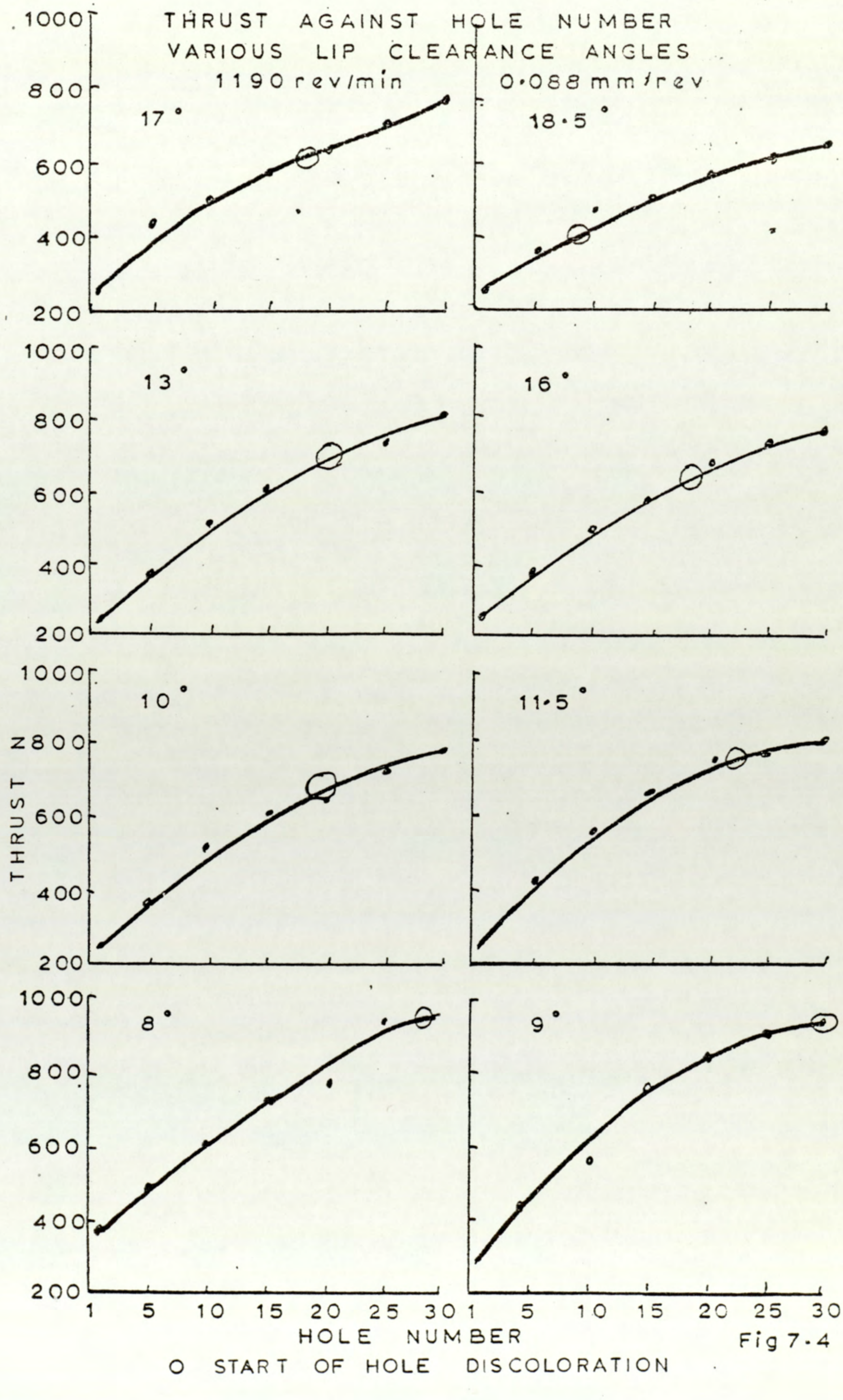

THRUST AGAINST HOLE NUMBER
VARIOUS LIP CLEARANCE ANGLES
1190 rev/min
0·088 mm/rev
17°
18·5°
13°
16°
10°
11·5°
8°
9°
THRUST N
1000
800
600
400
200
1
5
10
15
20
25
30
HOLE NUMBER
O START OF HOLE DISCOLORATION

Fig 7·4

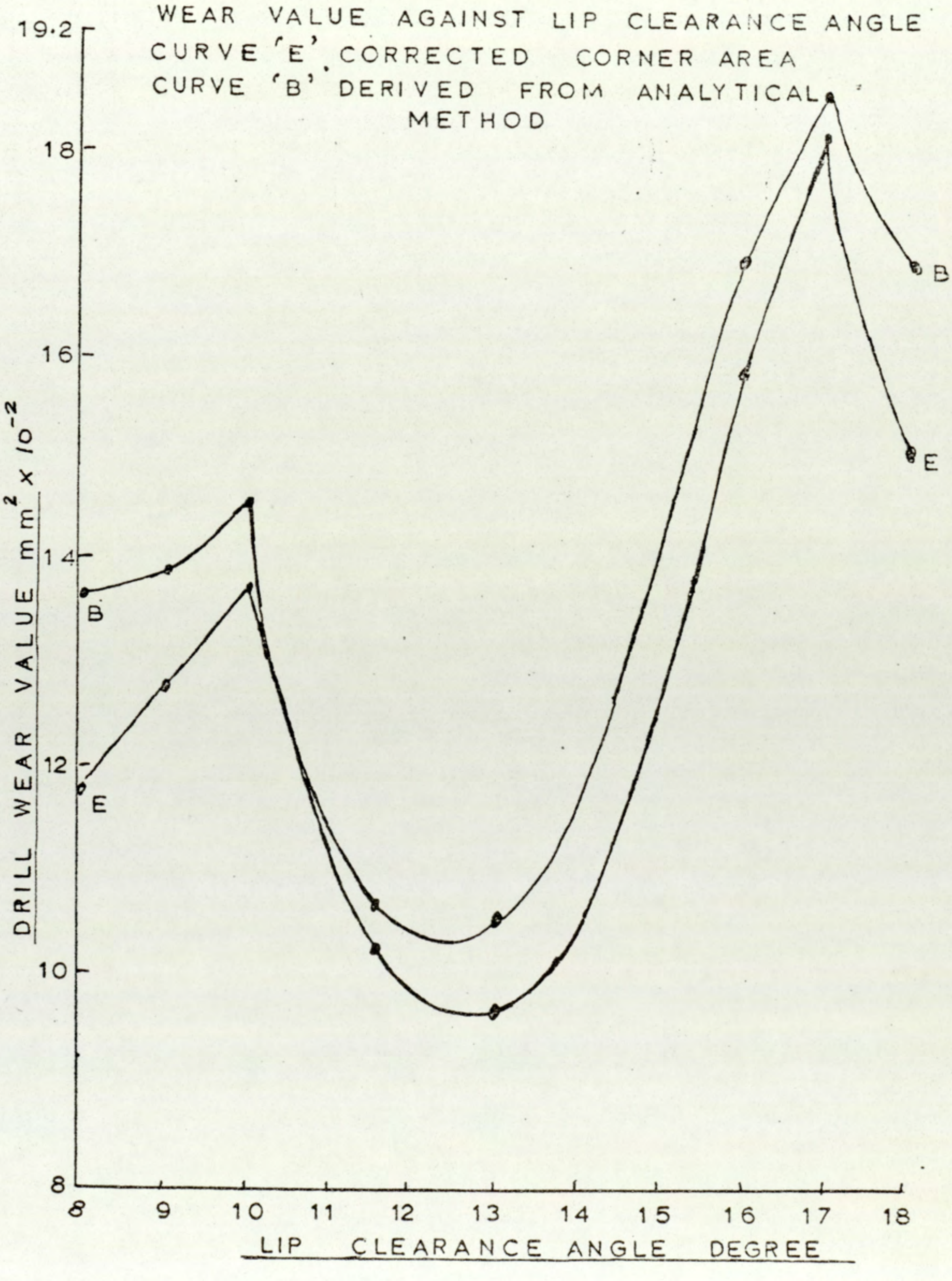

WEAR VALUE AGAINST LIP CLEARANCE ANGLE
CURVE 'E' CORRECTED CORNER AREA
CURVE 'B' DERIVED FROM ANALYTICAL METHOD
19.2
18
16
14
12
10
8
DRILL WEAR VALUE mm^2 x 10^{-2}
B
E
B
E
8
9
10
11
12
13
14
15
16
17
18
LIP CLEARANCE ANGLE DEGREE

Fig 7.5

NUMBER OF HOLES DRILLED TILL DISCOLOURATION AGAINGST LIP CLEARANCE ANGLE

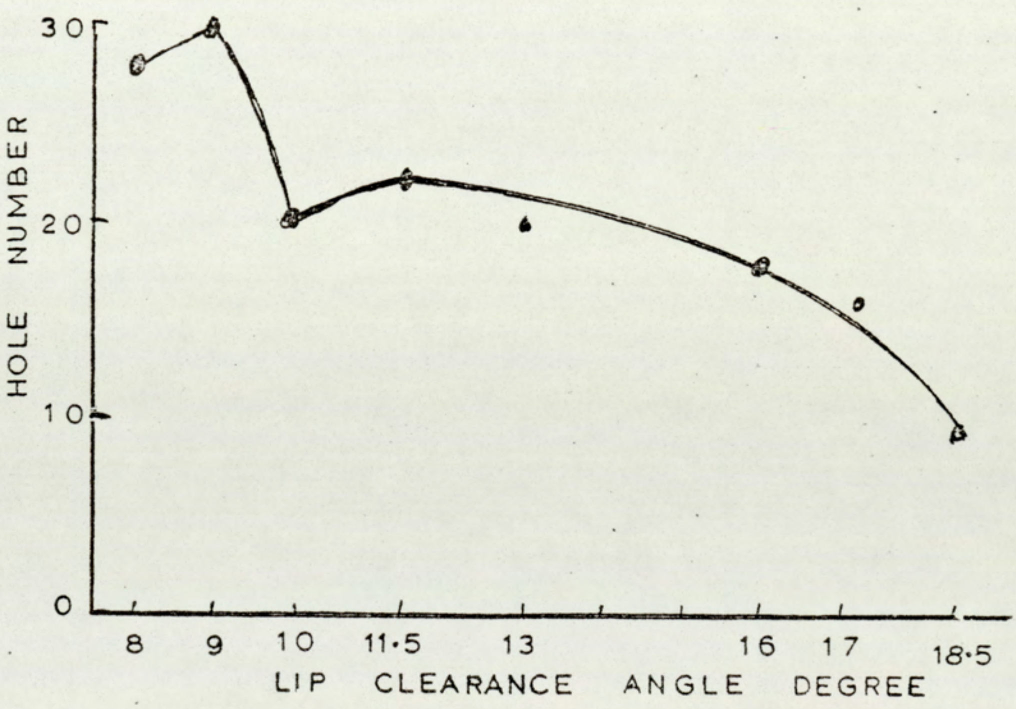
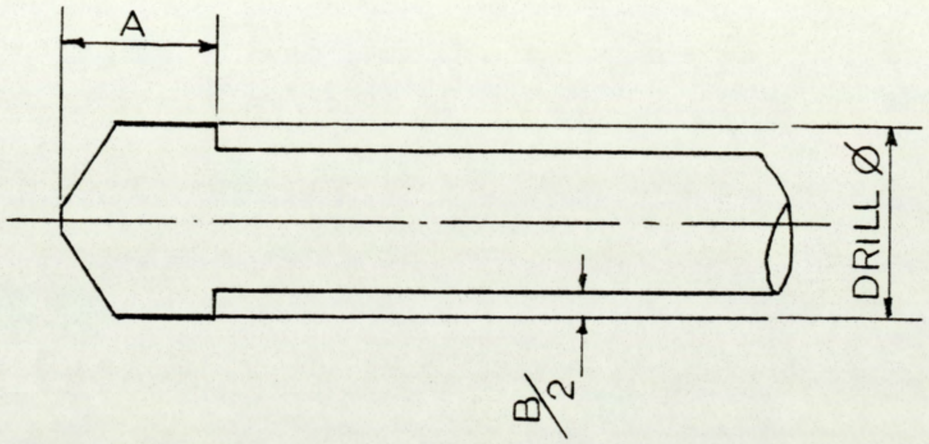


Fig 7·6



"A" DISTANCE FROM POINT TO START OF RELIEF

"B" AMOUNT REMOVED FROM DRILL BODY

Fig 7.7

TORQUE AGAINST HOLE NUMBER
FOR RELIEVED DRILLS
1190 rev/min 0·088 mm/rev
130° POINT ANGLE

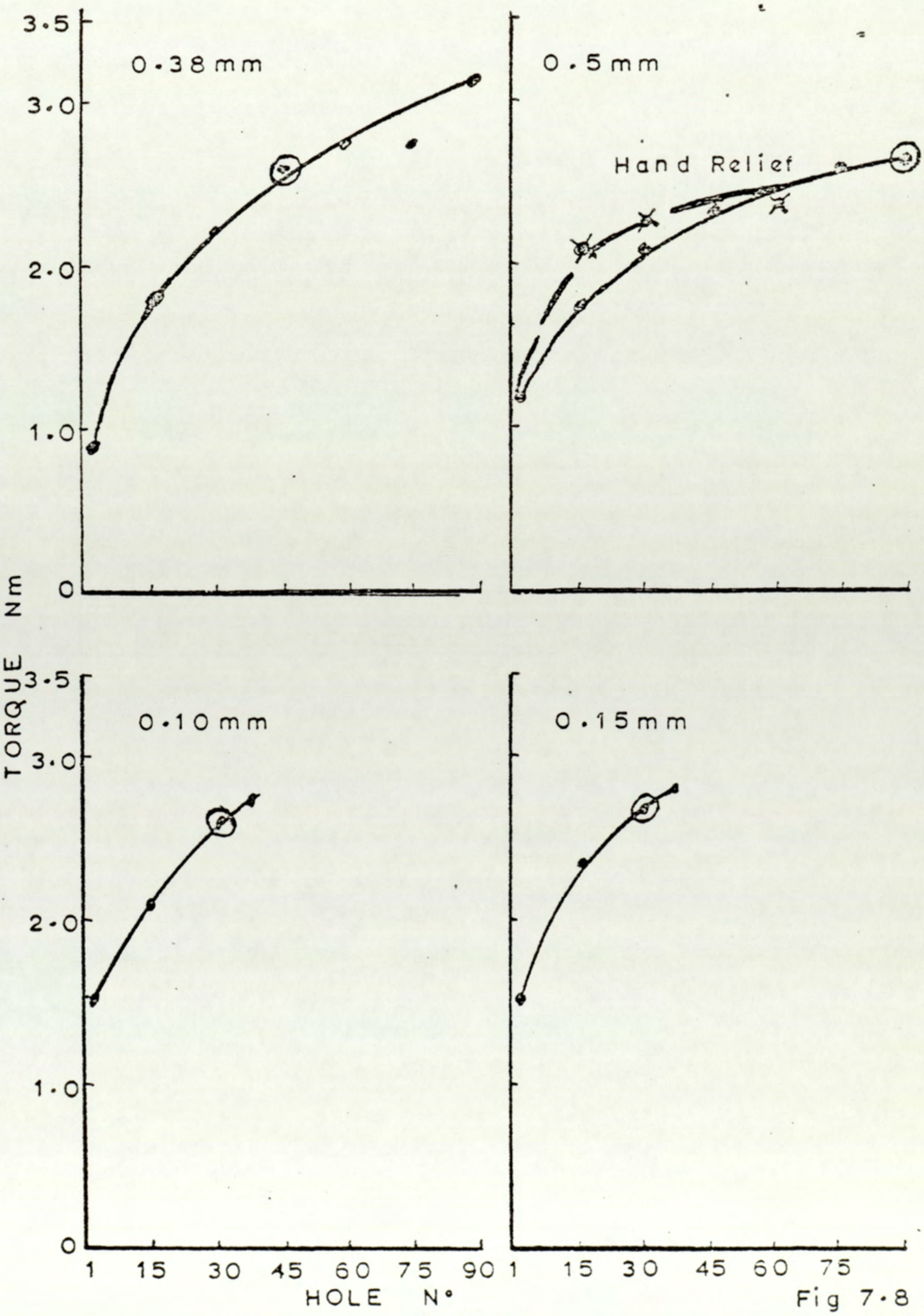


Fig 7·8

O START OF HOLE DISCOLORATION

VERTICAL FORCE AGAINST HOLE NUMBER
FOR RELIEVED DRILLS
1190 rev/min 0·088 mm/rev
130° POINT ANGLE

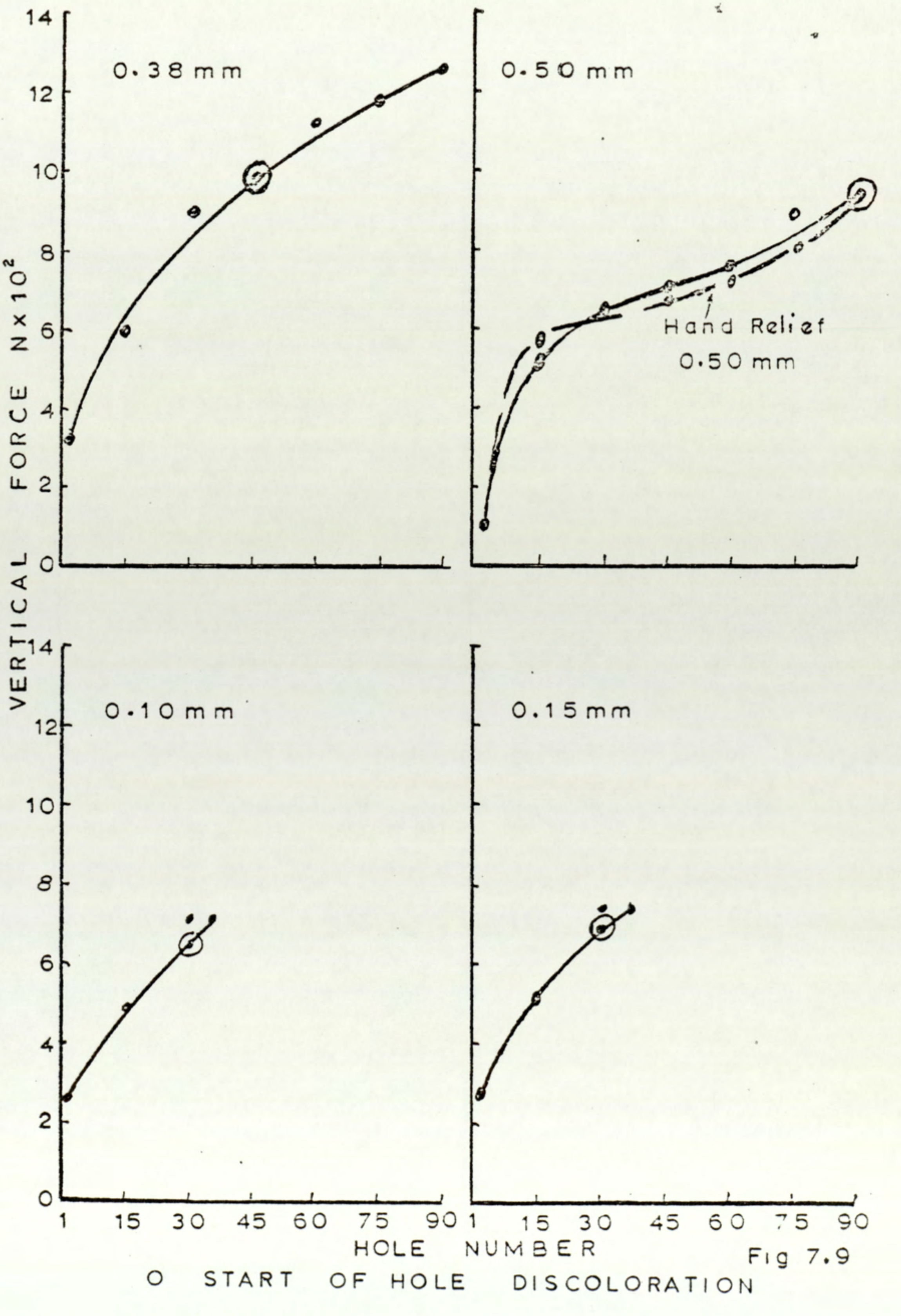


Fig 7.9

O START OF HOLE DISCOLORATION

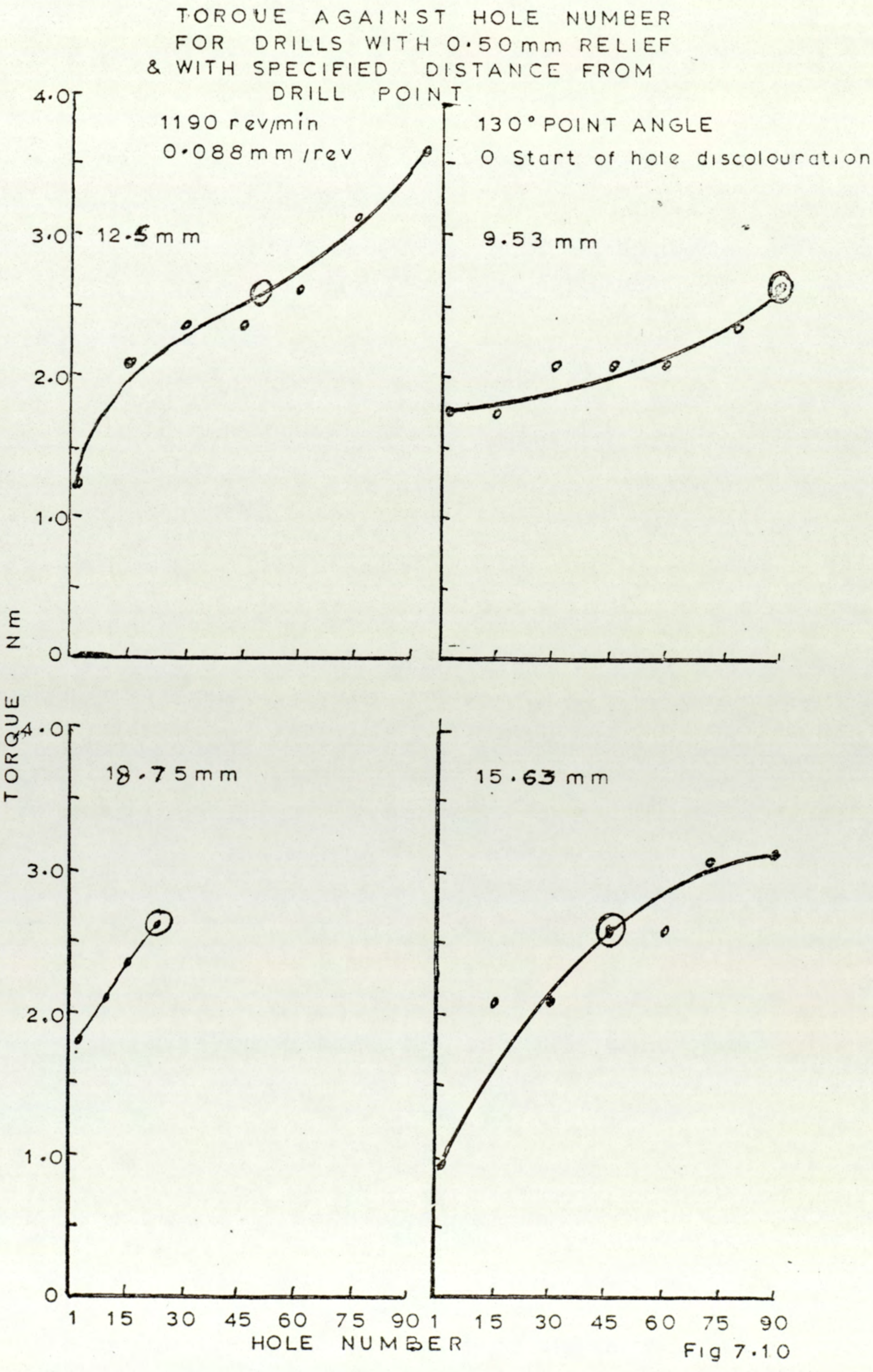

TORQUE AGAINST HOLE NUMBER
FOR DRILLS WITH 0·50mm RELIEF
& WITH SPECIFIED DISTANCE FROM
DRILL POINT
1190 rev/min
0·088mm/rev
130° POINT ANGLE
O Start of hole discolouration
12·5mm
9·53mm
18·75mm
15·63mm
TORQUE Nm
4·0
3·0
2·0
1·0
0
1 15 30 45 60 75 90
HOLE NUMBER

Fig 7·10

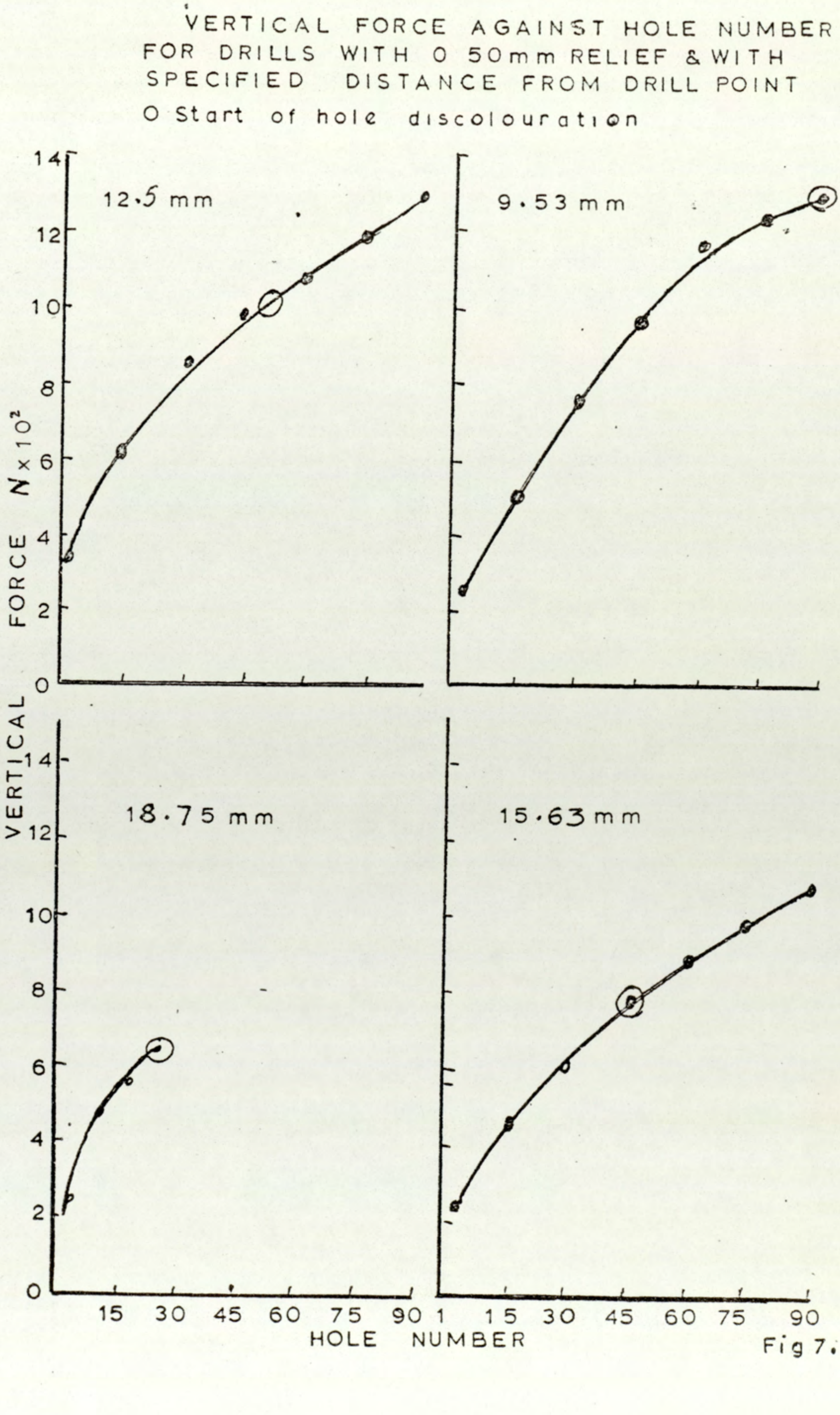

VERTICAL FORCE AGAINST HOLE NUMBER
FOR DRILLS WITH 0 50mm RELIEF & WITH
SPECIFIED DISTANCE FROM DRILL POINT
O Start of hole discolouration
12·5 mm
9·53 mm
18·75 mm
15·63 mm
VERTICAL FORCE N x 10²
0
2
4
6
8
10
12
14
15
30
45
60
75
90
1
HOLE NUMBER

Fig 7.11

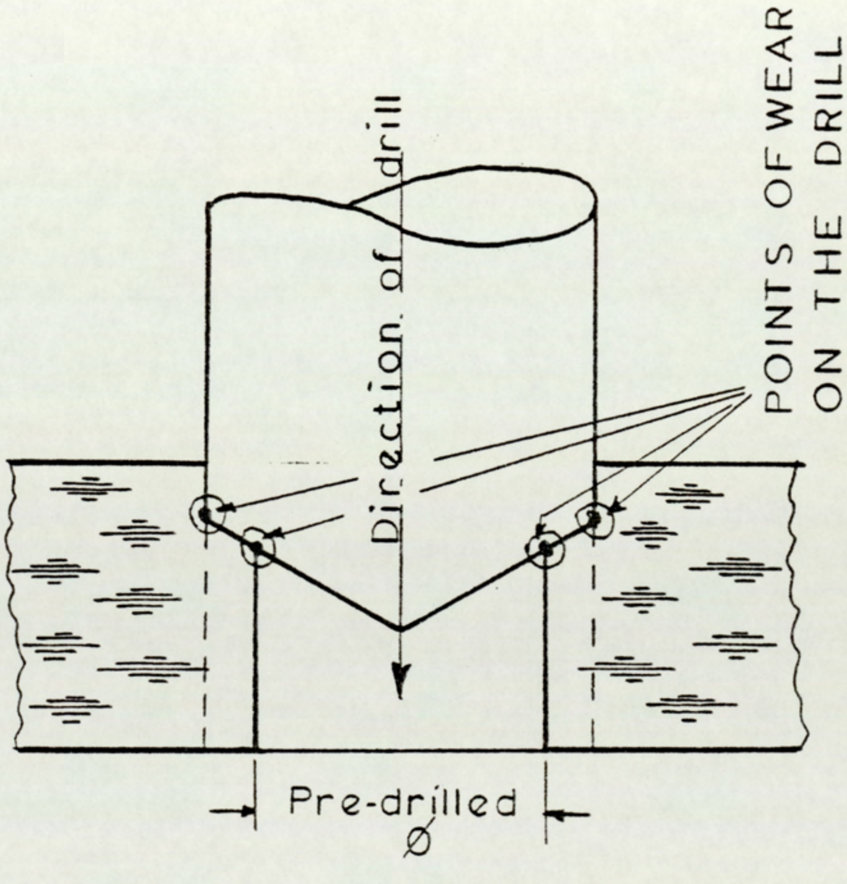


Fig 7.12

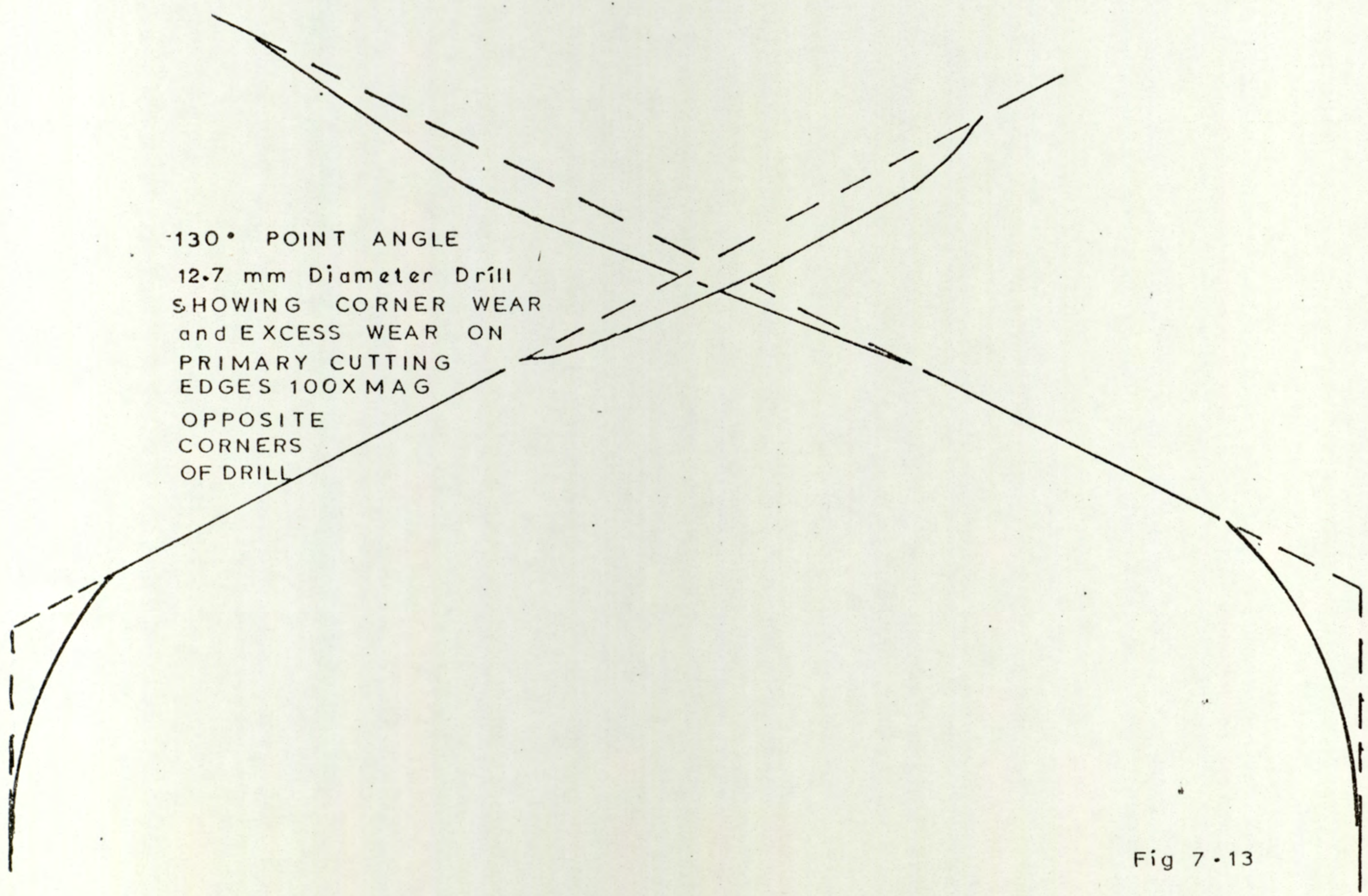

130° POINT ANGLE
12.7 mm Diameter Drill
SHOWING CORNER WEAR
and EXCESS WEAR ON
PRIMARY CUTTING
EDGES 100X MAG
OPPOSITE
CORNERS
OF DRILL

Fig 7.13