PARAMETERS FOR TOOL LIFE OPTIMISATION WITH RESPECT TO FACE MILLING

by

GEORGE DONALD KENDRICK

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G.D. Kendrick.

SUMMARY

Initially a review of the process of face milling is undertaken, including an outline of the methods of tool failure and ways of overcoming some of these failures.

A practical study is made of the tool life of indexable tungsten carbide inserts when being used to face mill a medium carbon steel. Tool life in this context is expressed in terms of the flankwear on the cutting tool.

Techniques are established for the method of conducting the cutting tests and the procedure for measuring the flankwear. A face mill containing a single insert is mounted directly in the main spindle of the milling machine and the down-cut and up-cut milling mode is obtained by varying the height of the testpiece, relative to the cutter, so that the main cutting force is always acting downwards towards the machine table.

Using conventional cutting speeds and feeds, standard positive rake and negative rake inserts are examined when up-cut and down-cut milling. A range of chamfer angles and chamfer widths are ground on standard inserts and the effects on tool life investigated. It was found that chamfering the positive rake inserts improved the tool life and that an optimum chamfer angle of 15° exists. The 15° angle improves the tool life from a few seconds to 35-40 minutes.

The cutting forces produced by the standard and modified inserts are studied, to ensure that changing the geometry of the inserts does not significantly alter the cutting forces.

George Donald Kendrick

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INSERTS, TOOL LIFE, OPTIMUM ANGLE

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INTRODUCTION

During the twentieth century rapid progress has been made in the development of cutting tool materials from plain carbon steels, to high speed steels, cast cobalt tools, cemented carbides, ceramics and diamond. Each development has brought about an increase in wear resistance of the tools, but the newly developed tool materials have never completely replaced the older ones and all are still in use throughout industry.

Carbide tool materials have become the most widely used metal cutting tools for a range of applications and have been developed from the hard brittle "straight" carbide grades, subject to rapid crater wear, to the steel cutting grades based on a mixed carbide alloy system of WC-TiC-TaC-Co.

When selecting a cutting tool material for a given application it is inevitable that a compromise is made between conflicting technological requirements and many economic criteria.

The choice of a cutting tool for a particular requirement is dependent on the speed and feed to be used, the rigidity of the machine tool, the composition and state of the workpiece and the physical strength of the workpiece.

Ideally a cutting tool should possess the following properties:

1. Sufficient toughness to withstand the shock loading encountered at the start and finish of each cut.
2. Wear resistance against the cutting mechanisms which bring about tool degradation.
3. Hot-hardness to resist softening and deformation at the elevated temperatures produced during metal cutting.
4. Resistance to fatigue due to cyclic fluctuations in stress caused by intermittent cutting.
5. Low coefficient of friction.
6. High thermal conductivity.
7. Chemical inertness with respect to the workpiece material.

All of these requirements can not be found in one material because some are incompatible, for instance hardness and toughness are mutually opposed properties and to increase one must lead to a reduction in the other. To enable a tool to cut as economically as possible for a given type of workpiece, under a specific set of conditions, must lead to a sacrifice of a proportion of the desirable properties in a tool material.

Any modification to a cutting tool that increases its life, without reducing the cutting speed and feedrate, must bring about a reduction in the machining costs due to a reduction in the cost of the tools themselves and also a reduction in the machine down-time, while the tools are being changed. The result is an improvement in machine utilisation but it can only be justified if the costs involved in modifying the tool can be more than offset by the savings made during service.

Recent developments have been the coating of carbide tools with various carbides, nitrides and oxides bringing about increases in tool life without loss in cutting speeds. All carbide manufacturers offer a wide range of coated carbide inserts which although costing more than an uncoated equivalent have an increased tool life. These tools have been readily accepted in industry, particularly for turning, where the cutting action is steady for the vast majority of applications, once full depth of cut and full feed/rev have been achieved. Milling, on the other hand, has many more problems than turning and each insert is engaged with and disengaged from the workpiece each revolution that the cutter makes. This intermittent cutting action can lead to premature failure of the insert due to mechanical weakness, coating of the insert can not overcome this problem.

Face milling is widely used in industry for both bulk removal of metal and finer finishing cuts and the applications are growing due to the increased use of numerically controlled machining centres using cutting tools mounted in an internally tapered spindle. Ideally a positive rake cutter should be used for many applications, giving a smoother cutting action and requiring less power, but because of the weak shape of the cutting edge a negative rake insert is used because it can withstand the cutting action.

The work carried out in this research investigates the effect of chamfering the cutting edge, on both positive and negative rake inserts, with a view to increasing the life of the insert; tool life being defined in terms of the flank wear produced on the insert.

Chamfering a cutting edge produces a stronger tool, capable of withstanding shock loads and yet when using positive rake inserts permits the chip to flow easily across the face of the tool.

Flankwear was chosen as a measure of tool life because it is easily measured optically, but more importantly if the rate of flank wear can be reduced the tools will maintain the component size over a longer period of time. This latter feature is of considerable importance when the tools are used for batch or mass production.

If a chamfered cutting edge can be shown to increase tool life it is intended to establish the most suitable chamfer angle and also to determine the optimum width of chamfer, related to the feedrate.

CHAPTER 2

MILLING

CHAPTER 2: MILLING

2.1 THE MILLING PROCESS

2.1.1 The Cutting Action

Milling is a method of metal removal from work which is fed normally against a multi-toothed cutter, rotating about its own axis. The profile of the machined surface is determined by the intersection of a plane perpendicular to the motion of the work and the outline of the body of revolution, generated by the rotating cutter.

The process is a unique cutting action, in that the cutting is intermittent and the undeformed chip thickness is not uniform.

Many workers have researched into intermittent cutting using a cylindrical workpiece, with a slot machined along its length (Lenz et al[1]). The cylinder was rotated in a lathe and the cutting tool was held in the toolpost. Others (Bhatia et al[2,3,4,5], Braiden and Dugdale[6]) have used rectangular bars held in a specially designed turning fixture. After each cut the workpieces were adjusted radially in the fixture so that the ratio of cutting time to free time was maintained and also the cutting speed was then kept constant.

Any method reproducing intermittent cutting on a lathe may be valid for such a condition when turning, but none may be considered as simulating a milling operation (Konig & Essel[7]).

When milling, the cutting teeth generate a looped trochoid relative to the work (Martellotti[8]) and the undeformed chip thickness varies depending on whether the cutter is being used for up-cut or down-cut milling. When up-cut milling (fig 2.1a) the undeformed chip thickness commences at zero and increases to a maximum, which may reach a value equivalent to the feed per tooth. The advantages of up-cut milling are that the cutter rotates against the feed and the cutting edge travels through clean metal and emerges through a surface which may be contaminated by rust, rolling-mill scale, sand from a moulding etc. The disadvantage is that unless the cutting edge is extremely sharp it resists the initial cutting of a thin chip, resulting in high localized radial cutting forces, leading to mechanical failure of the tool and high cutting temperatures which may cause work hardening of the workpiece. (Singh[9])

Down-cut milling (fig 2.1b) can cause problems of snatching the workpiece and machine table under the cutter, giving rise to the name for this type of cutting as "climb milling". The problem may be reduced by using a backlash eliminator on a mechanical leadscrew. The big advantage of down-cut milling is that the tool is required to cut immediately on contact with the work-piece and hence less wear takes place than with up-cut milling. Most cutting tools perform better when made to cut rather than skim the surface.

Sabberwal[31] concludes that in down milling the forces are generally higher than in up milling, but they assist the feed motion. The cutting pressures are also higher, therefore greater power is required to rotate the spindle, but less power is required to feed the work.

Early use of cemented carbide cutting tools produced inserts unable to withstand the shock of down-cut milling, but modern inserts are much tougher and are capable of giving an acceptable life.

To confirm the complexity of milling Yellowly & Barrow[10] listed the variables affecting tool life as

work material
tool material
tool geometry
cutting speed
feed per tooth
depth of cut
width of cut
time in cut
time out of cut
cutter diameter
entry conditions
exit conditions

2.1.2 Chip Equivalent

In an attempt to reduce the many machining variables and geometric parameters of the milling process some researchers have effectively achieved this by using the 'chip equivalent'.

The chip equivalent q, was first suggested for turning by Woxen[11] in 1932 expressed as

$$q = \frac{L}{A} \text{ mm}^{-1}$$

where L = the engaged cutting edge length of the tool

A = the area of the cut as shown in fig 2.2

This was developed by Colding[12] for milling by introducing a characteristic chip cross sectional area A_c, related to the volume continuity of chip formulae determined by the cutter speed V, the depth of cut t, the width of cut b and the work speed v so that

$$A_c = \frac{v}{V}.b.t. \quad \text{mm}^2$$

and the characteristic depth of cut is

$$h_c = \frac{A_c}{b} = \frac{v}{V}\, t \text{ mm}$$

The reciprocal of the chip equivalent q, called the chip thickness, was used by Barrow[13] and Brewer and Rueda[14] for turning. The equivalent chip thickness was developed for specific milling cutters by Orundas[15].

The equivalent chip thickness for a positive rake Walter Face Milling Cutter, type Wendelnovex F244 was calculated to be

$$h_W = \frac{W.d.f.z / \pi . D_W}{l_W + \dfrac{d}{\sin \theta_W \cos \delta_W}} \qquad \text{(see fig 2.3)}$$

where W = width of workpiece
d = depth of cut
f = feed per tooth
z = number of teeth
D_W = nominal diam. of cutter
θ_W = approach angle of cutter
δ_W = rake angle
l_W = horizontal contact length of cutter

The equivalent chip thickness for a negative rake Sandvik Face Milling Cutter, No. R265.1 - 100M, was calculated for two conditions as follows -

condition a (fig. 2.4) when $d < l_a$

$$h_{s1} = \frac{W.d.f.z / \pi . D_s}{l_s + \dfrac{\left[l_\theta + \dfrac{d}{\sin \phi} - l_\theta \dfrac{\sin \theta_s}{\sin \phi} \right]}{\cos \gamma_s}}$$

where D_s = nominal diam. of cutter
l_s & l_θ = length of cutting edges
θ_s & ϕ = approach angles
γ_s = rake angle

condition b (fig 2.4) when $d > l_a$

$$h_{s2} = \frac{W.d.f.z/\pi.D_s}{l_s + \dfrac{\left[l_\theta + l_\phi + \dfrac{d}{\sin\lambda_s} - \left(l_\phi + l_\theta \dfrac{\sin\theta_s}{\sin\phi}\right)\dfrac{\sin\phi}{\sin\lambda_s}\right]}{\cos\gamma_s}}$$

Consideration was given to the use of the chip equivalent, or some derivation for this research, but it was not adopted. The reason for rejecting the chip equivalent with its obvious advantage was due to the intended modification to the geometry of the cutting tool, so producing a double rake. The chip equivalent is based on a plane surface and the area associated with that surface.

2.2 TOOL FAILURE

The end of the life of a cutting tool may be defined in various ways (Hsü[16]), as the actual fracture of the cutting edge so that the tool ceases to cut, or the unacceptable deterioration of the work surface finish, or the excessive deviation from a nominal dimension due to tool wear. Generally however a tool may reach the end of its useful life due to

1. Plastic deformation
2. Thermal cracking and mechanical chipping of the cutting edge
3. Cratering of the rake face
4. Wear on the flank of the tool

2.2.1 Plastic Deformation

Plastic deformation was noted by Draper & Barrow[17] when turning high strength steels with carbide tools and Uehara & Kanda[18], when face milling a 1% carbon steel hardened to 60-62 Rockwell C. The deformation was sometimes accompanied by chipping of the cutting edge, which may lead to brittle failure of the tool after little wear. The fracture appeared to originate from cracks penetrating into the tool from the flank face (fig 2.5). Immediately prior to the failure of the cutting edge a small bulge occurred on the rake face caused by plastic deformation.

2.2.2 Thermal Cracks

Thermal cracks (fig 2.6) rarely occur when turning, but are quite common when milling. The original concept of intermittent cutting associated with milling was considered an advantage when using high speed steel cutters, due to the cooling action on the cutting edge during its free rotation in air or coolant. The introduction of cemented carbides for cutting tools presented a problem when using them for intermittent cutting, for when carbides are subjected to alternate heating and cooling as with the milling action,temperature gradients are introduced into the surface layers (Zorev[19]) producing high tensile stresses which result in parallel cracks appearing in the carbide, approximately perpendicular to the cutting edge, but inclined towards the direction of the chip flow. (Okushima & Hoshi[22,23])

Boston & Gilbert[26] were the first to observe these cracks and Pekelharing[36] coined the term "comb cracks". The close proximity of the cutting edge allows stress relief of the thermal stresses near the cutting edge but not if the stress induced further back into the body of the tool. Shinozaki[56] states that it is better to cut dry than to increase the severity of the quench by applying coolant. He also reports that the cracks increase in number as the depth of cut increases and as the feed increases, up to a maximum feed of 0.25 mm/tooth. The number of cracks is also a function of the width of work. If the width of work is equal to the diameter of the cutter when face milling it is unlikely that thermal cracks will be induced but as the width of the work reduces the frequency of thermal cracks is increased. Braiden & Dugdale[6] have investigated the formation of thermal cracks using intermittent cutting on a lathe and observed that tool failure often occurs in cemented carbide due to a portion of the tool face becoming dislodged between two thermal cracks.

2.2 3 Mechanical Failure

Carbide cutting tools may fail mechanically through chipping (gradual damage of the cutting edge) (fig 2.7) or breakage (fracture of a larger portion of the tool wedge) (fig 2.8). Tlusty & Masood[28] concluded that chipping is a ductile failure accompanied by an amount of plastic flow and that breakage is a brittle fracture as a result of tensile stresses.

Khadin-Al-Tornachi & Dugdale[29] studied the formation of comb cracks and mechanical cracks denoted p-cracks induced in cemented carbide when face milling. Mechanical cracks appeared in the rake face and clearance face running parallel to the cutting edge. The conclusions drawn were p-cracks appeared at feed rates higher than the practical limit when machining soft steels and within practical limits when machining hard steels. The origin of such cracks are usually the first point on the cutting edge to enter the workpiece. At high feedrates catastrophic failure of the edge occurred very quickly after the formation of p-cracks. p-cracks provide the direct cause of chipping since such cracks alone can cause chipping without the assistance of comb cracks, while comb cracks need the assistance of p-cracks to cause failure.

2.2.4 Cratering of the Rake Face

The chip produced during the cutting action flows across the rake face and produces a crater (fig 2.9). The crater is situated away from the cutting edge and the profile follows the curvature of the chip. Cook[30] concludes that the crater occurs where the contact forces between the chip and tool cause high interference temperature and wear.

Venkatesh et al[32] state that the crater in coated carbide inserts was produced by plastic deformation and show that when cratering occurs traces of the coating remain in the crater even though the crater was 25μm deep and the coating only 5μm thick.

Cratering is slow in developing and difficult to measure and hence it is rarely used as a measure of tool life.

2.2.5 Flank Wear

Flank wear (fig 2.10) exists during virtually all conditions of machining. The development of the width of wear fllows the classic wear curve (fig 2.11). The initial sharpness of the cutting edge is rapidly broken down and flank wear established in a matter of seconds. (Stage I). The first stage is followed by a period of constant wear rate (Stage II), the rate being dependent on such variables as tool material, workpiece material, cutting speed, feed etc. The period of constant wear rate is followed by a rapid breakdown of the cutting edge (Stage III) leading to a complete collapse of the edge. Flank wear has been used extensively by researchers as a measure of tool life.

When a cutting tool is used in industry the amount of flank wear that can be tolerated depends upon the type of machining, the finish required on the component and whether the tool is to be reground or discarded at the end of its life. If the tool is to be reground it is usually withdrawn from service after about 0.4 mm wear otherwise the cost of refurbishing the tool becomes excessive. If however indexable throw-away inserts are being used they are usually retained until the flank wear is about 0.8 to 1 mm. If the insert is retained longer than this it rarely performs in a satisfactory manner for much longer and is close to its final catastrophic collapse, which may result in the workpiece being scrapped.

The flankwear of modern carbide cutting tools is usually a slow process and tool life tests may be extremely costly in test-piece material and a protracted exercise for obtaining data. It is common practice during research into metal cutting to use a relatively small flank wear as the criterion for tool life. Hsu[16], Fleischer & Koenigsberger[33] and Wu[34] showed that the rate of flank wear is constant after about 0.1 mm and Cook[30] quotes data from nine research programmes around the world using 0.008 inches (0.2 mm) flankwear as the limiting dimension of tool life.

In addition to the flankwear land that forms there also occurs at times grooving of the tool at the point where the trailing edge of the chip passes the cutting edge (fig 2.12). Trailing edge grooving was first noted in the 1950's and has since been attributed to a variety of causes. Pekelharing[35] stated that the origin of the grooves could be due to the uniform abrasion wear of the cutting edge caused by the regular feed pattern. He[36] later connected the wear with work hardening of the workpiece, a theory supported by Hovenkamp & Van Emden[37]. Work carried out by Taylor & Ansell[38] contradicted the above findings by producing grooving in cutting tools when machining previously chemically machined surfaces having no workhardening. Albrecht[39] suggested that grooving was due to built-up edge containing oxydised tool particles escaping from the region of high pressure. Solaja[40] studied the effects of grooving rather than the causes and suggested that all of the above mechanisms contribute to the grooving phenomenon and in addition that fatigue was important. Draper[41] noted that when turning slender ausformed bars requiring a travelling steady for support that grooving of the tool was a function of the vibrations present in the set-up. Grooving was eliminated by supporting the bar immediately behind the tool. Further investigations by Draper produced an oscillating body rubbing against a rotating one making it analogous to that of the mechanism of fretting corrosion i.e. the destruction of metal surfaces by a combination of adhesion, abrasion and corrosive action. This produced similar grooving and lead to the conclusion that although vibrations may not be the sole cause of trailing edge grooving they act as a catalyst for the other conditions.

In this research flankwear has been adopted as the measurement of tool life and the width of the flank wear land has been measured at a specific point (Section 4.1, fig 4.4).

2.3 ENTRY AND EXIT ANGLES

Kronenberg[49] analysed the entry and exit conditions when face milling. Fig 2.13 shows a face-milling cutter at an instant shortly before the tooth engages with the side of the work (the plane of engagement), The material removed by a tooth having a straight cutting edge is indicated by the parallelogram STUV, the height being dependent on the depth of cut and the width is determined by the feed per tooth. It is possible for a given set of conditions, for the cutter to make contact over either the area STUV, or a line contact ST, TU, UV or VS or more likely a point contact at S, T, U or V. Kronenberg developed a mathematical model and a geometrical method, for determining the initial contact and exit conditions for a given set of variables, i.e. depth of cut, feed per tooth, rake angle, cutter approach angle and the position of the centre of the cutter relative to the entry and exit face of the work piece. A measurement for the magnitude of impact was derived from:

$$\text{impact factor} = \frac{\text{chip cross sectional area}}{\text{penetration time}}$$

the penetration time being the time taken for the chip to develop, from zero to full size. The faster the chip develops the larger the impact.

The effects of impact on tool wear was studied by using a single-tooth cutter to face mill a narrow workpiece ($\frac{3}{4}$ inch), so that little wear took place due to the cutting action and the changes in the tool would be mainly a result of the impact with the workpiece. The inserts used were 10° negative rake having a corner angle of 30°, the depth of cut was 1/8 in., the feed per tooth 0.009 in. and the cutting speed 490 ft. per min. The tool was examined after 13 300, 20 000 and 26 600 impacts and the wear (crater), on the rake face was measured perpendicular to the cutting edge and the following conclusions relating to the wear were established.

a. The combined effects of location and magnitude of impact was a major factor in the wear of sintered carbide tools.

b. A small impact at U seemed to be the most desirable condition although a small impact at V was better than a large impact at U.

c. The most desirable conditions can be obtained by careful co-ordination of axial rake, radial rake, corner angle, chamfer angle and angle of engagement.

Perotti[69] showed that when tools had a chamfer the impact conditions changed and the penetration time was significantly increased. He also reported that an increase in penetration time brings about a fall in workpiece vibration.

Philip[70] reported that when face-milling chromium-molybedenum hardened steel, the tool life expressed in terms of number of impact cycles was lowest in the range of transition from V to VU contact. It was also found that the machined volume per cutting edge was highest when using large positive values for the angle of engagement ϵ (fig 2.14). A comparable performance is obtained when using a T contact and a moderate negative value for ϵ (fig 2.13)

Yellowly & Barrow[10] state that the thermal effects have a much greater influence on tool life than the mechanical effects associated with cutter stiffness and entry and exit conditions. They further stated however that impact should be kept away from the cutting point S, if tool breakage is to be avoided. Considering exit conditions they reported that failure on exit was generally due to chip adhesion, which led to chipping of the cutting edge. The effect was most pronounced when machining work hardening materials and they attributed the failure to the formation of tensile cracks in the final shearing process, as the tool point approached the free surface.

All of the cutting tests used in this research have had a constant entry condition for up-cut and down-cut milling, by setting the centre of the cutter in line with the appropriate entry face of the test piece. (fig 2.15)

2.4 MODIFIED CUTTING TOOLS

2.4.1 Coated Carbide Tools

The early carbide cutting tools although extremely hard were very brittle and it was not until the particles of tungsten carbide were held in a ductile cobalt matrix that the tools became a viable production tool. The addition of titanium carbide to the tungsten carbide-cobalt mixture permitted higher cutting speeds and an improvement in the efficiency, when machining such as nodular irons.

It was considered that the improvement in tool life, due to TiC, was caused by oxide layers forming on the surface of the cutting tool. Stanislaò et al[42] studied the formation of such oxides and concluded that the oxides protecting the surface of cemented tungsten carbide - titanium carbide cutting tools was the sesquioxide of titanium, Ti_2O_3, which formed during maching. High speeds and high temperatures, associated with metal cutting, are advantageous in the formation of Ti_2O_3 which creates a diffusion barrier reducing diffusion wear[32,44], one of the main causes of tool failure at high cutting temperatures.

A logical step was to coat the carbide cutting tools with various oxides and study the effects on tool life. Sur et al[45,46] coated the tools with pastes of oxides and heated the tools at a temperature of 1200-1400°C for three hours in a vacuum (10^{-4} to 10^{-5} torr). Improvements in tool life were obtained by coating the tools with oxides of titanium, aluminium, zirconium, hafnium and chromium.

In 1969 the first commercial TiC coated cemented carbide tools were introduced in America[47]. Claims were made of increases in tool life of up to four times that of uncoated tools.

More recently alternative coatings have been applied by better controlled processes, such as:

Chemical Vapour Deposition (CVD) (Kee[27])

In this process the coating material is condensed from a suitable gaseous environment, onto the substrate carbide, under conditions of high temperature and low atmospheric pressure.

Physical Vapour Deposition (PVD)

(i) Ion plating - ion plating depends on the existence of a highly energised plasma enclosing the substrate which acts as the cathode in a D.C. circuit. The coating material source is heated by an electron gun system and the coating flux is carried to the substrate cathode by the plasma.

(ii) Sputtering - the material to be sputtered is made the cathode in a low pressure discharge system. The substrate to be coated is placed between the cathode and anode and a discharge of upto 20 000V set up between them. Metallic ions are then ejected from the cathode and deposited on the substrate.

Activated Reactive Evaporation (ARE)

Flux carrying plasma is allowed to react with an injected gas, such as methane or acetylene, prior to reaching the substrate target. The substrate temperature is maintained below 500°C, thus making the process suitable for coating high speed steels, without having to reharden.

The ARE process is the most suitable for coating cutting tools, giving fine control of the coating variables and mixed coatings may be applied relatively easily. Even though CVD is not acknowledged to be the best process regarding control it is the most popular method employed, because it is suitable for high volume production.

Two of the coatings commonly applied are titanium carbide and titanium nitride, the former tending to breakdown during severe conditions, such as milling and the latter is prone to flaking[48]. Titanium carbide sets up a brittle eta layer, where bonding occurs with the substrate, forming three structurally related forms of the eta carbide Co_2W_4C, Co_3W_3C and Co_6W_6C denoted by eta 2/4, 3/3 and 6/6 and although titanium nitride avoids this layer it can only be bonded by way of a thin and sharply defined stratum allowing flaking to occur.

To avoid the formation of eta layer a thin coating (0.5μm) of TiC may be deposited, which is too thin to allow the eta layer to form, followed by a more substantial layer of titanium carbonitride. The second layer bonds effectively to the TiC layer and produces a coating which contains more nitride towards the surface where it is virtually pure nitride[48]. Sproul & Richman[43], on the other hand, claim that the eta layer may actually enhance tool life. They produced TiC coated cemented carbide tools, with and without the eta layer, by sputtering, followed by heat treatment and concluded that the tools containing eta carbide had an improved life. It was suggested that eta carbide provided a secondary diffusion barrier.

All of the leading manufacturers of tungsten carbide offer a wide range of coated indexable throw-away inserts claiming an increased tool life for many operations when compared to standard uncoated tools. Coated tungsten carbides can also be operated at higher cutting speeds than uncoated carbides of the same grade and yet they still maintain an acceptable tool life.

Coated carbides have not been used for this research, because of the inconsistent results so far obtained when milling, and it is intended to modify the geometry of the inserts which would destroy the coating.

2.4.2 Double Rake Tooling

The geometry of the cutting tool may be modified from the normal concept of a wedge by producing a negative land or chamfer on a positive rake cutting tool (and occasionally on a negative rake tool) fig 2.16). The object is to produce a cutting edge which is much stronger than a standard tool and yet retains the positive rake to allow the chip to flow smoothly. The concept of chamfered or radiused tools has been studied for a number of years but as stated by Draper & Barrow[17] the conclusions drawn from the investigations were largely inconclusive and often contradictory.

Most of the work in this area has been undertaken for turning and little has been done involving the milling process.

In 1925 Klopstock[57] designed a cutting tool having a restricted tool face and in 1928, Herbert[58] used a cutting tool having both an obtuse and an acute rake angle. Armitage & Schmidt[59] investigated the performance of double rake tools for face milling. They suggested that a positive rake avoided the deformation of the chip and workpiece providing good chip flow and that a negative rake provided a stronger cutting edge avoiding chipping and also reducing wear. The two requirements were embodied in a single tool having a primary rake of -12° and a secondary rake of $+12^{\circ}$. They also found that the tool life increased as the primary land width increased upto a maximum of about twice the feed at which point the tool life of the compound tool was double that of a plain 12° negative rake tool. It was also reported that the power requirements were less than a 12° negative tool and a 6° positive tool. The workpiece temperature was also lower when using the double rake tool.

Jenson[60] reported that when boring hard steels (400 B.H.N) using tungsten carbide positive rake tools they failed through chipping and that negative rake tools increased the amount of chatter because of the lack of rigidity. Using a tool having a double rake with a negative primary rake of 30°, 0.030 in. wide and a positive secondary rake of 5° and after boring using a wide range of feedrates several vague conclusions were drawn which have since been refuted by many researchers. He was however able to machine successfully at cutting speeds of 630 ft/min.

Kibbey & Moore[61] found that by increasing the negative primary angle and primary land width that the tool life increased for both ceramic and carbide tools when turning hard steels (51 Rc). A negative rake of 30° having a width of 0.008 in. and a secondary positive rake of 5° gave an increase in tool life, when compared to sharp edged ceramic and carbide tools.

Hitomi[62] used a 30° negative primary land and a 15° to 30° positive secondary rake in the development of the 'silver white chip' cutting tool. The land forms a stable built-up edge which is induced to flow out continuously along the side cutting edge and which effectively acts as a cutting edge. The tool is claimed to reduce the cutting resistance and cutting temperature and it is also claimed that tool life and surface finish are improved. The optimum feed to land ratio was found to be $\frac{1}{2}$ to $\frac{3}{4}$.

Bagley[63] used ceramic tools having a negative primary rake of 45° with a land width varying upto as high as 0.065 in. for turning hardened tool steels (62 Rc). A cutting speed of 400 ft/min was used and because of the high forces and temperatures feedrates of 0.005 in/rev could not be exceeded. A very rigid set-up was also needed. The high ratio of landwidth to feedrate meant that effectively the tool is wholly negative and no benefit is derived from the double rake angle.

Albrecht[64] investigated double rake tooling when milling high strength steels. He suggested that during the milling process the stress field that develops in the cutter tooth may be such that fracture would occur and that the nature of the stress field depended on the intensity of the initial impact and the shape of the edge on the initial impact. The second factor was the only one open to change and by varying the geometry he found that a double rake gave the best results. Two different geometries were tested, one a negative primary land of 30^o having a negative secondary rake of 5^o and another with a 0^o primary rake with a positive secondary rake of 25^o. It was found that the cutting forces decreased as the land width decreased and that the maximum reduction occurred at zero width or in other words a standard tool. This conclusion is as expected because the cutting forces increase with increased negative rake angles. (see Section 7.2.1). It was suggested that the best ratio of land width to feed was 2.4 but that in practice a 1 : 1 ratio would probably be used.

Clark & Ludwig[65] working at PERA obtained longer tool life from negative rake tools than positive rake tools when turning. They also used double rake tooling and concluded that the ratio of landwidth to feedrate should be 1 : 2.

Agnew[66] describes three methods of preparing the edge of cutting tools (i) chamfering, (ii) honing and (iii) chamfering and honing, and each preparation has a specific application. He states that ground edges which produce minute notches which serve as starting places for cracks, edge chipping or actual breaks are suitable for finishing cuts in steel (upto 0.005 in feed) for cast-iron and most non-ferrous materials. Honed edges are for finish, semifinish or light cuts in steel (0.006 to 0.020 in. feed) for cast iron and non-ferrous materials. Chamfered edges are for heavy cuts, scale, interrupted cuts and conditions too rough for a simple hone. Chamfered and honed edges are used to eliminate notch effect in chamfered tools. Ground edges are the simplest and cheapest and should be used wherever possible.

Agnew[67] also states that tool life is increased by (i) strengthening the cutting edge, (ii) weakening the chip, (iii) directing the cutting force into the tool shank, (iv) removing obstructions to the chip flow. He further investigated the effects of edge preparation and claimed increases in tool life of 200% by simple honing of the edge by tumbling the insert in an abrasive slurry. The honed radius should not exceed 30% of the chip thickness. Agnew differentiates between a chamfer and a negative land. A chamfer is considered as having an angle of about 40° off the top face of a negative rake insert and about 50° of the top face of a positive rake insert giving a 45° bevel. This type of chamfer it is claimed should be no more than 30% of the chip thickness.

A negative land is also a bevel and should be as wide or wider than the chip thickness so that effectively the rake angle is changed. It is reported that there is no advantage in having a negative land greater than 15°.

Lenz et al[1] used a variety of chamfer angles and land widths on lathe tools turning a normalised steel bar 250 mm diameter and having a hardness of BHN 185. The bar had two diametrically opposed slots 9.5 mm wide. A chamfer of approximately 20° improved the tool life considerably, tool life in this case being measured as the number of impacts that the tool withstood before failure. It was considered that the number of impacts related directly to the volume of metal removed and also to other forms of life measurement. Although this research was related to intermittent cutting it can not be considered as analogous to milling (see Section 2.1.1).

Chamfering cutting tools has not been limited to metal removal processes, Ozaki & Yamasaki[68] applied chamfers of upto 45° to dies used for blanking sheet metal, these dies were used in conjunction with punches having conical tapers upto angles of 20°. Although producing a better finish to the sheared edge the burr often associated with piecing was increased.

It is amongst the confusion of chamfer angles and land to chip thickness ratios that this current research is being presented.

2.5 CLASSIFICATION OF CARBIDE TOOL MATERIALS

There are two systems of classification for carbide tool materials commonly used in the United Kingdom.

i) International Standards Organisation Systems (ISO)

ii) British Hardmetal Association System (BHMA)

2.5.1 ISO System

The aim of the system was to examine all of the available carbides to determine suitable grades for accurately defined applications and then issue standards against which specifications could be measured and quantified Due to commercial secrecy most of the technical information was not available, therefore the ISO system does not take into account the composition of the carbide but bases its classification on suitable applications.

The classification divides all grades into three colour-coded groups

K grades (colour red) - straight tungsten carbides - for machining cast iron and non-ferrous metals.

P grades (colour blue)- highly alloyed carbides - mainly used for machining steels.

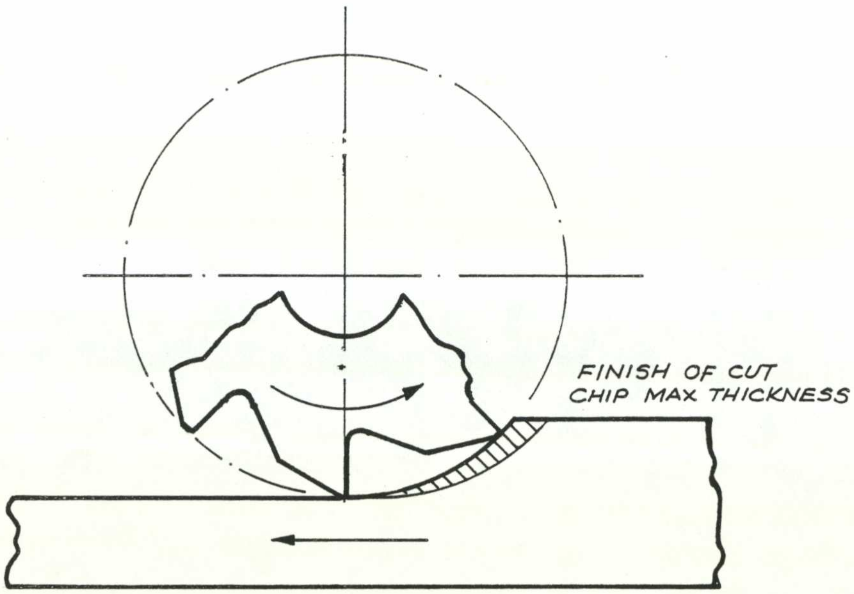
M grades (colour yellow) - moderately alloyed carbides - used for general purpose machining.

Each grade within a group is given a number between 01 and 50 ranging from maximum hardness to maximum toughness.

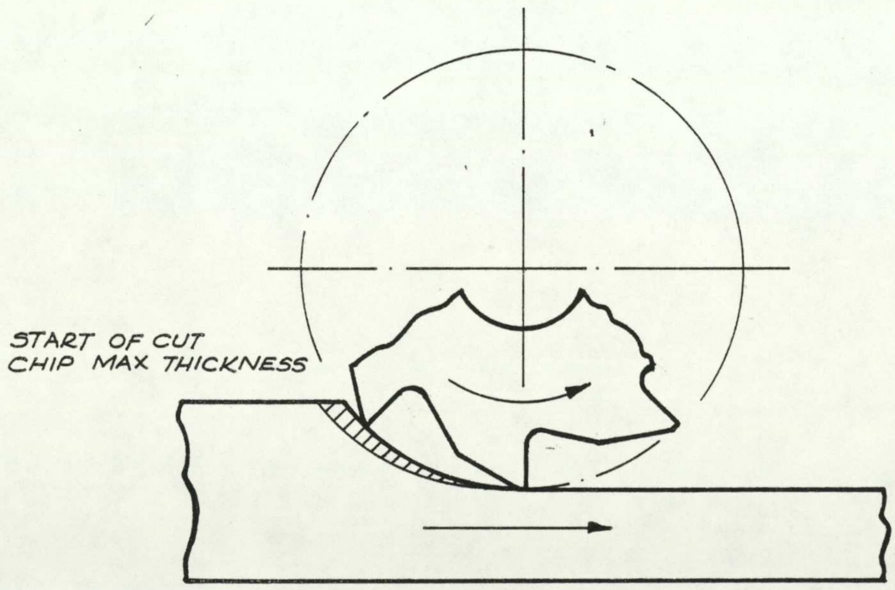
The suitability of a carbide for a certain application is that considered by the manufacturer so that a specific grade (say P 20) by one manufacturer may have a totally different composition to that offered by a second manufacturer. Also carbides having similar compositions may be listed under different gradings by different manufacturers.

2.5.2. BHMA System

The British Hardmetal Association introduced its own system because of the inconsistencies of the ISO system. The BHMA system is based on measurable parameters - abrasion, shock and cratering. Abrasiom resistance is measured by hardness tests. Transverse rupture strength is used to measure toughness and crater resistance is measured in terms of the volume of crater resistant carbides present in the tool. Each property is classified in the above order from 0 to 9, the higher the number the higher the measured value.

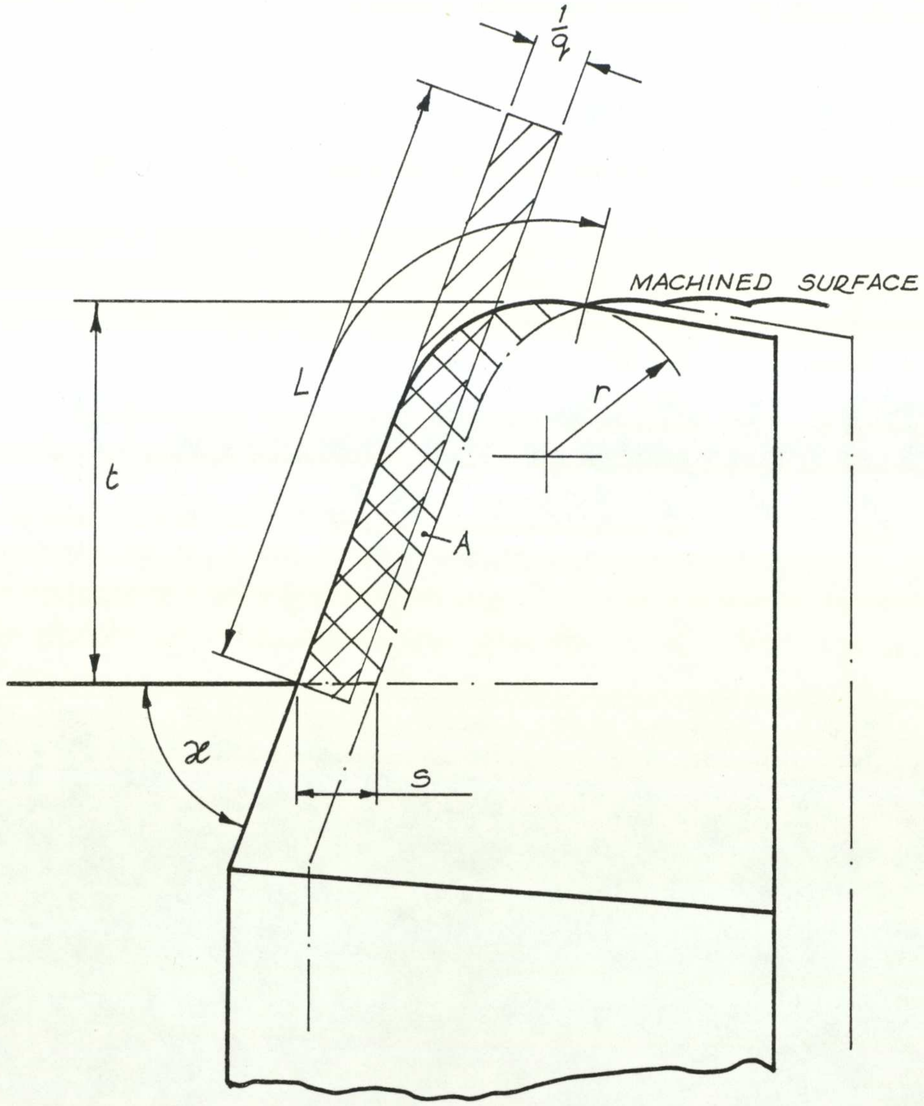


(a) UP-CUT MILLING



(b) DOWN-CUT MILLING

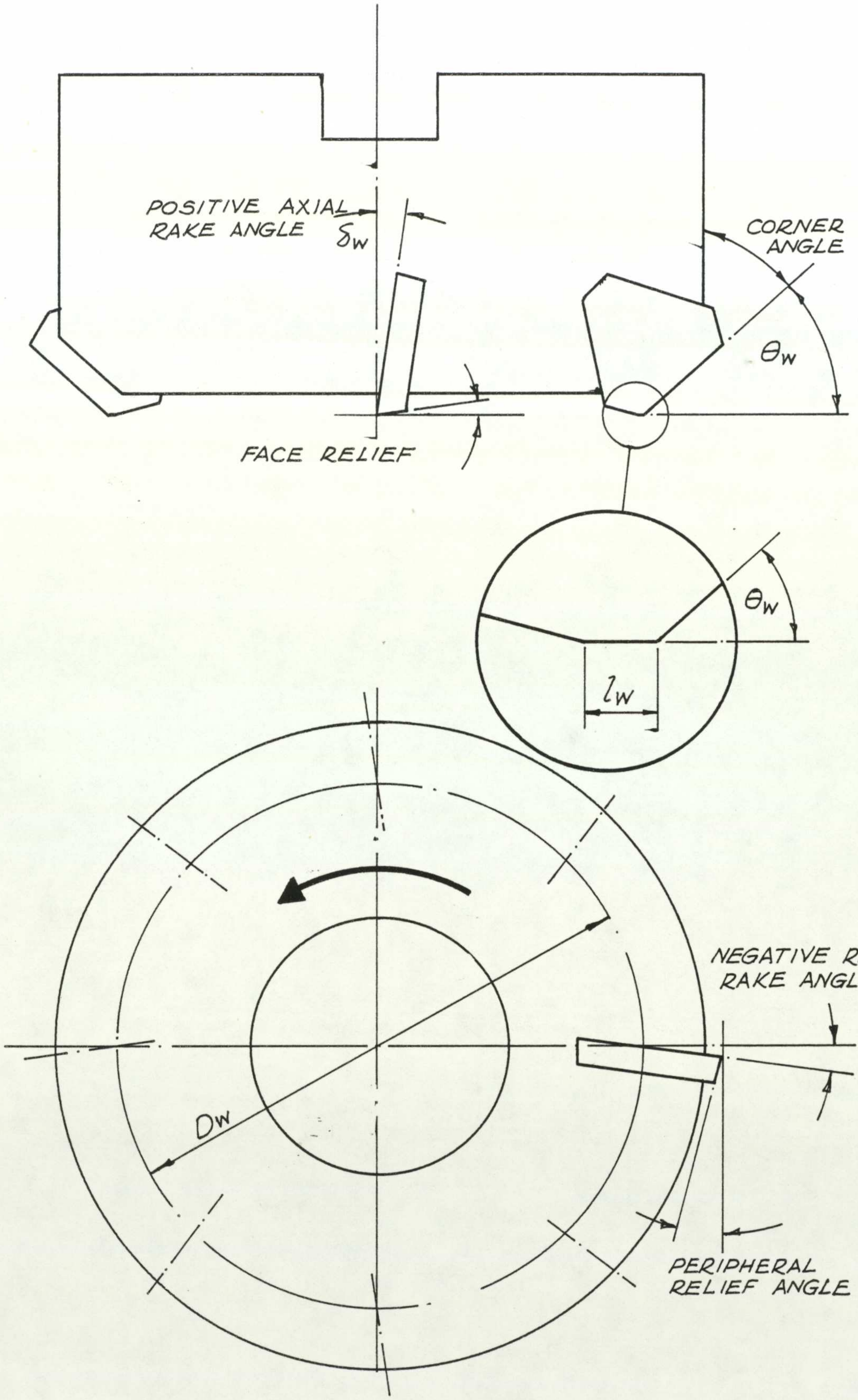
FIG 2.1 UP-CUT & DOWN-CUT MILLING



A = CHIP CROSS SECTIONAL AREA mm^2
L = CUTTING EDGE LENGTH mm
r = NOSE RADIUS mm
S = FEED PER REV OF W/PIECE mm
t = DEPTH OF CUT mm
$\varkappa$ = SIDE CUTTING EDGE ANGLE
$q = \frac{L}{A}$ mm^{-1}

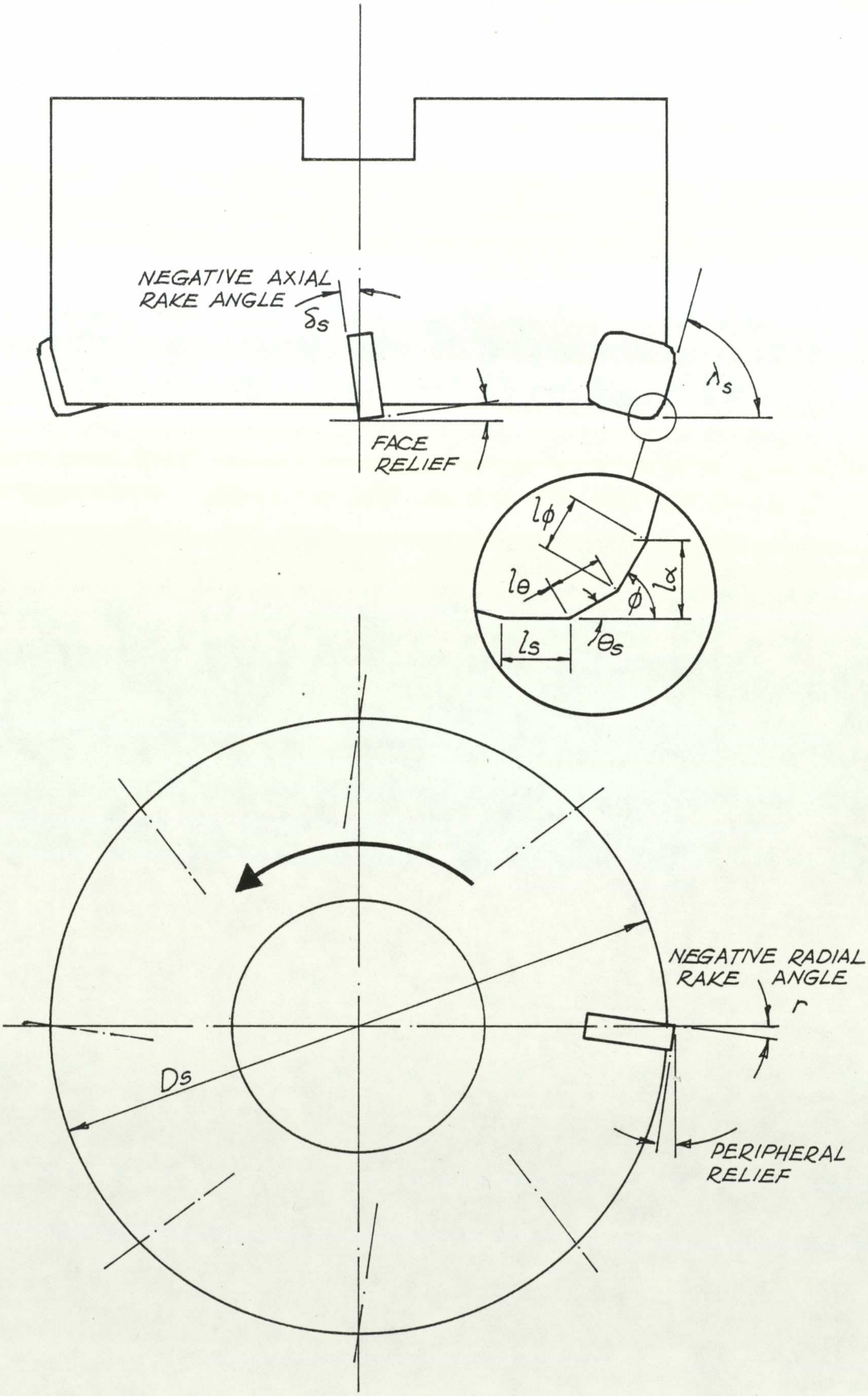
$$q \cong \frac{\frac{t - r(1-\cos\varkappa)}{\sin\varkappa} + \frac{\varkappa}{180}\pi r + \frac{s}{2}}{t \times s} \ mm^{-1}$$

FIG. 2.2 CHIP EQUIVALENT



WENDELNOVEX F244 WALTER FACE MILL

FIG. 2.3



T-MAX 265.1 SANDVIK FACE MILL

FIG. 2.4

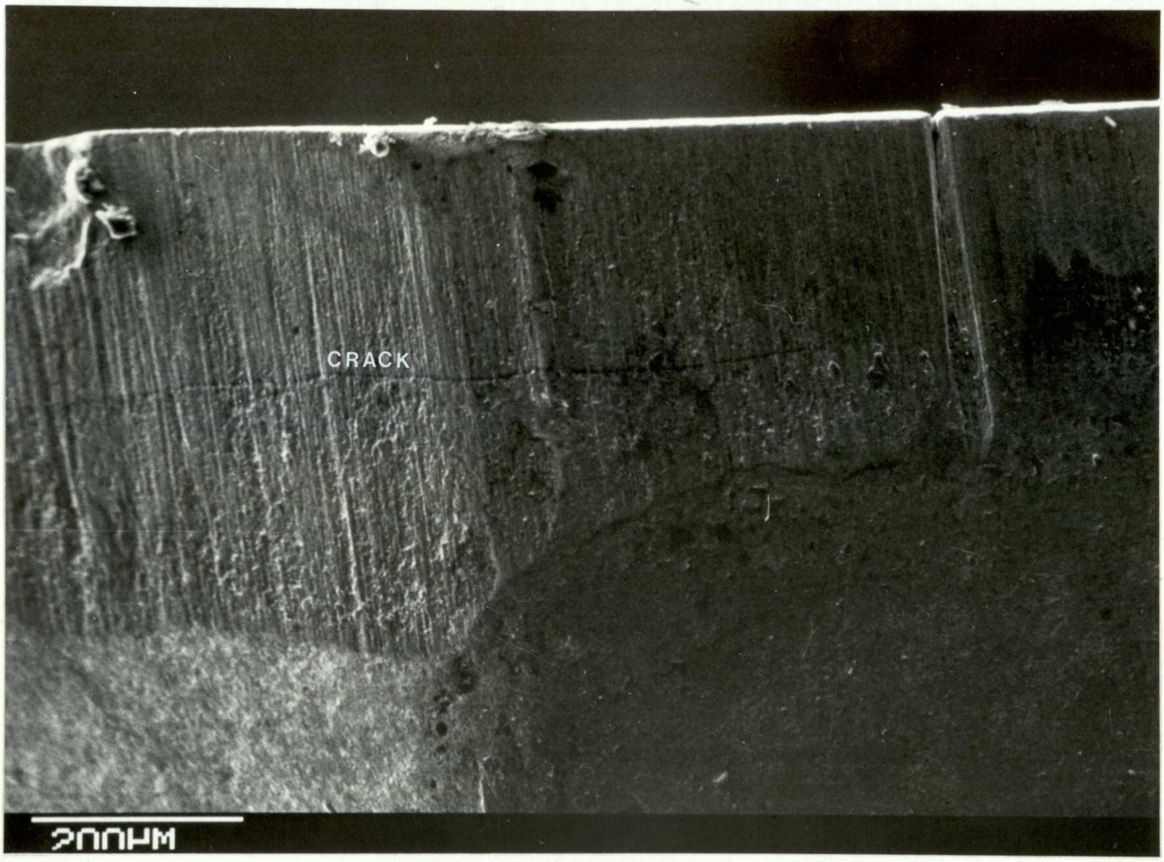


FIG 2.5 MECHANICAL CRACK

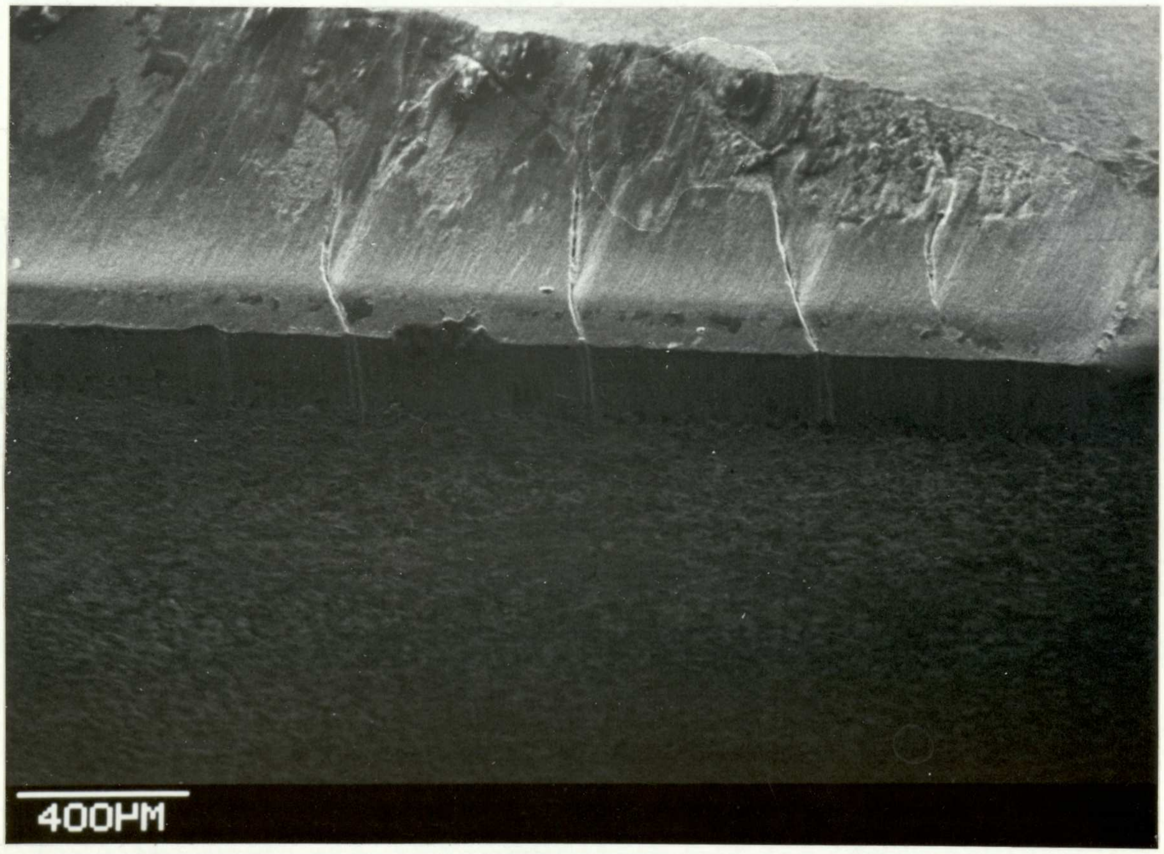


FIG 2.6 THERMAL CRACKS

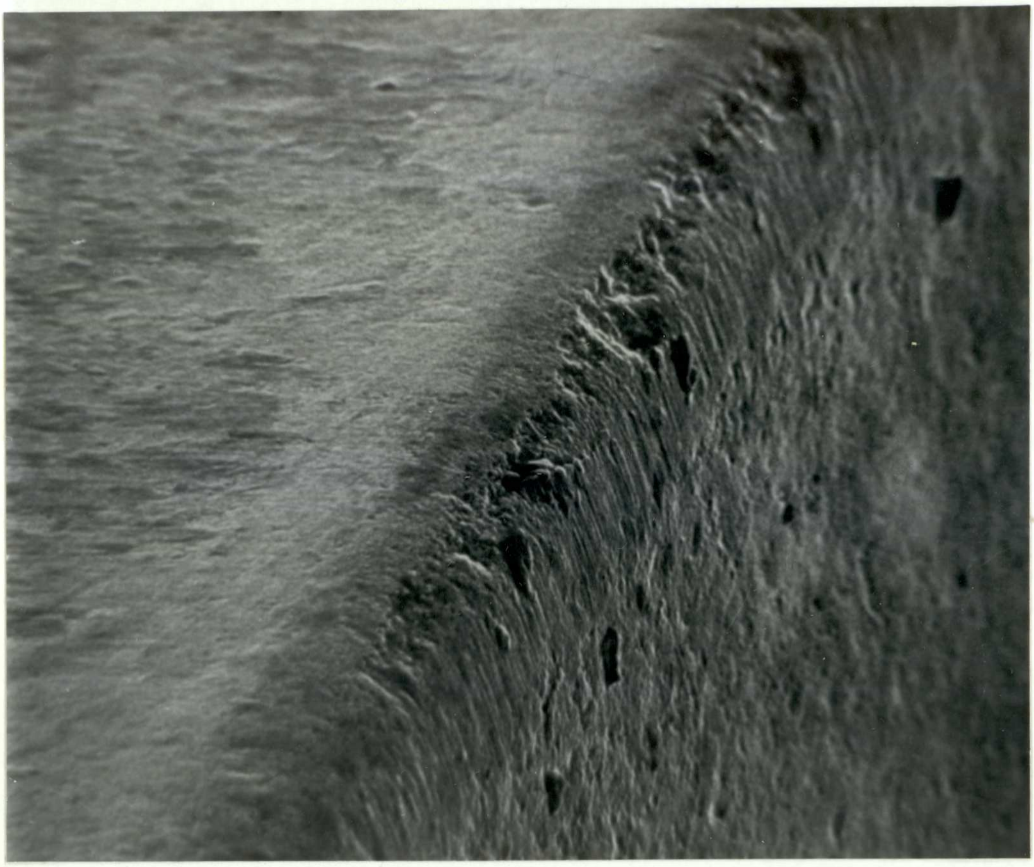


FIG 2.7 CHIPPING OF CUTTING EDGE

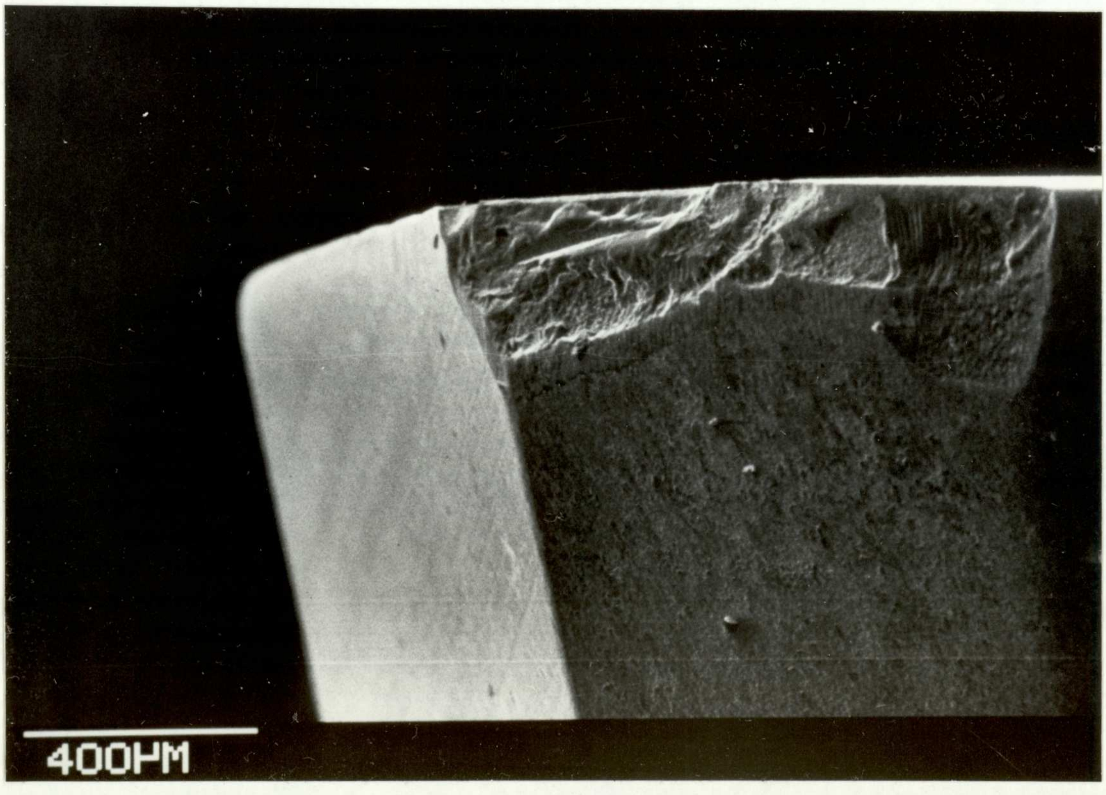


FIG 2.8 BREAKAGE OF CUTTING EDGE

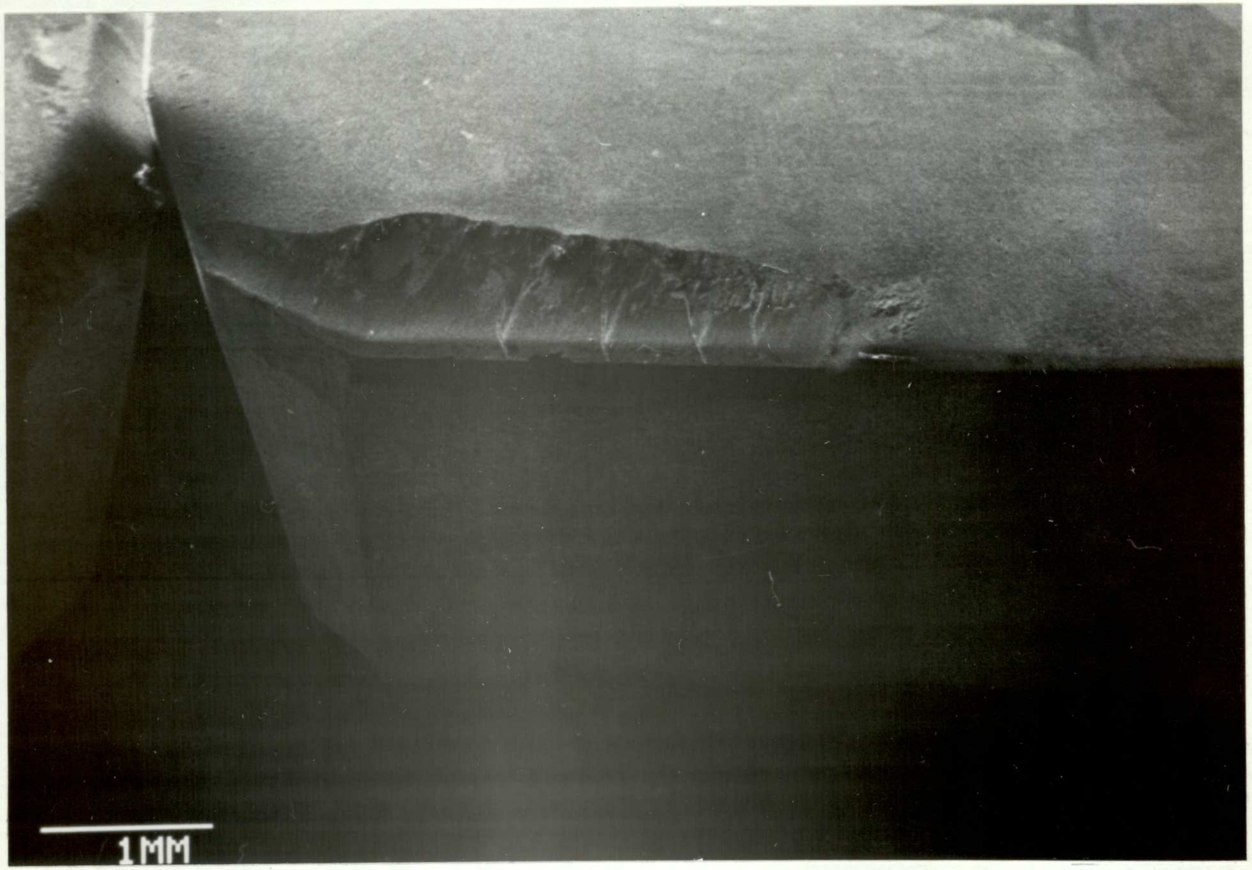


FIG 2.9 CRATERING - PLUS THERMAL CRACKS

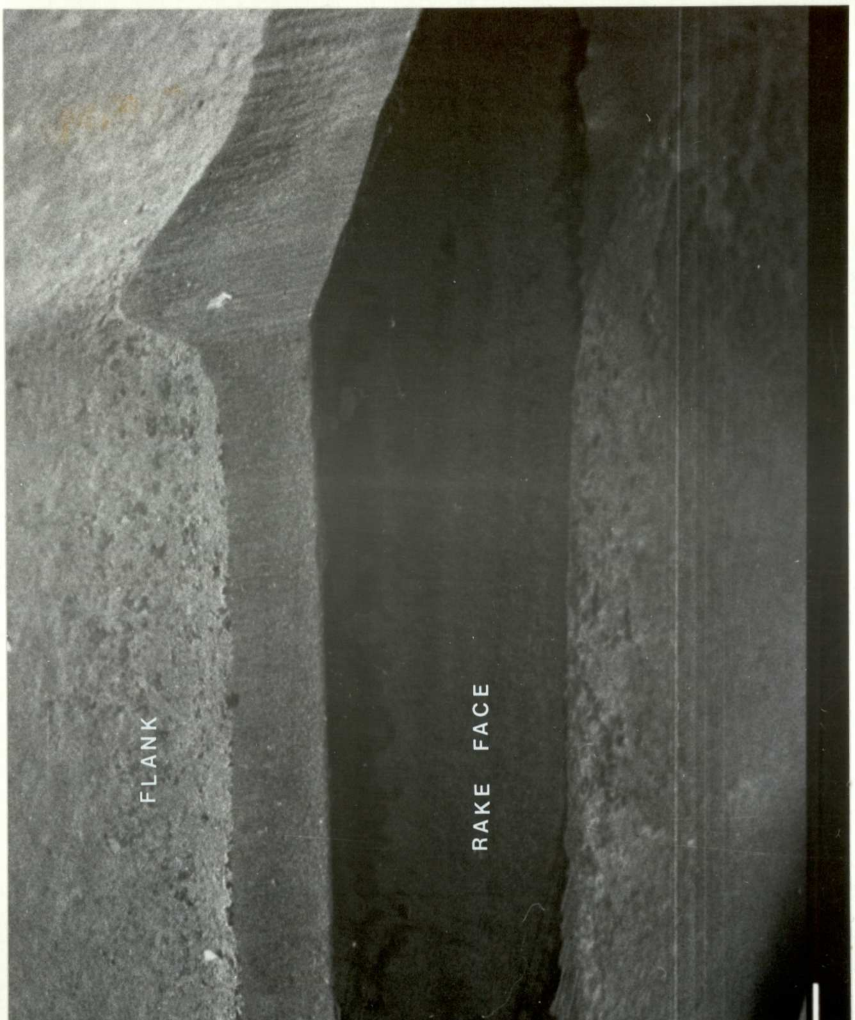


FIG 2.10 FLANK WEAR - (INSERT INVERTED)

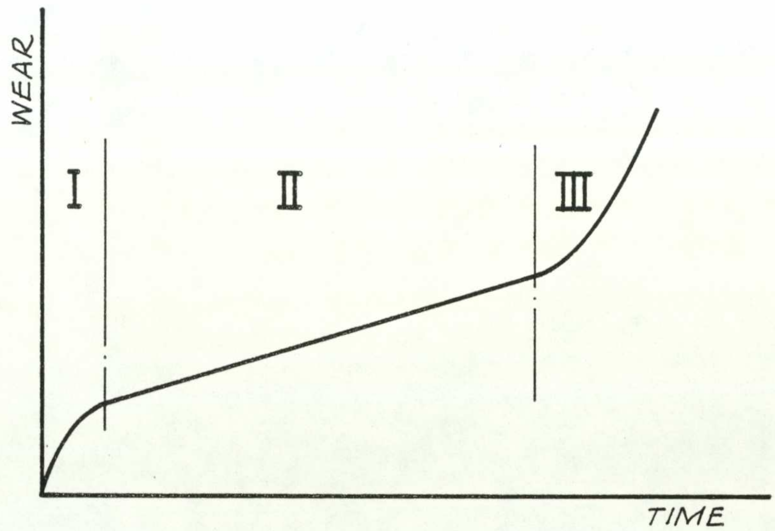


FIG 2.11 WEAR / TIME CURVE

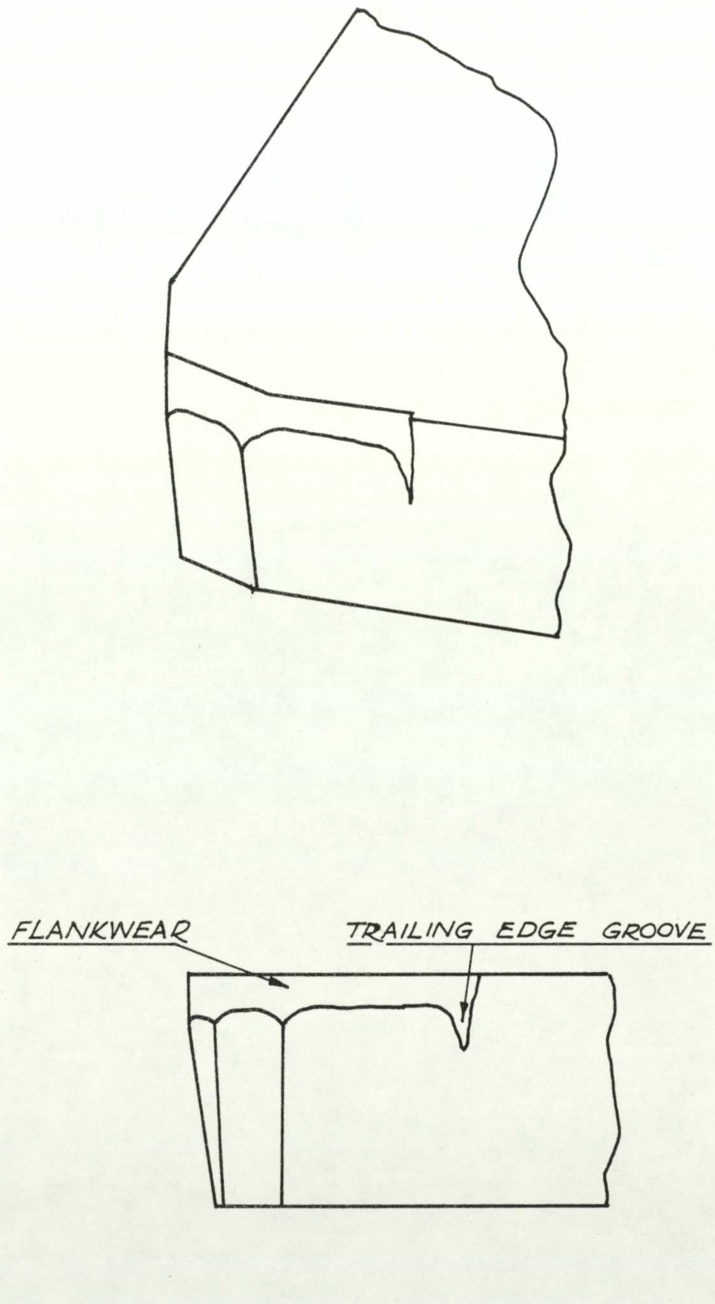
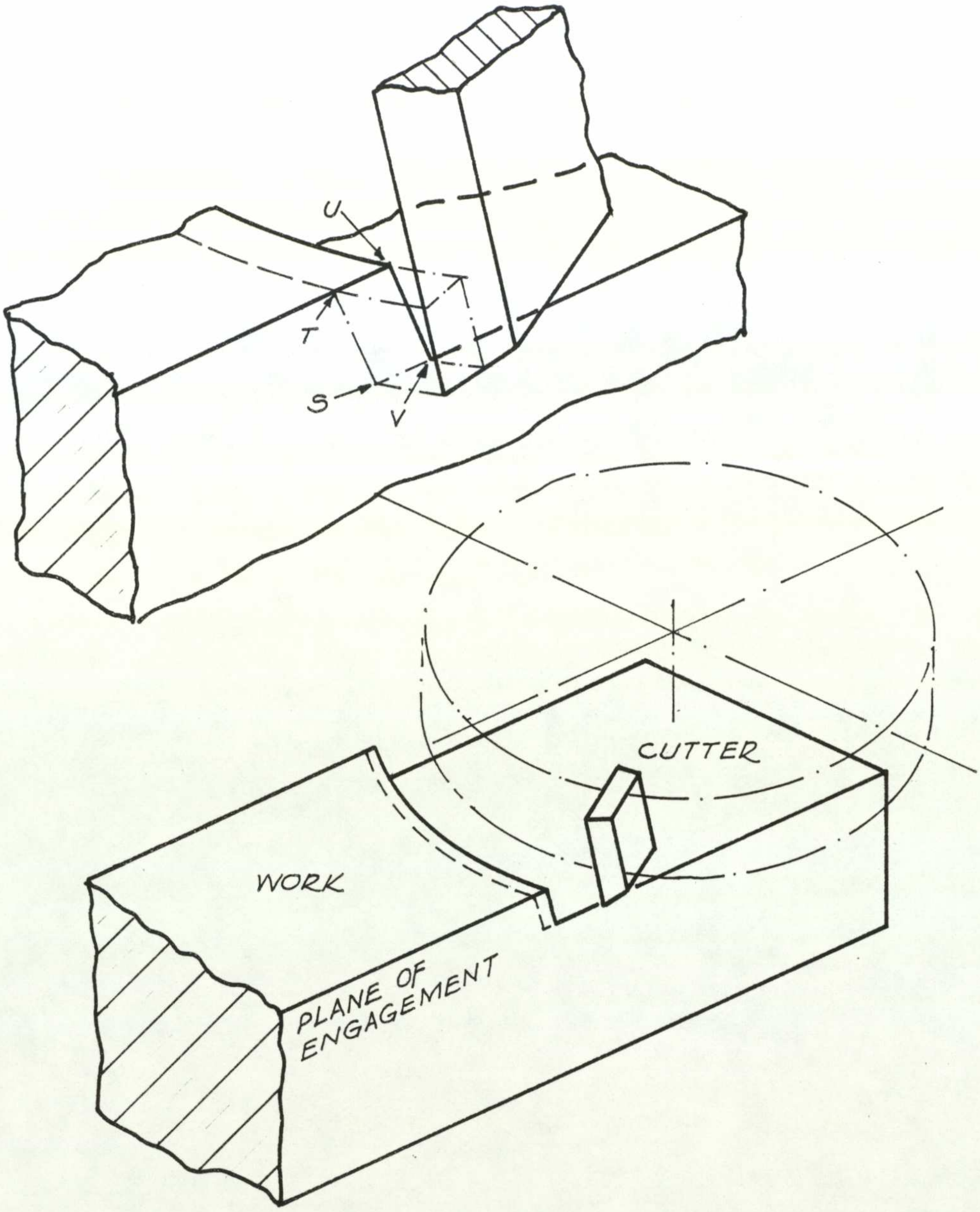
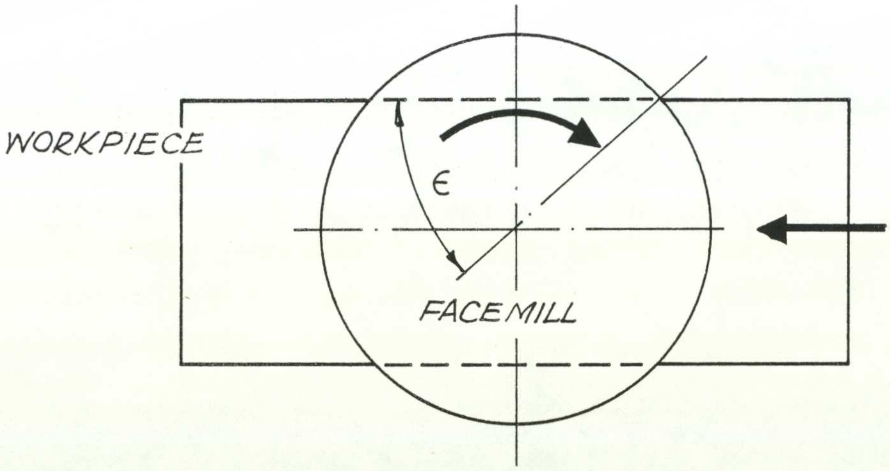


FIG 2.12 TRAILING EDGE GROOVE (POSITIVE INSERT)

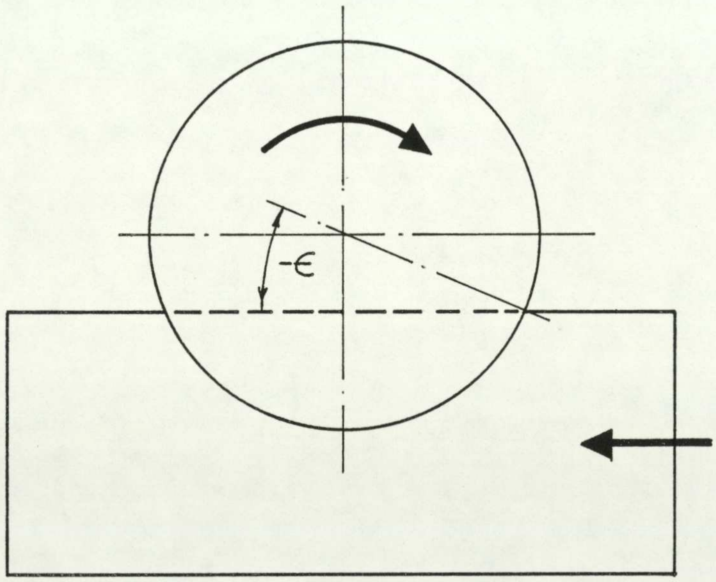


DIAGRAMMATIC VIEW OF CUTTER & WORK
SHORTLY BEFORE INITIAL CONTACT

FIG 2.13

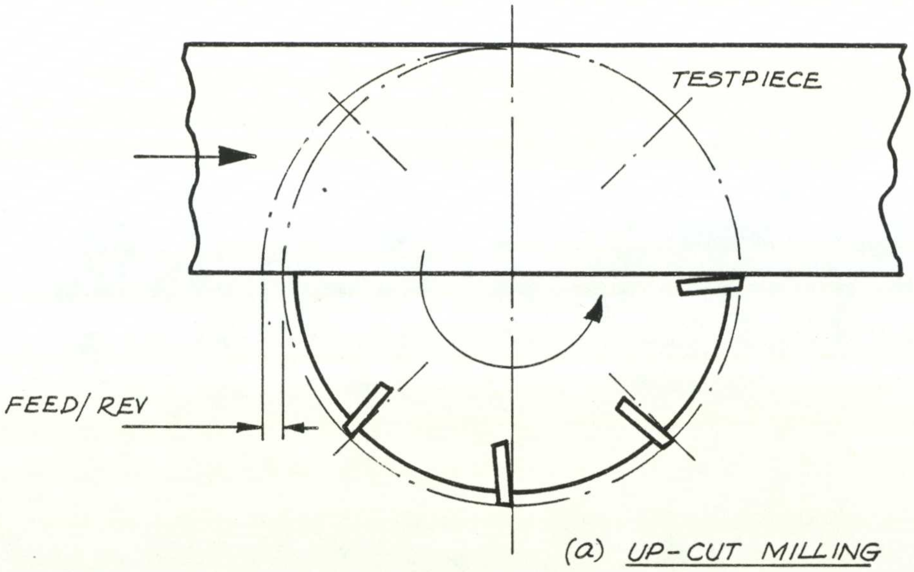


POSITIVE ENTRY ANGLE

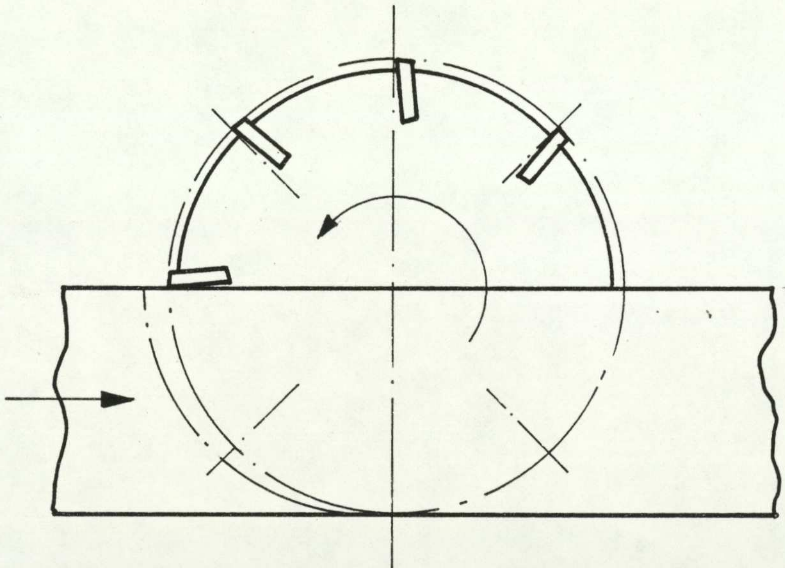


NEGATIVE ENTRY ANGLE

FIG 2.14 ENTRY ANGLES FOR FACEMILLS



(a) UP-CUT MILLING



(b) DOWN-CUT MILLING

FIG 2.15 UP-CUT & DOWN-CUT MILLING
AS SET FOR CUTTING TESTS

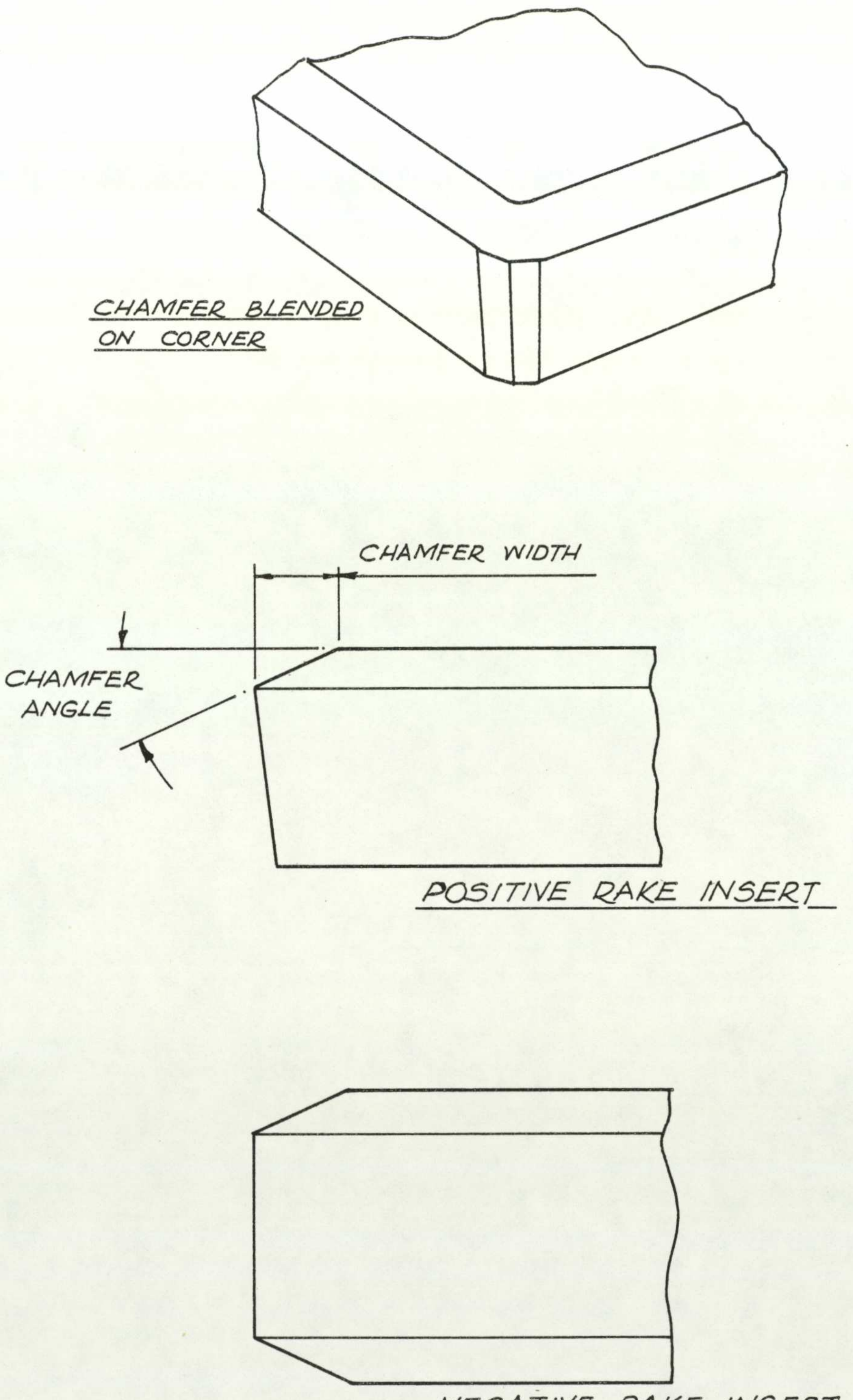


FIG 2.16 DETAILS OF CHAMFER

CHAPTER 3

EXPERIMENTAL EQUIPMENT

CHAPTER 3: EXPERIMENTAL EQUIPMENT

3.1 THE MACHINE TOOL

All of the cutting tests were performed on a Cincinatti horizontal knee type milling machine, used for teaching purposes and research in the Department of Production Technology and Production Management. The machine had an 11 kW motor and was fitted with a flywheel to the main spindle to reduce tortional vibrations (fig 3.1). The spindle speeds were displayed on a tachometer fitted to the machine and it was noted that, when the spindle was rotating, the tachometer reading was different from that indicated on the machine speed change dial. The spindle speeds were checked using an independent tachometer, which confirmed that the fitted tachometer registered the correct speed.

The actual speeds and indicated speeds used were found to be

Indicated speed rev/min	Actual speed rev/min
357	370
445	460
550	580

The feedrates were checked by noting the distance travelled when the table traverse was engaged for a specific period of time (5 minutes for the lower feed rates and 3 minutes for the higher ones). The milling machine had Imperial scales fitted and the actual feedrates differed from those stated on the machine. The feedrates were converted from inches/min to mm/min as given below

Indicated feedrate in/min	Actual feedrate	
	in/min	mm/min
$1\frac{3}{4}$	1.76	45
$3\frac{1}{4}$	3.51	89
4	4.32	110
5	5.46	139
$6^3/_8$	6.88	175
$7\frac{3}{4}$	8.55	217

The machine was fitted with a backlash eliminator which was engaged when down-cut milling and it was released when up-cut milling.

3.2 THE TESTPIECE

The testpiece material used throughout the cutting tests was EN8 steel having the following composition

C 0.42, Si 0.2, Mn 0.9, S 0.02, P 0.03

The steel as supplied was hot rolled from one ingot to ensure as near as practicable that the composition and structure was uniform for all the testpieces. The material was in its normalized condition, the hardness was 195 BHN. All of the scale was removed by rough machining the testpieces to the following dimensions: 460 x 300 x 50 mm.

Several samples were taken from the testpieces, some in the direction of rolling and others at right angles to the rolling. These were checked for hardness and after polishing and etching they were viewed under a metallurgical microscope and photographed. Typical microstructures of the samples are shown in fig 3.2 and the inspection revealed that the structure and the hardness of the billet was uniform throughout.

The testpieces were drilled for holding purposes as described in Section 4.1 and shown in fig 4.10.

3.3 THE CUTTERS

Two cutters were selected, one having a positive rake and the other a negative rake. The cutters were standard Sandvik T-Max Facemills

No. R265.1 - 100M

and No. R265.2 - 100M,

having an entering angle of 75° and a nominal diameter of 100 mm, figs 3.3 and 3.4.

The facemills were mounted on stub arbors and secured in the main spindle of the milling machine by means of a drawbar, the cutters were used in the horizontal position.

The facemills had the capacity to accept eight $\frac{1}{2}$ inch (12 mm nominal) square indexable inserts.

Using these cutters meant that the cutting speeds when rotating at the spindle speeds previously determined (Section 3.1) were

Spindle Speed rev/min	Cutting Speed m/min
370	116
460	145
580	182

3.4 THE INSERTS

The inserts selected for the cutting tests were

negative inserts SNKN 1204 ENR grade SM (P25)

positive inserts SPKN 1203 EDR grade SM (P25)

being standard uncoated tungsten carbide inserts readily available from the suppliers and of a grade suitable for machining a medium carbon steel such as EN8 (see Section 2.5.1).

When setting indexable inserts into face milling cutters it is extremely difficult and time consuming to try and ensure that each insert cuts a similar amount of testpiece material as do all of the others. Ber & Feldman[50] state that it was not possible for all of the inserts in a face milling cutter to participate equally in the cutting process. They concluded that the inserts wore unevenly due to the "throw" in the radial and axial directions. The throw was due to a set of independent variables such as the manufacturing tolerance on the cutter body and inserts and the run out of the machine spindle.

Martellotti[8] analysed the surface of a workpiece produced by slab milling (fig 3.5) and observed tooth marks which corresponded to the tooth frequency and periodic variations having a wavy appearance, the frequency of the waves being equal to the frequency of rotation of the cutter. The amplitude of the wave was a function of the eccentricity of the cutter.

Often in industrial applications the problem of unequal participation by indexable inserts is ignored and the inserts are simply loaded into the facemill using reasonable care. If however it is necessary to set the inserts as concentrically as possible they are mounted in the cutter and checked away from the milling machine. Standard inspection instruments are used to check the position of each insert relative to the back of the cutter. Once the cutter is mounted in the machine the datum is changed from the back of the cutter to the bore, the usual mounting being a stub arbor, therefore the concentricity of the inserts could no longer be guaranteed.

During service the inserts in the cutter may wear at different rates due to different work loads imposed on the inserts. If a study of tool wear is to be made using a cutter containing a number of inserts the wear on all of them must be established and then averaged to obtain a representative value for cutter wear.

In addition to the protracted procedure of wear measurement a further problem is the large quantity of material being machined away if cutting tests are to be carried out.

To reduce the costs of test-piece material and inserts and to reduce the time taken to set the cutter and measure the cutter wear, one insert at a time was used throughout this research. The method is not a new concept when studying tool wear during milling, Kuljanic[51,52], Ernst & Field[53], Crawford & Merchant[54], Gilbert et al[55], Shinozaki[56] and Okushima & Hoshi[20,21,22,23,24,25] all used single cutting tools when studying milling. Crawford & Merchant state 'Only one tooth was used so that tool life results could be obtained with the least amount of stock and time'. Okushima & Hoshi used a lathe tool as a fly-cutter into which is mechanically clamped a single insert. The fly-cutter can be adjusted to produce a variable diameter cutter.

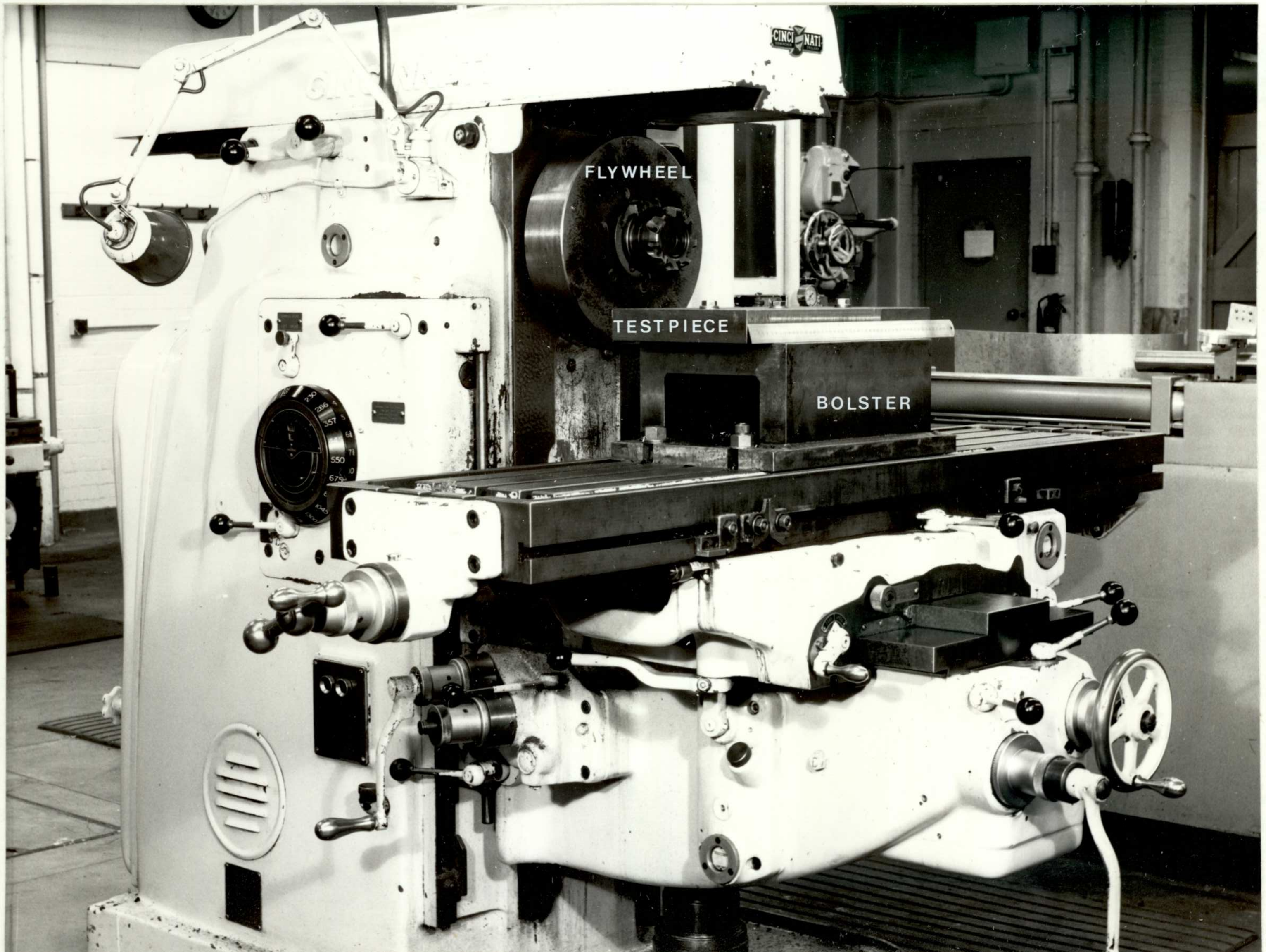


FIG 3.1 GENERAL VIEW OF MILLING MACHINE

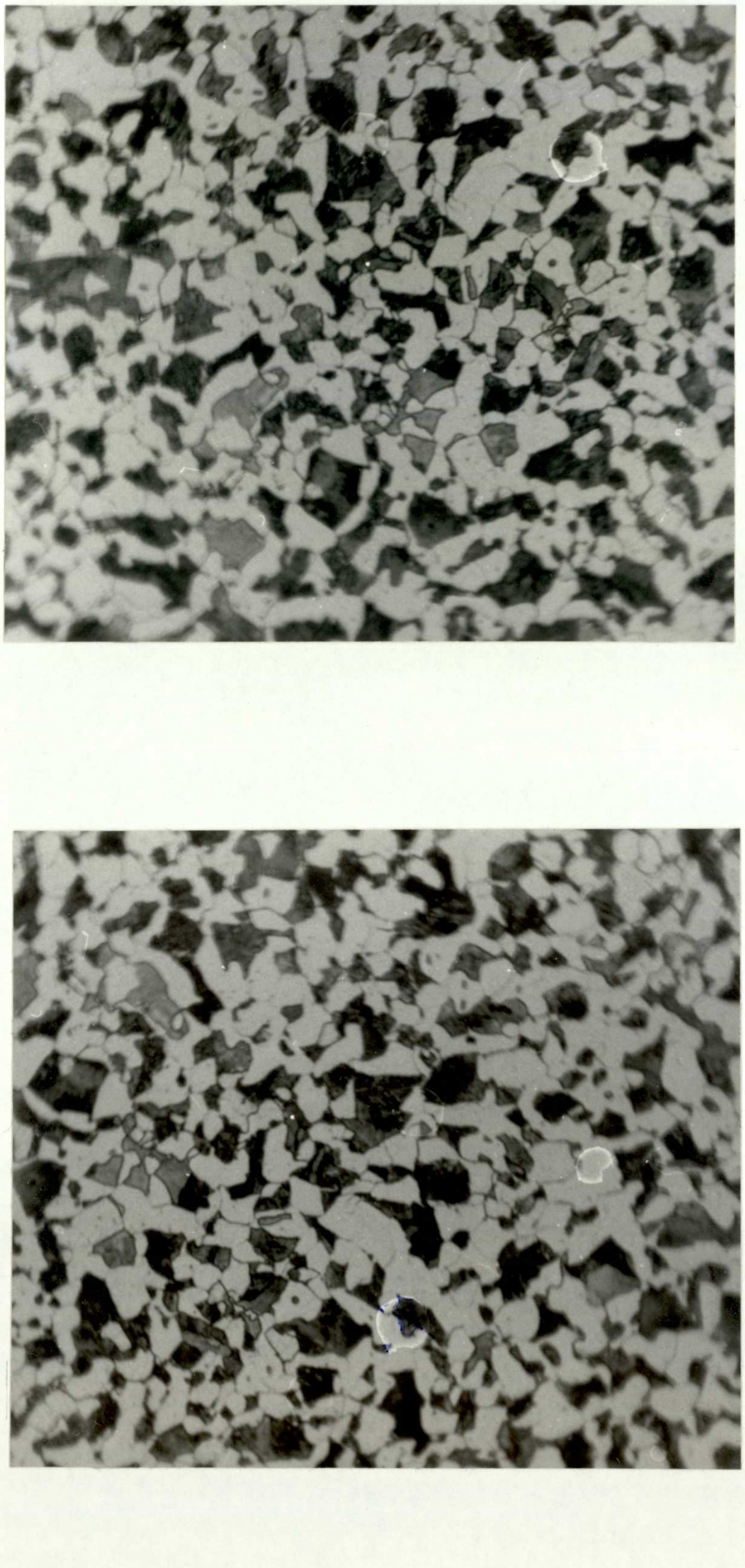


FIG 3.2 TYPICAL MICROSTRUCTURES OF TESTPIECES

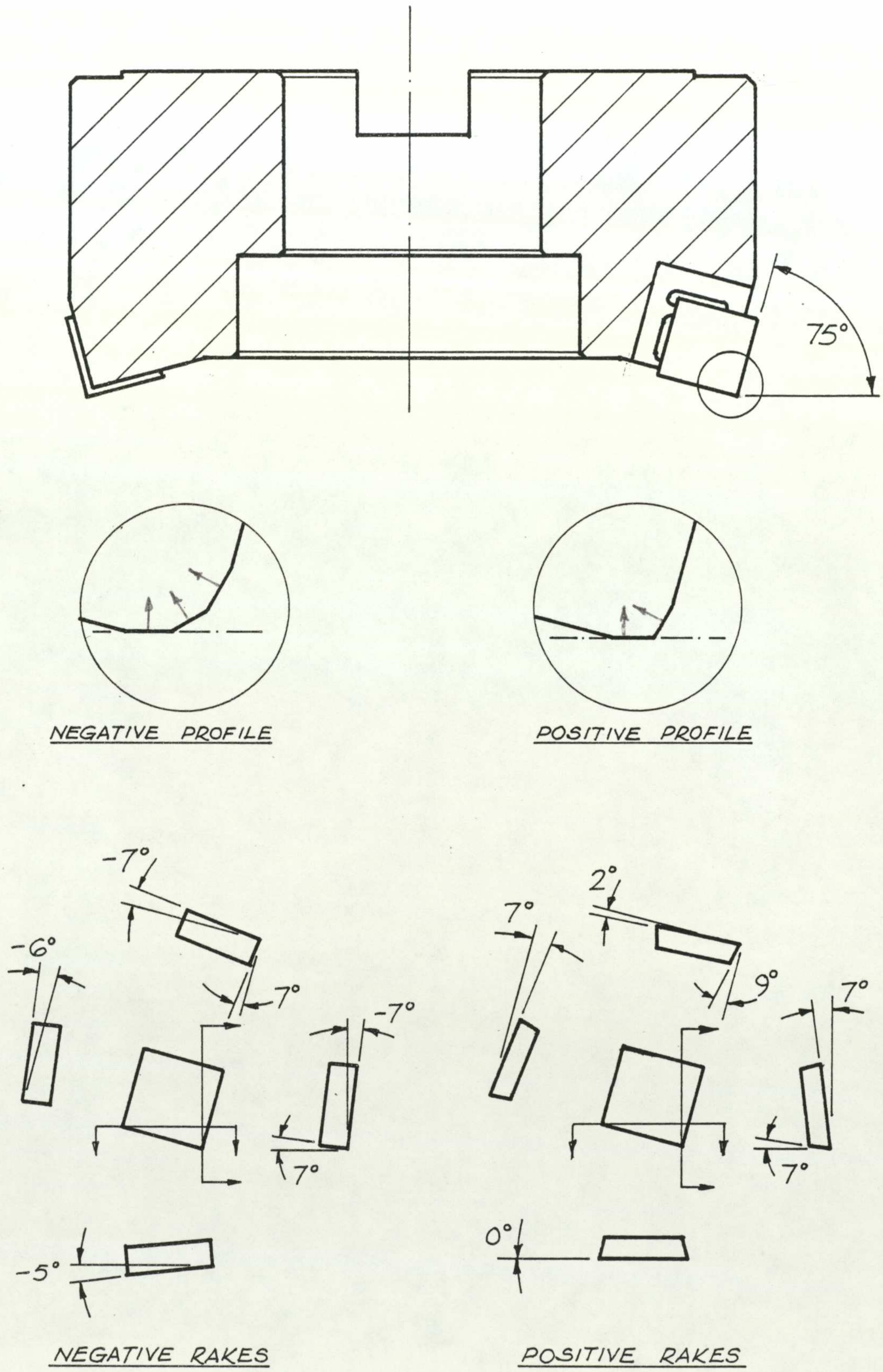


FIG 3.3 DETAILS OF FACE MILLING CUTTERS

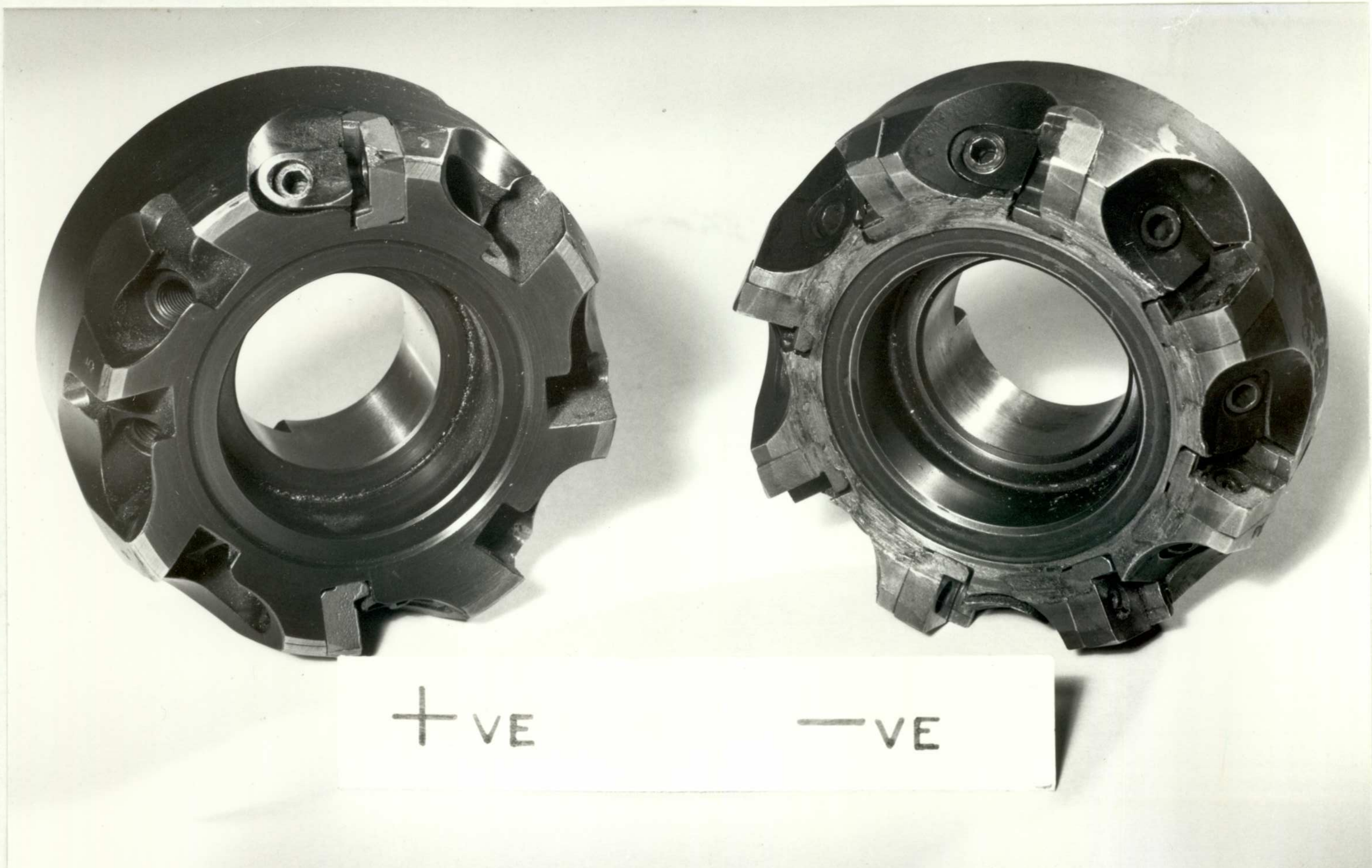
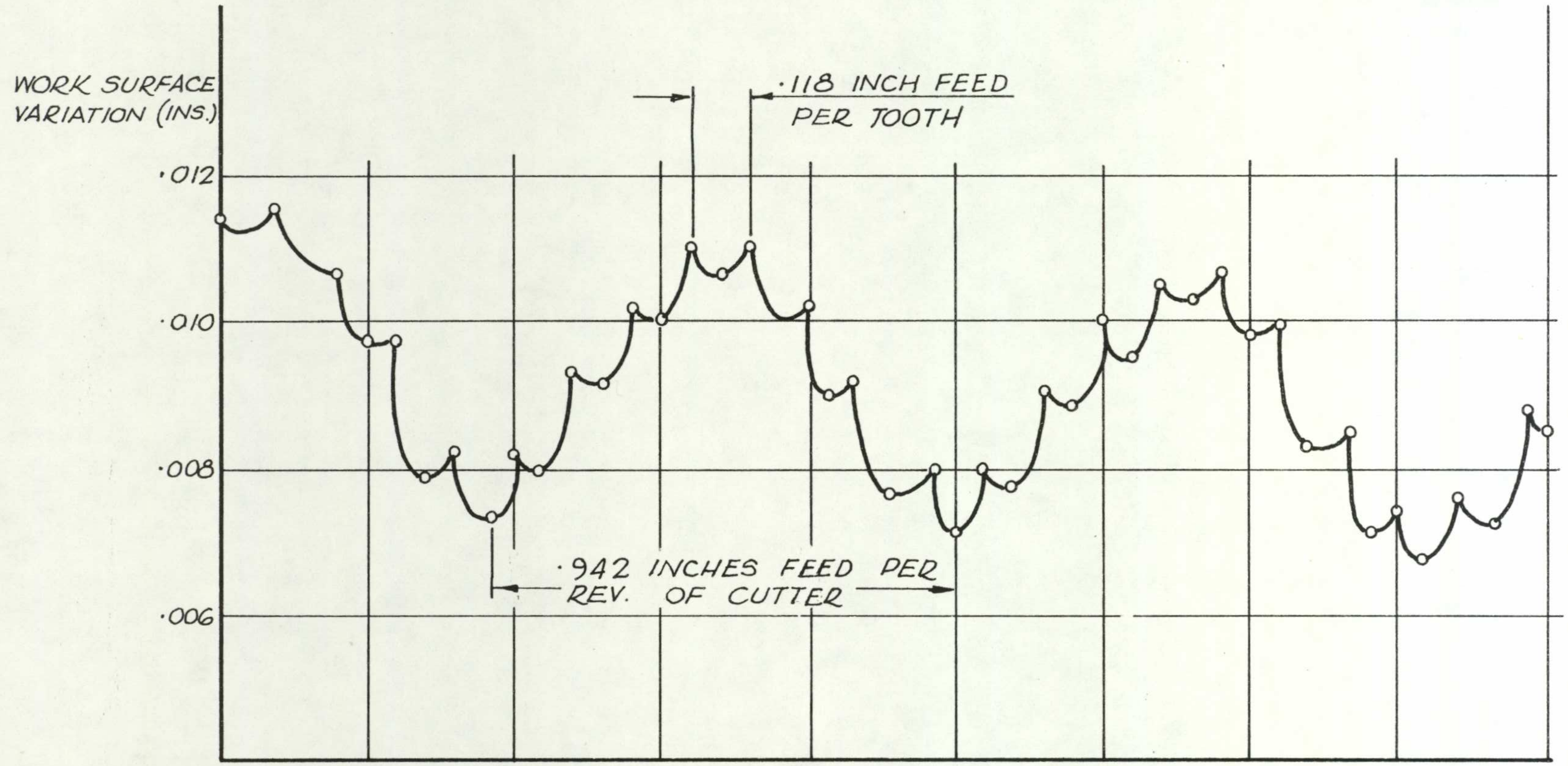


FIG 3.4 POSITIVE & NEGATIVE RAKE FACEMILLS



VARIATIONS PRODUCED BY TOOTH AND REVOLUTION MARKS ON A MILLED SURFACE (AFTER MARTELLOTTI)

FIG 3.5

CHAPTER 4

PRELIMINARY CUTTING TESTS

CHAPTER 4: PRELIMINARY CUTTING TESTS

4.1 CUTTING TESTS USING STANDARD INSERTS

A series of cutting tests were performed using positive inserts and negative inserts for both up-cut and down-cut milling, varying the cutting speed and feedrates.

The principal objects of these initial tests were

i) to ensure that the amount of overhang of the workpiece from its sub-bolster when being machined did not affect the tool life of the insert.

ii) to establish the procedure for measuring the flank wear on the cutting tool.

iii) to confirm that the flank wear on the cutting tool followed the classical wear pattern (fig 2.11).

iv) to select suitable speeds and feedrates for the main cutting tests

A negative rake face milling cutter was mounted directly into the main spindle and retained by means of a draw-bar, thus the cutter was used in the horizontal position. One insert only was mounted in the cutter (see Section 3.4).

The milling machine had a flywheel fitted as an integral part of the main spindle to reduce the effects of torsional vibration. The flywheel prevented the table from being raised high enough to enable the cutter to machine the testpiece when it was bolted directly onto the table. To overcome this a sub-bolster was used (fig 4.1) which raised the workpiece 180 mm above the table.

The testpiece was clamped onto the sub-bolster allowing 4 mm to overhang and a cut of 3 mm was taken using a spindle speed of 370 rev/min and a feedrate of 89 mm/min. The cutting speed and feedrate were selected by making reference to the insert manufacturer's handbook. Using a single insert in the cutter meant that the feed per tooth was 89/370 = 0.24 mm. The cutter was positioned relative to the test piece to produce down-cut milling, (fig 4.2) the entry angle being zero. This was achieved by removing the cutter from its stub arbor which was then used as a setting bar. The table and testpiece were raised under the arbor and using the top face of the testpiece as a datum it was set relative to the arbor by means of a slip gauge. The testpiece was then wound clear of the arbor and the table was raised through a height equal to the radius of the arbor (20 mm) plus the thickness of the slip gauge (see fig 4.3). When up-cut milling was required the table was raised an additional height equal to the thickness of the testpiece. This brought the centre of the cutter in line with the bottom edge of the testpiece and produced an entry angle of 90^{o} (fig 4.3). These standards were maintained for all of the wear tests.

After one cut had been taken along the length of the testpiece the single insert was removed from the cutter and placed into a fixture on the table of a Watts Engineers Microscope. The fixture held the rake face of the insert perpendicular to the table of the microscope and parallel to the axis of one of the micrometers. The flankwear was measured at a position 1 mm from the corner of the insert (fig 4.4) to ensure that future measurements would be taken at the same position. This safeguard was to prevent any possible problems associated with obtaining false values due to uneven flank wear.

Having noted the flankwear the insert was returned to the cutter and the testpiece repositioned to allow 4 mm to project from the sub-bolster. This dimension was checked using a rule but the previously machined surface of the testpiece was aligned with the table traverse by means of a dial test indicator, thus ensuring that the next cut would be of constant depth. A second cut of 3 mm depth was taken and the flankwear determined.

The above procedure was repeated using constant cutting conditions until a flank wear of at least 250μm had been obtained.

The whole process was repeated with the testpiece overhanging the sub-bolster by a constant 50 mm and the other cutting conditions being maintained. Further tests were carried out using different speeds and feeds with the testpiece projecting 4 mm and 50 mm but maintaining a cutting depth of 3 mm. The results are shown graphically in figs 4.5 to 4.7.

The table was raised as described earlier to enable the cutter to be used in the up-cut milling mode and the rotation of the cutter and the direction of the table traverse was maintained so that although up-cut milling the cutting forces were acting downwards. The entry angle was then 90°, the cutting speed was 116 m/min, the feedrate 0.24 mm/tooth and the procedure of taking cuts and measuring flank wear was repeated until a flank wear of 250μm was obtained for both 4 mm and 50 mm workpiece projection.

The data obtained from the above tests was compared and it was concluded that there was no significant difference between 4 mm and 50 mm projection of the testpiece (figs 4.8 and 4.9). All future cutting tests were carried out with the testpieces drilled as shown in fig 4.10 and bolted to the sub-bolster, permitting 50 mm to project from the sub-bolster. An initial cut was taken to align the surface with the table traverse using an insert reserved for that purpose and after 16 test cuts of 3 mm depth the test piece was advanced 2 inches (50.8 mm) and the face realigned by taking a light cut along its length.

A more comprehensive series of cutting tests were taken varying speeds and feeds using up-cut and down-cut milling and positive rake and negative rake inserts. The results are shown in tabular form in Appendix I and graphically in figs 4.11 to 4.25.

In order to assess the flankwear taking place, positive rake and negative rake inserts were used to machine a testpiece, each insert being used for a different period of time. All of these cutting tests were carried out using down-cut milling, at 145 m/min (460 rev/min), a feedrate of 0.38 mm/tooth and a depth of cut of 3 mm. The machining times used for each set of positive and negative inserts were 10, 30 and 60 sec. and an extended test of 5 mins.

After each cutting test the inserts were cleaned and mounted for viewing in a scanning electron microscope. The photographs obtained from the microscope are shown in figs. 4.36 to 4.45.

It is evident from figs 4.36 and 4.40 that there are clear signs of flankwear after only 10 seconds machining time, confirming that the original cutting edge is rapidly changed. The positive rake insert used for machining for 5 minutes (fig 4.43) showed signs of a thermal crack, this was enlarged and can be seen in figs 4.44 and 4.45.

4.1.1 Conclusions

The conclusions drawn from this series of tests were

1. The amount of projection of the testpiece from the sub-bolster, upto 50 mm, did not affect the

performance of the insert (figs 4.5 to 4.9). All subsequent cutting tests were carried out with the testpiece projecting 50 mm initially and after about 16 cutting tests, of 3 mm depth, it was reset at 50 mm projection.

2. When attempting to facemill in the up-cut mode using positive rake inserts the cutting edge failed by breaking within a few seconds of the commencement of the cutting. This breakage occurred whatever combination of speed and feed were selected.

3. The rate of flankwear on the inserts was constant, after the initial rapid wear of the cutting edge (except as stated in 2 above). The initial wear often took place during the first pass along the testpiece and a constant wear rate was established (within the range tested) from the second cut onwards. Due to this the graphs drawn of flankwear plotted against the number of passes made by the cutter generally ignore the first points, where it is obvious that they represent the period of initial rapid wear.

4. As a result of 3 above, future cutting tests could be carried out using a flankwear less than 250μm and if needed the greater values could be extrapolated.

5. Generally positive rake inserts did not perform as efficiently as negative rake inserts, due to

the premature failure of the cutting edge. Because of this rapid failure the number of tests using positive rake inserts was reduced from those planned.

Down-cut Milling

6. When cutting with negative rake inserts the rate of flankwear reduced as the feedrate increased (for a constant cutting speed) fig 4.16. This suggests that much higher feedrates should be used in industry than are generally used. This must be considered in its true perspective and the effects on the machine tool and workpiece when using a cutter containing its maximum number of inserts. The maximum feed per tooth was obtained when cutting at 370 rev/min, using a feedrate of 217 mm/min, giving 217/370 = 0.59 mm/tooth. If this condition was adopted for a cutter containing 8 inserts (a relatively small facemill) the feedrate demanded from the machine would be 217 x 8 = 1736 mm/min. This feedrate is far in excess of that available on most commercial milling machines and is possibly requiring more power than that available from most milling machines used in industry.

7. For a constant feed/tooth it was found that the life of the inserts reduced as the cutting speed increased (fig 4.11 to 4.14). This could be expected and follows the general rule for any

cutting tool.

Up-cut Milling

8. The behaviour of the inserts was not as consistent when up-cut milling as when down-cut milling, but in general the life of the inserts reduced as the cutting speed increased, (figs 4.18 to 4.21).

9. Unlike down-cut milling it would appear that a longer cutter life could be obtained by using a small feedrate (fig 4.23). This must be considered against the volume of material removed during the life of the tool. If prolonging the tool life leads to a reduction in the volume of workpiece material removed per unit of time, it may not be as economic as more metal removal and more tools used.
Reducing the feedrate to a figure less than that used for these tests would result in the tool rubbing and the life of the tool would then be shortened.

4.2 CUTTING TESTS USING INSERTS WITH MODIFIED GEOMETRY

Positive rake and negative rake inserts were modified by grinding a chamfer on the cutting edge (fig 4.26).

The chamfer was ground by hand using a special grinding fixture (fig 4.27). A high speed motor supported in the frame was used to directly drive a diamond lap type D 6A2 SD 150 R50B. Various chamfer angles were obtained by interchanging the angle plates A and various chamfer widths were obtained by adjusting plate B to alter the gap between the two plates. The top face of the insert was held against plate A and while being supported by plate B the insert was moved slowly across the face of the diamond lap. The procedure was repeated until by adjustment of plate B the desired chamfer width was obtained. The dimension of the chamfer width was checked using a toolmakers microscope.

Chamfer angles of 10° and 30° were chosen for both the positive and negative rake inserts. The angle of 10° was considered to be a slight modification to the standard insert and the 30° angle was considered as being in the vicinity of the optimum chamfer angle as suggested by earlier researchers[60,61,62], chamfer widths of 0.25 mm and 0.5 mm were used so that the selected feedrates would be less than the chamfer for some tests and greater than the chamfer for others.

A spindle speed of 460 rev/min was used giving a cutting speed of 145 m/min and feedrates of 89 mm/min and 175 mm/min were selected giving the feed/tooth as 0.19 mm and 0.38 mm respectively.

Cuts were taken using both the up-cut and down-cut mode for positive rake and negative rake inserts.

The tables of the results are shown in Appendix II and they are shown graphically in figs 4.28 to 4.35.

The straight line graphs were obtained by the method of least-square regression.

4.2.1 Conclusions

The conclusions drawn from these tests were

1. When up-cut milling using positive rake inserts any of the modified inserts improved the tool life (see figs 4.32 and 4.33. The standard inserts failed within seconds of commencing the cut (as experienced earlier, Section 4.1), whereas all of the chamfered inserts withstood the cutting action and gave a more acceptable life.

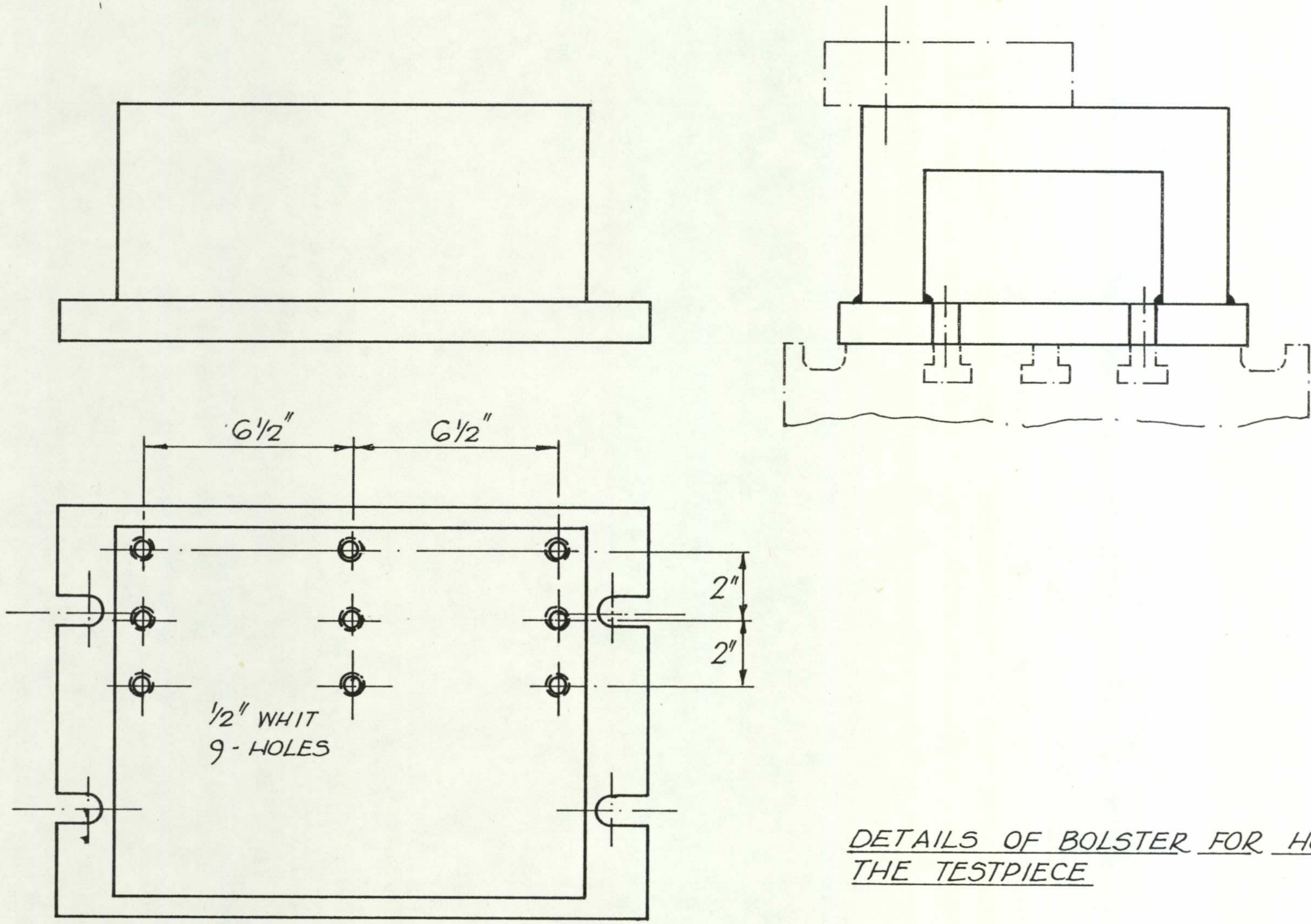
2. In each series of tests an improvement was obtained with at least one of the modified inserts

   a) Negative rake inserts (figs 4.28 to 4.31). The flankwear was generally less on the inserts having a chamfer of 10^o than that on the unchamfered inserts.

   b) Positive rake inserts (figs 4.32 to 4.35). When up-cut milling any chamfer is better than none (see above). When down-cut milling the rate of wear is less on the inserts having a 10^o chamfer than that on the unchamfered tools. The advantage being that as more passes are taken the actual flankwear will be less on the chamfered inserts than the standard ones.

3. The higher feedrate produced a longer tool life in the negative rake inserts than that obtained when using the lower feedrate (see Section 4.1.1). Little difference was noticed when using positive rake inserts.
4. Generally the improved performance was greater for the positive rake inserts than that experienced with the negative rake tools.

From the results it was not possible to state that a specific geometry was the optimum shape although the 10° chamfer appeared to produce better results than the 30° chamfer. In an attempt to clarify the situation a much more comprehensive series of tests were carried out (see Cahpter 5).



DETAILS OF BOLSTER FOR HOLDING THE TESTPIECE

FIG 4.1

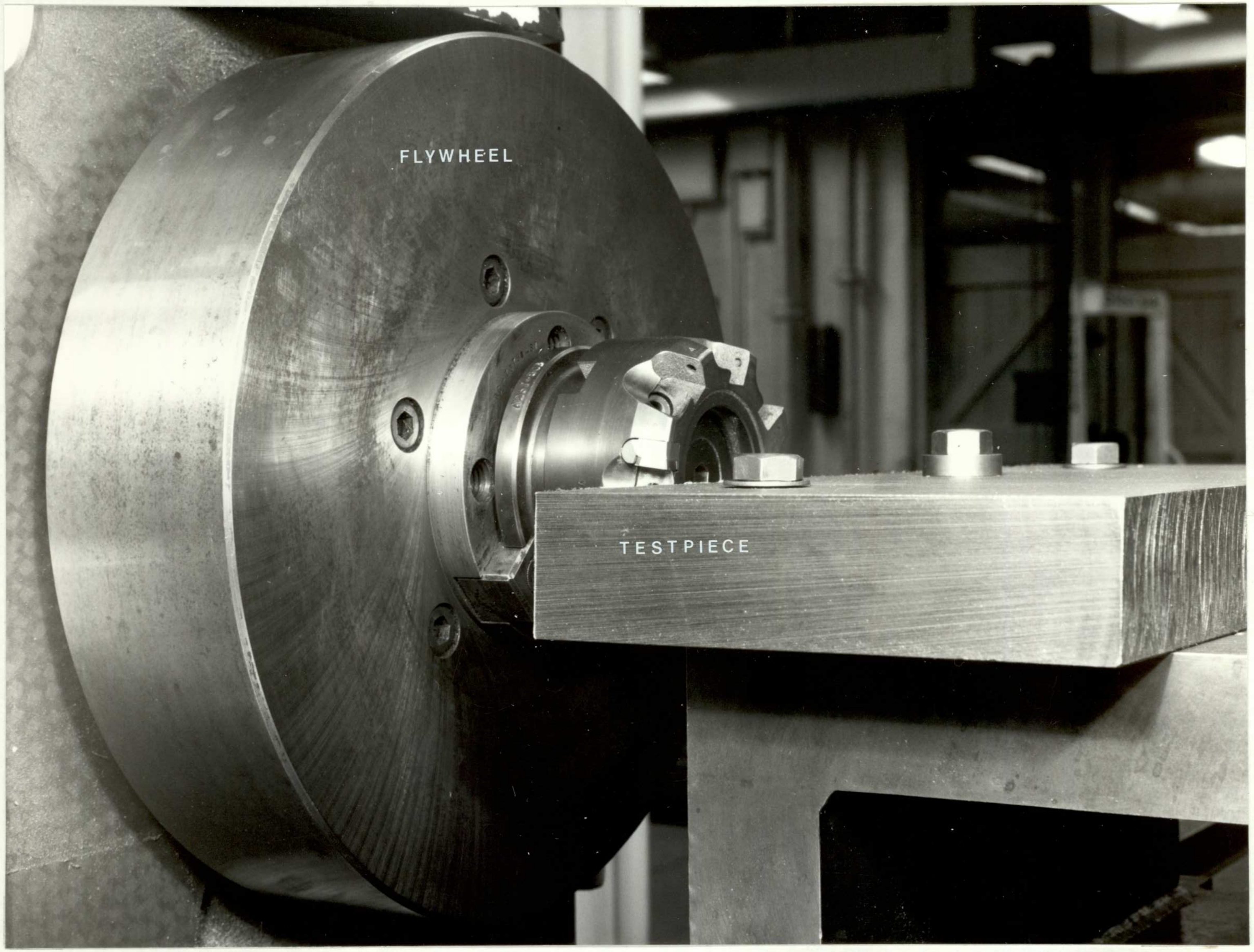


FIG 4.2 CUTTER/TESTPIECE RELATIONSHIP FOR DOWN-CUT MILLING

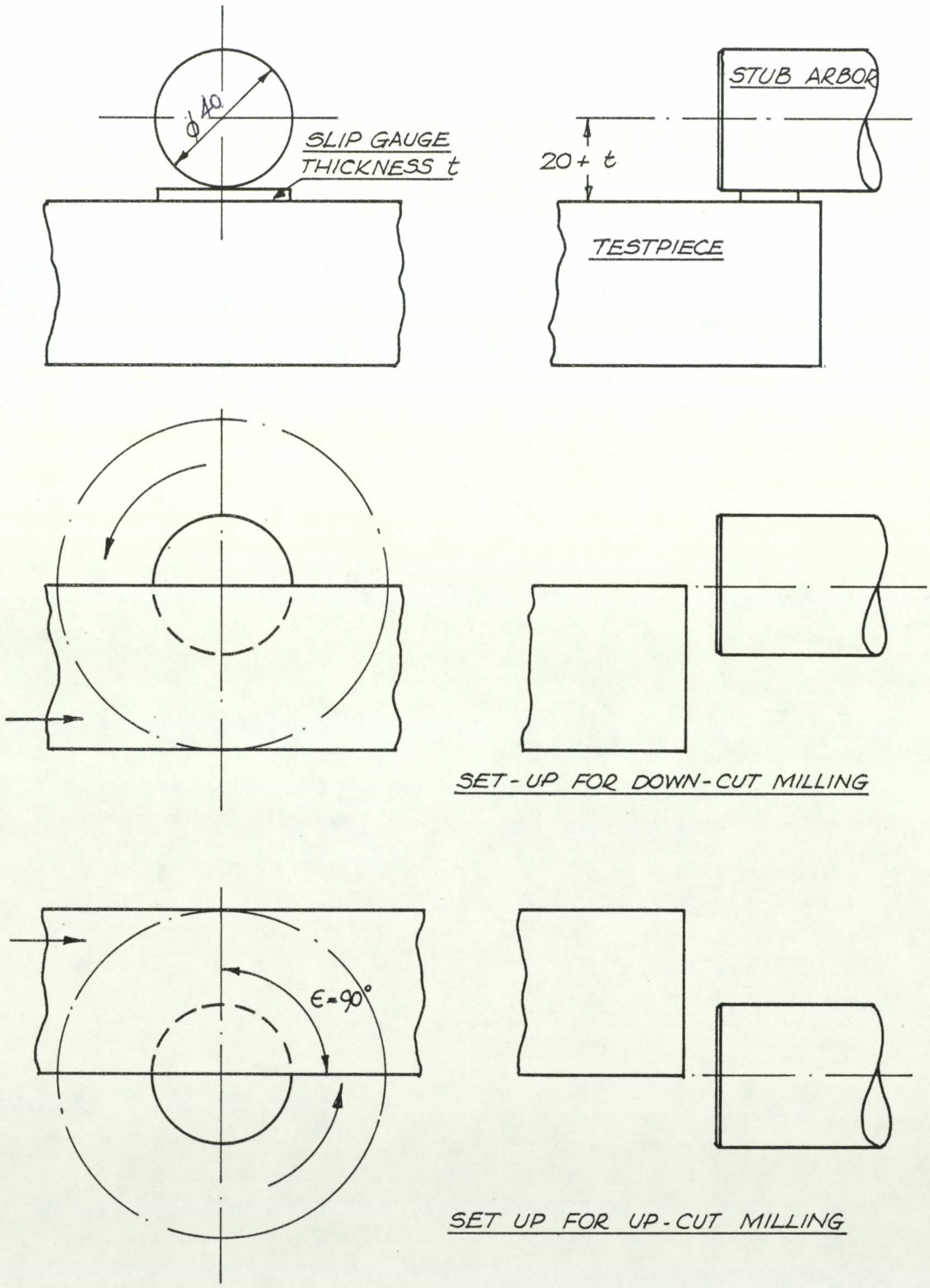
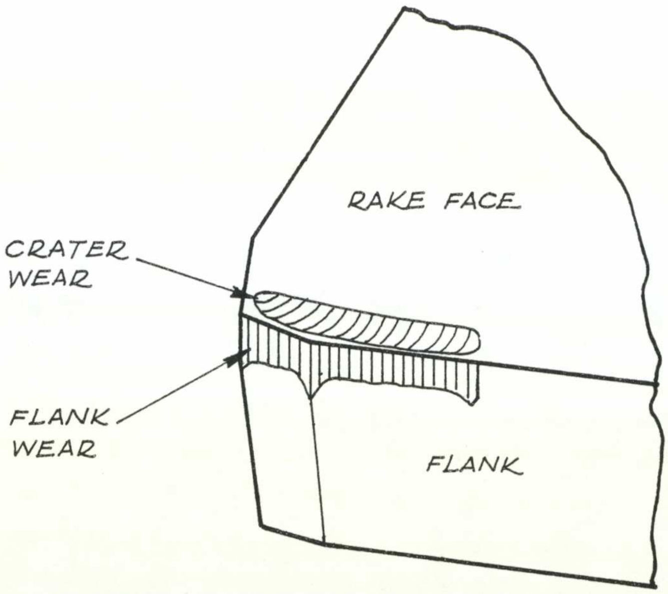


FIG. 4.3 SETTING CUTTER/TESTPIECE RELATIONSHIP



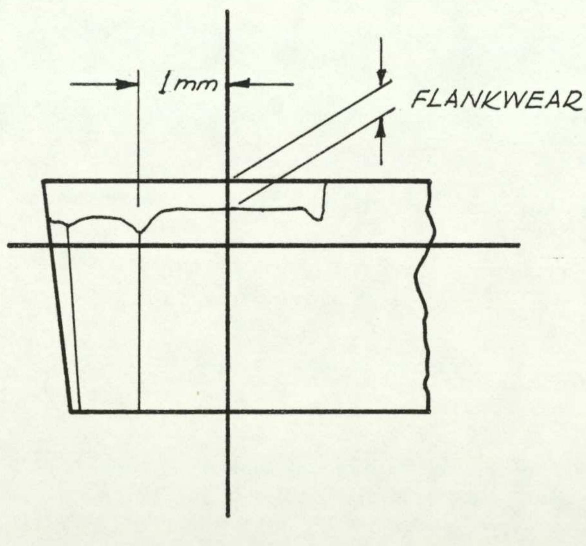


FIG 4.4 POSITION FOR MEASURING FLANKWEAR

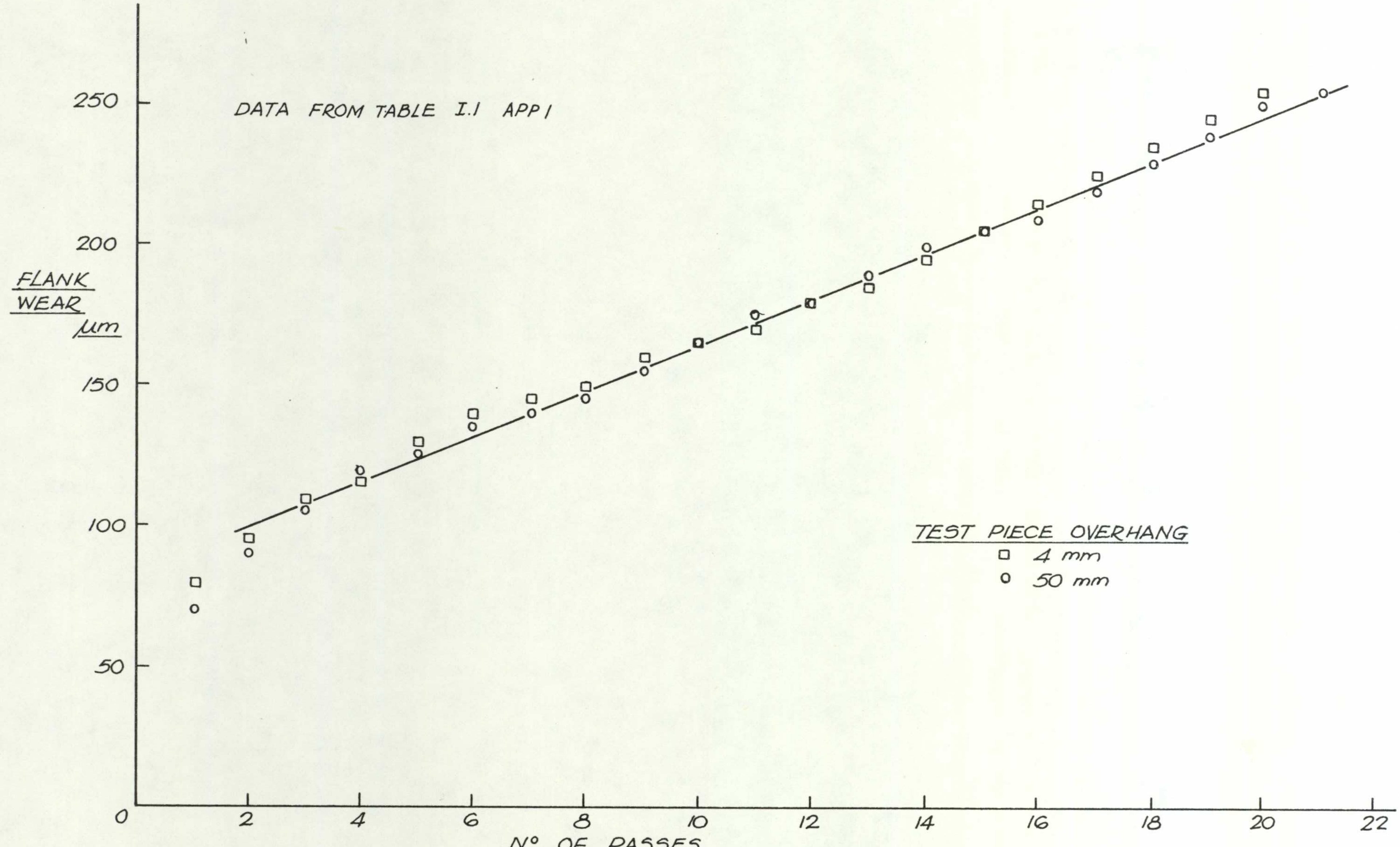


FIG 4.5 NEGATIVE RAKE DOWN-CUT MILLING 370 REV/MIN 89 mm/MIN FEED

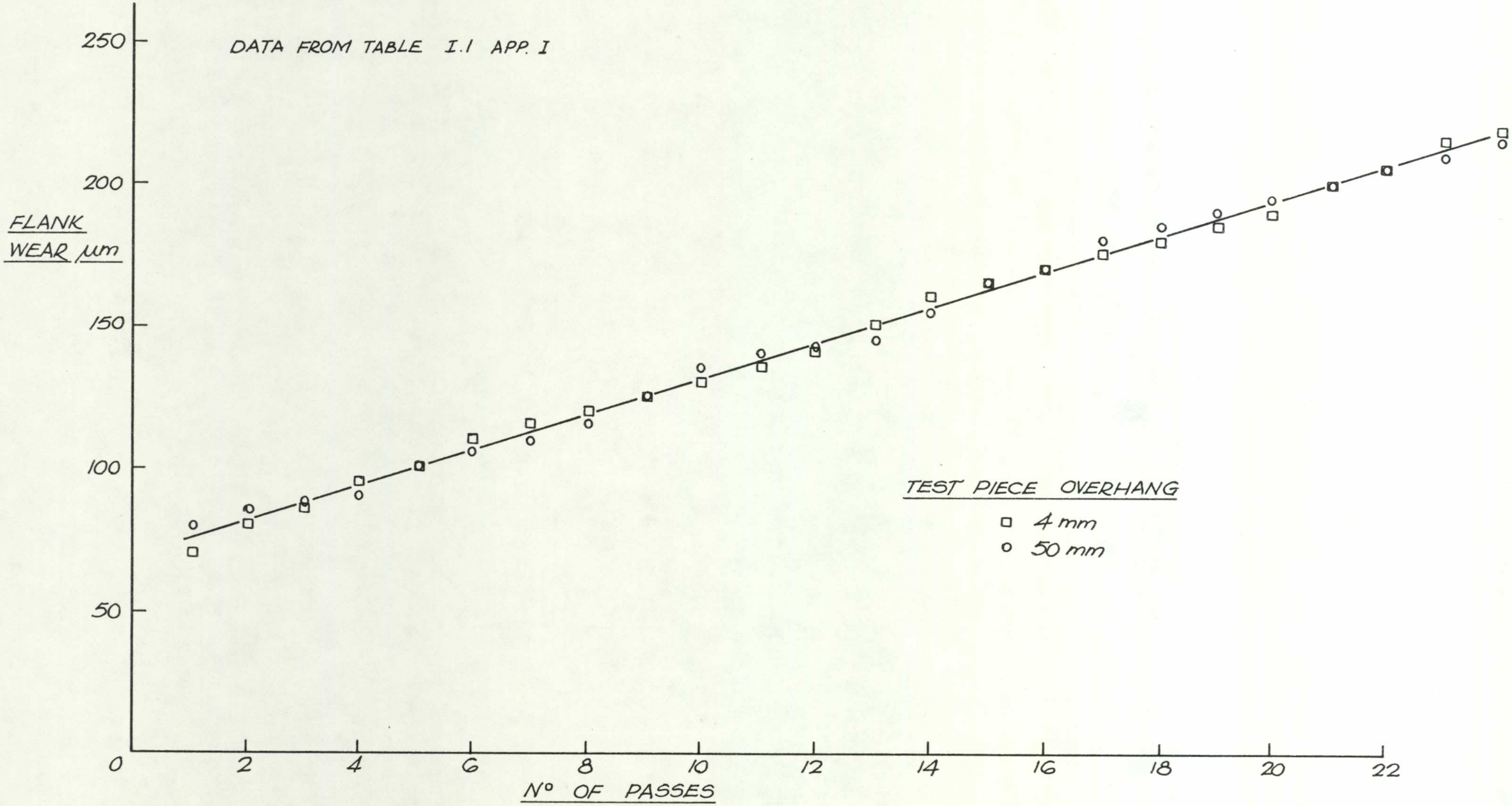


FIG 4.6 NEGATIVE RAKE DOWN-CUT MILLING 370 REV/MIN 175 mm/MIN FEED

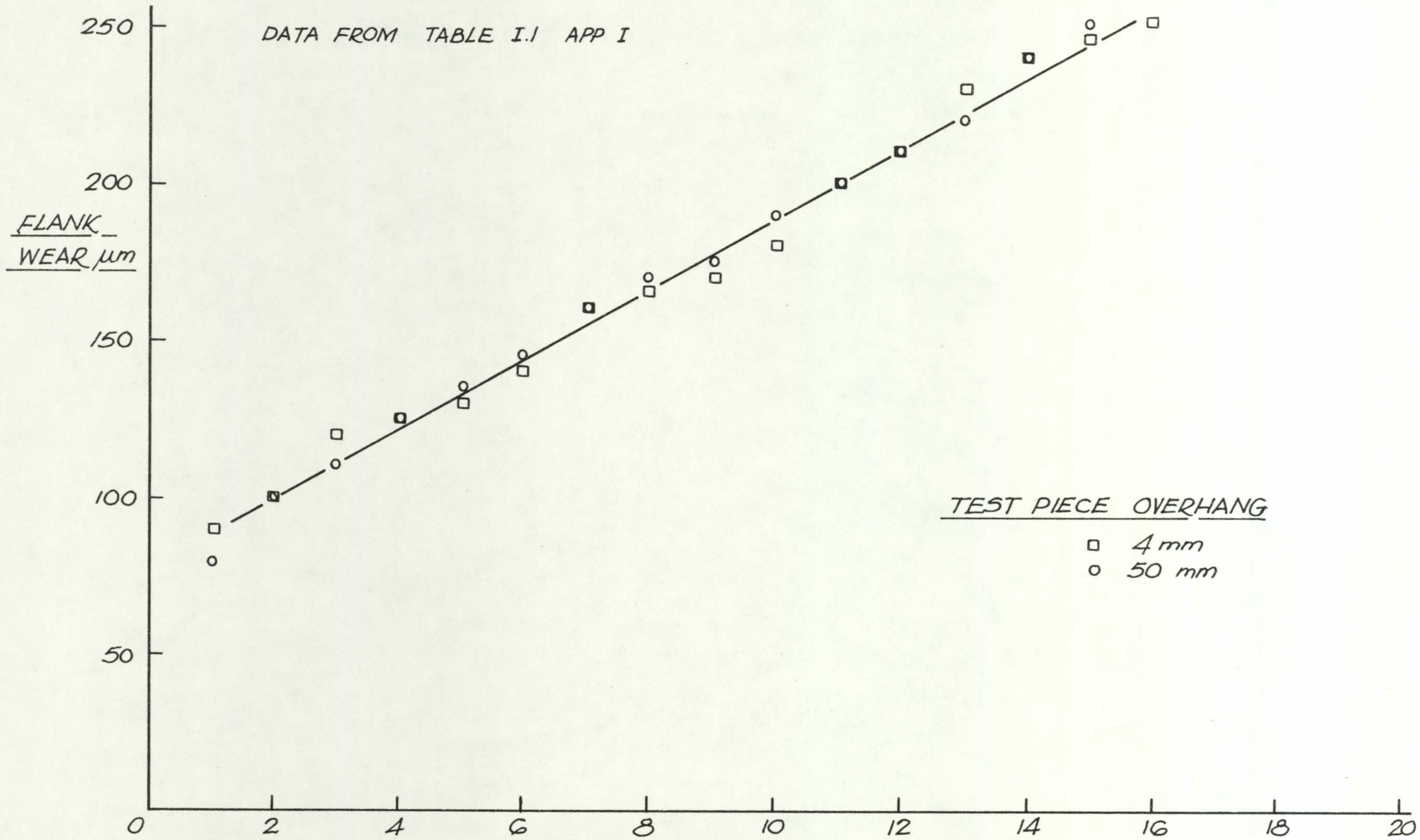


FIG 4.7 NEGATIVE RAKE DOWN-CUT MILLING 460 REV/MIN 217 mm/MIN FEED

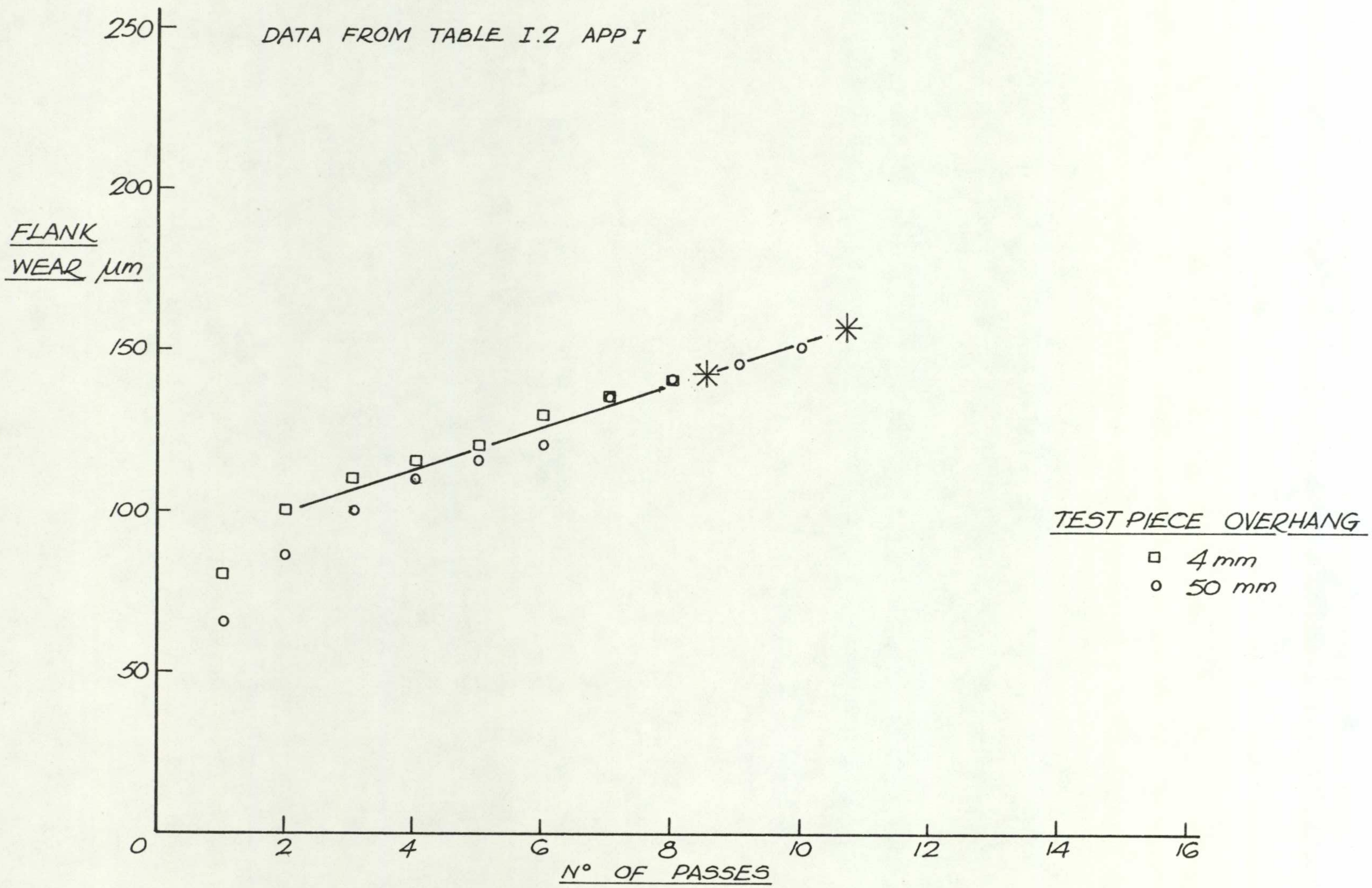


FIG 4.8 NEGATIVE RAKE MILLING UP- CUT 360 REV/MIN 89 mm/MIN FEED

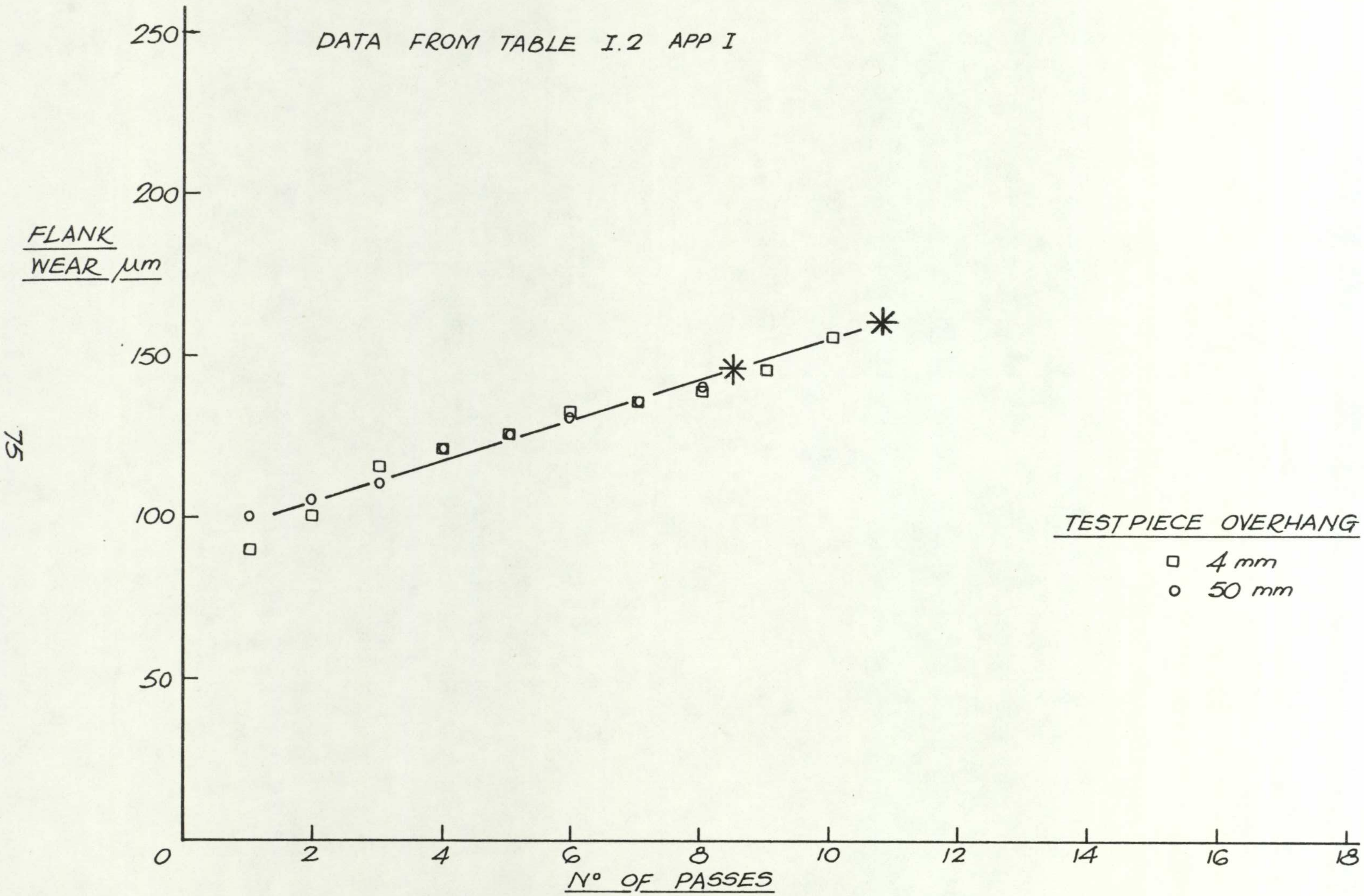


FIG 4.9 NEGATIVE RAKE UP-CUT MILLING 370 REV/MIN 175 mm/MIN FEED

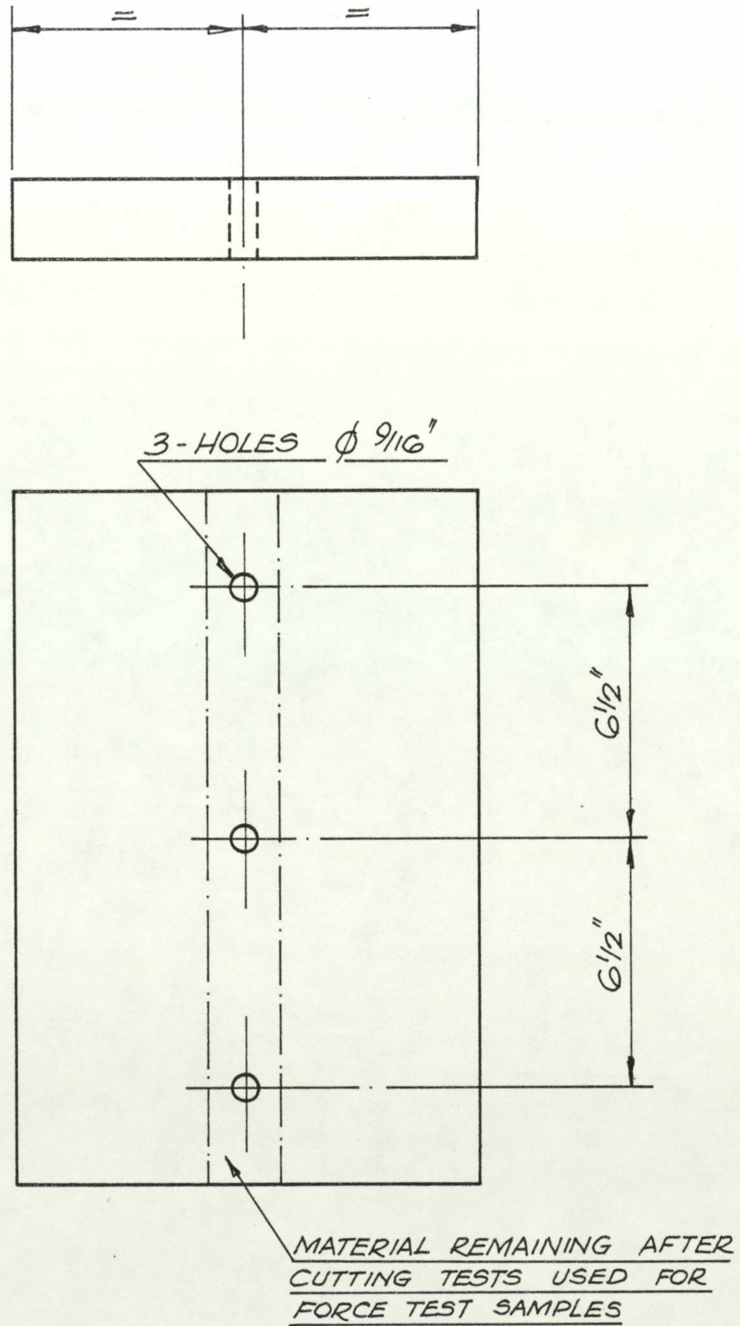


FIG 4.10 DETAILS OF TESTPIECE

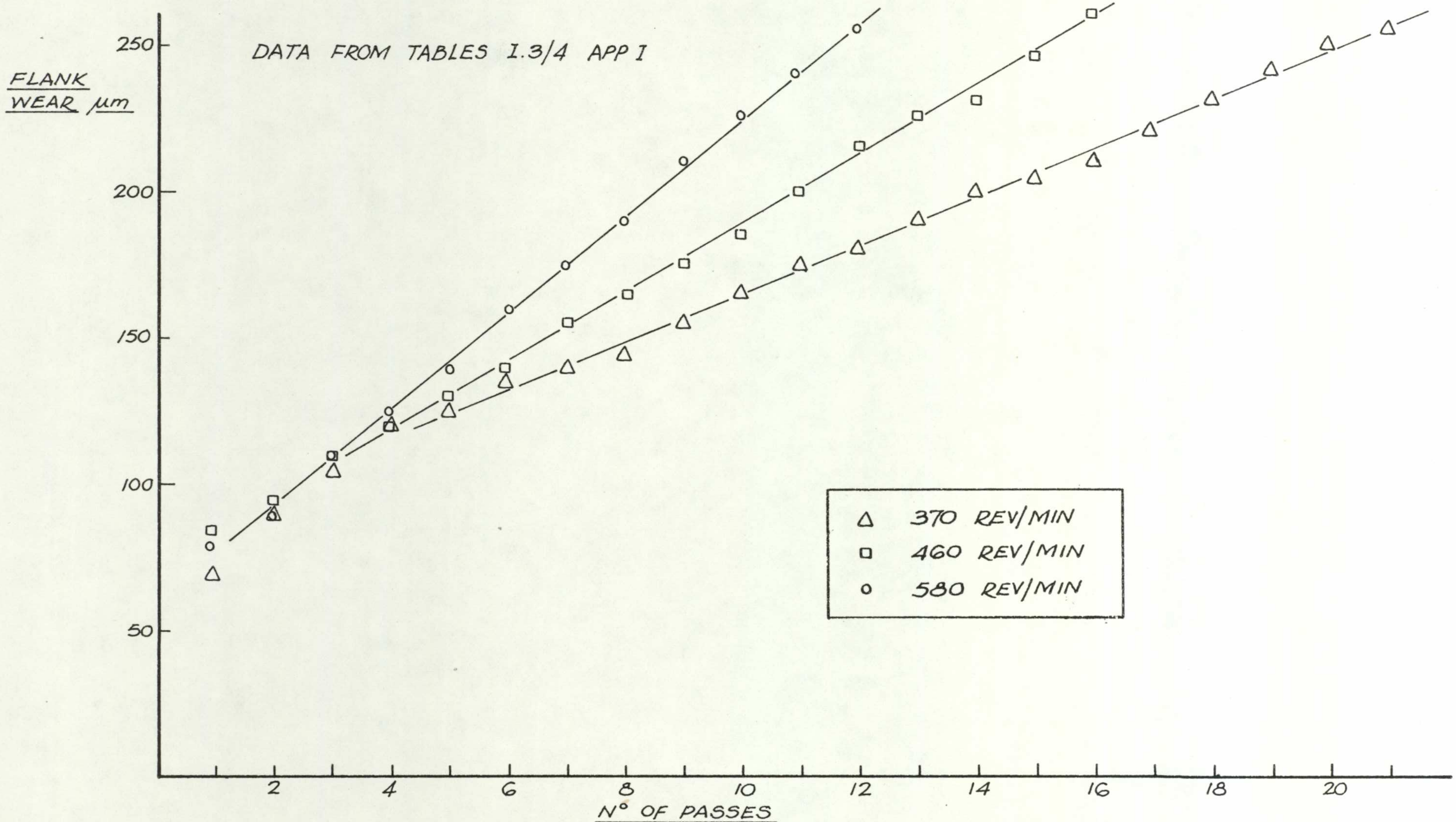


FIG 4.11. NEGATIVE RAKE DOWN-CUT MILLING FEED 0·24 mm/TOOTH

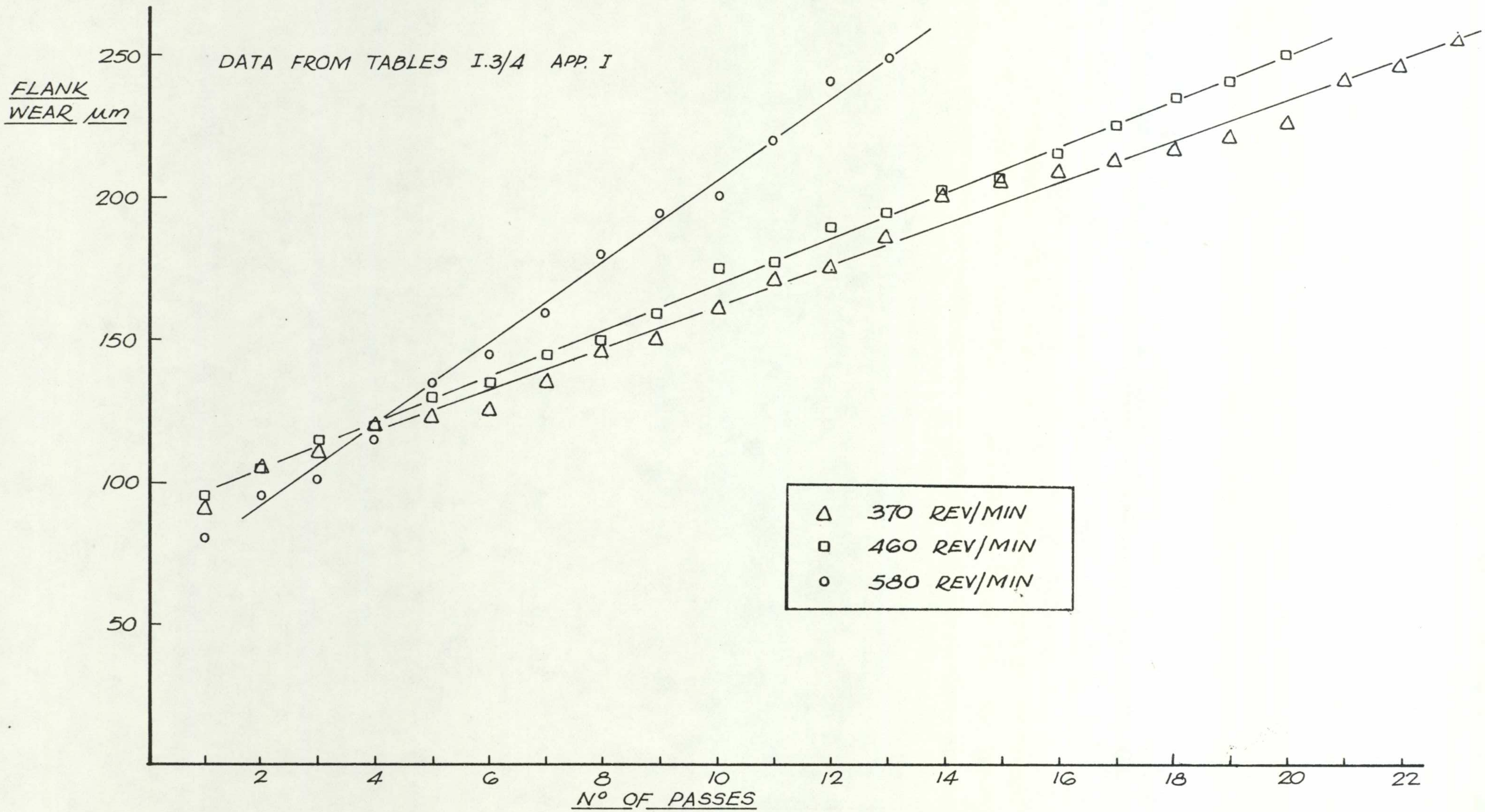


FIG 4.12 NEGATIVE RAKE DOWN-CUT MILLING FEED 0·30 mm/TOOTH

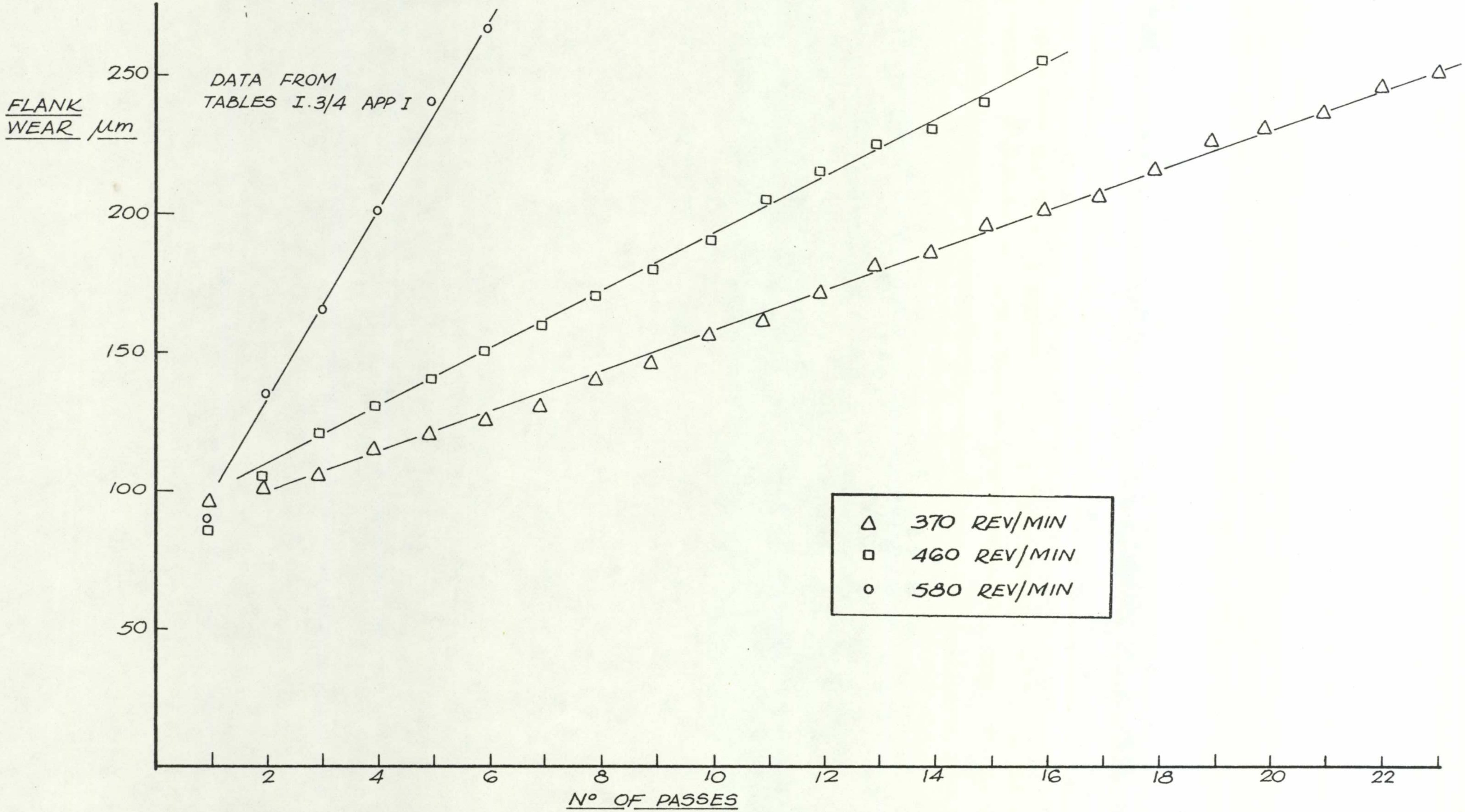


FIG 4.13 NEGATIVE RAKE DOWN-CUT MILLING FEED 0·38 mm/TOOTH

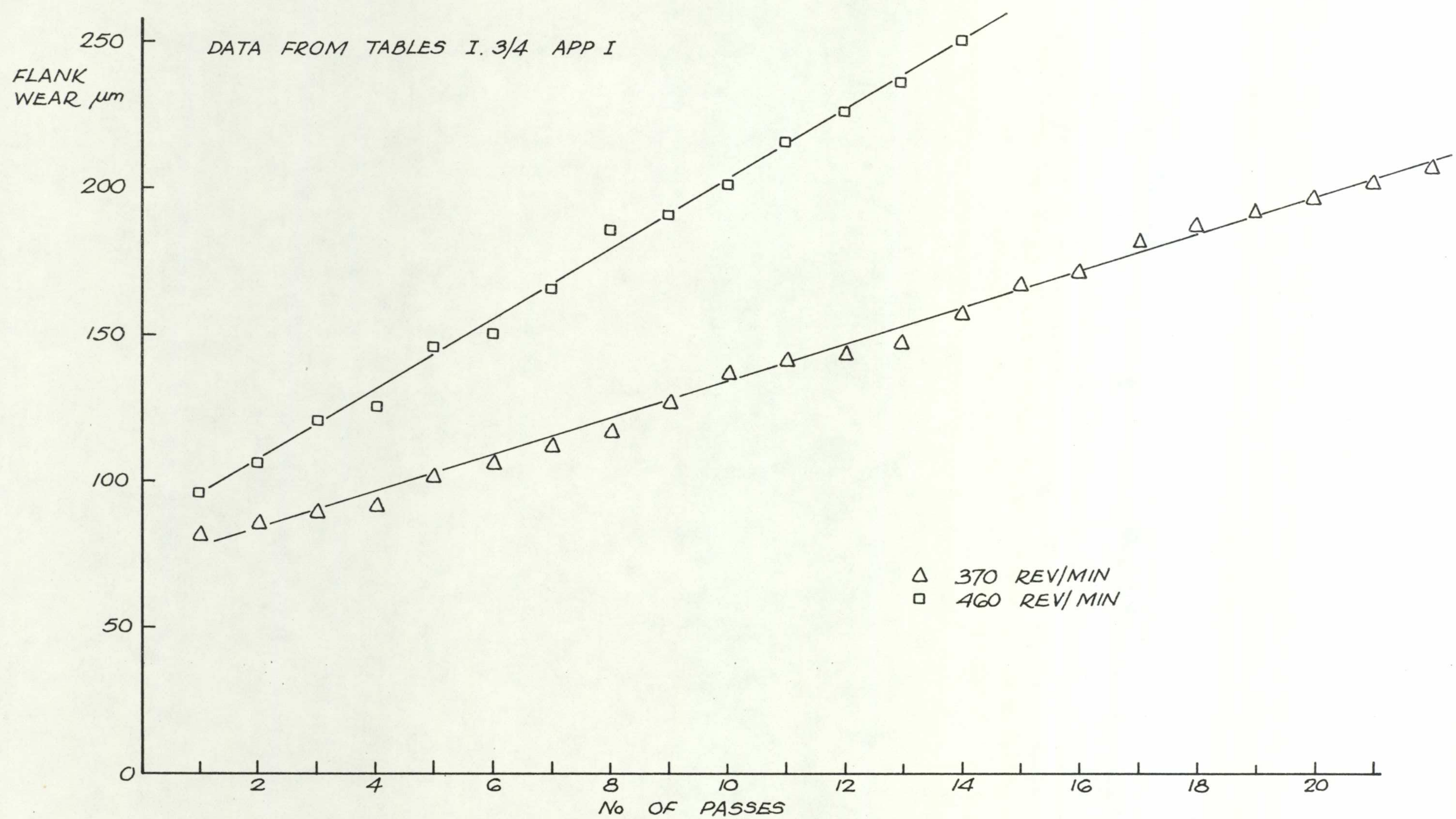


FIG 4.14 NEGATIVE RAKE DOWN-CUT MILLING FEED/TOOTH 0·47

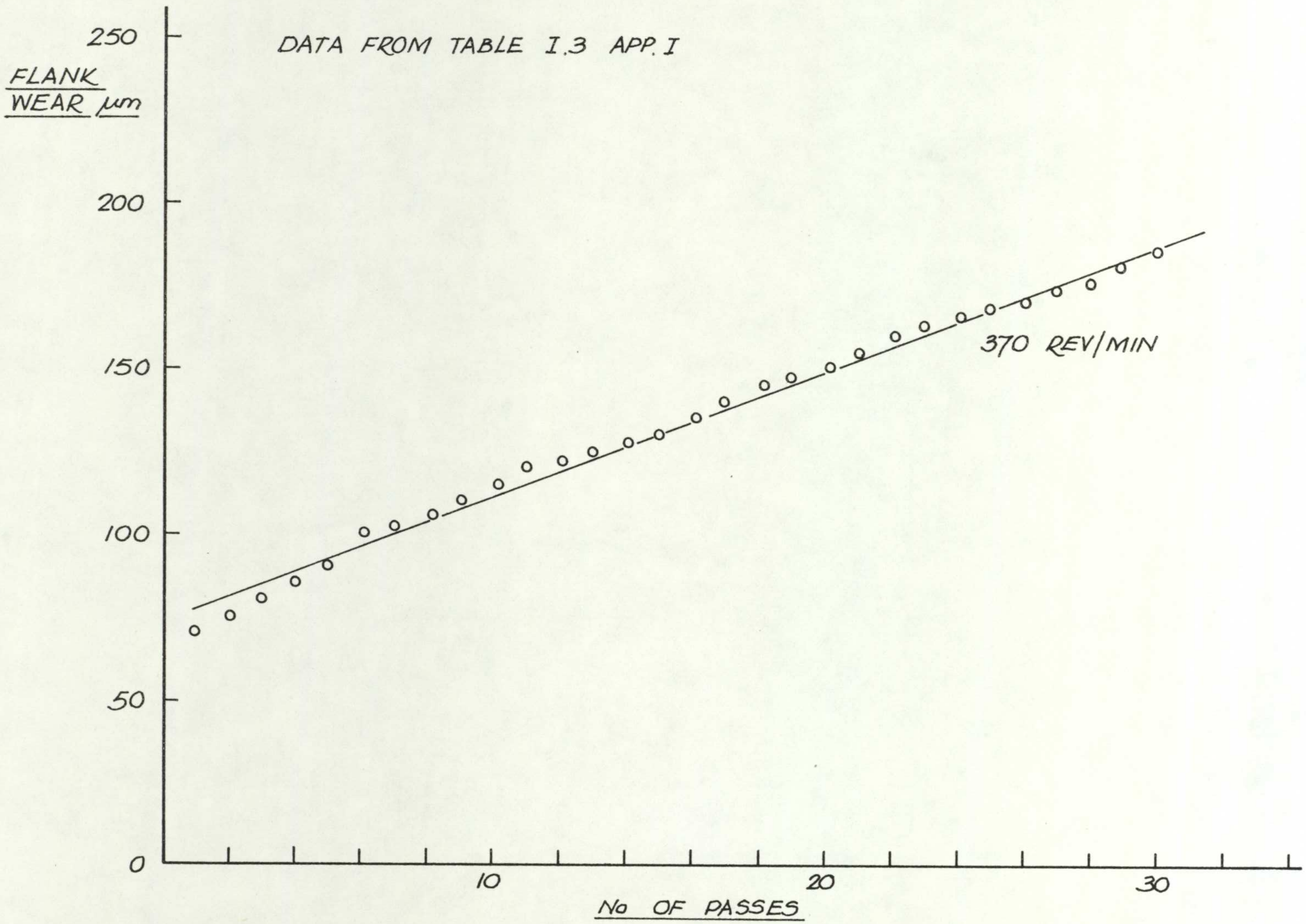


FIG 4.15 NEGATIVE RAKE DOWN-CUT MILLING FEED/TOOTH 0·59

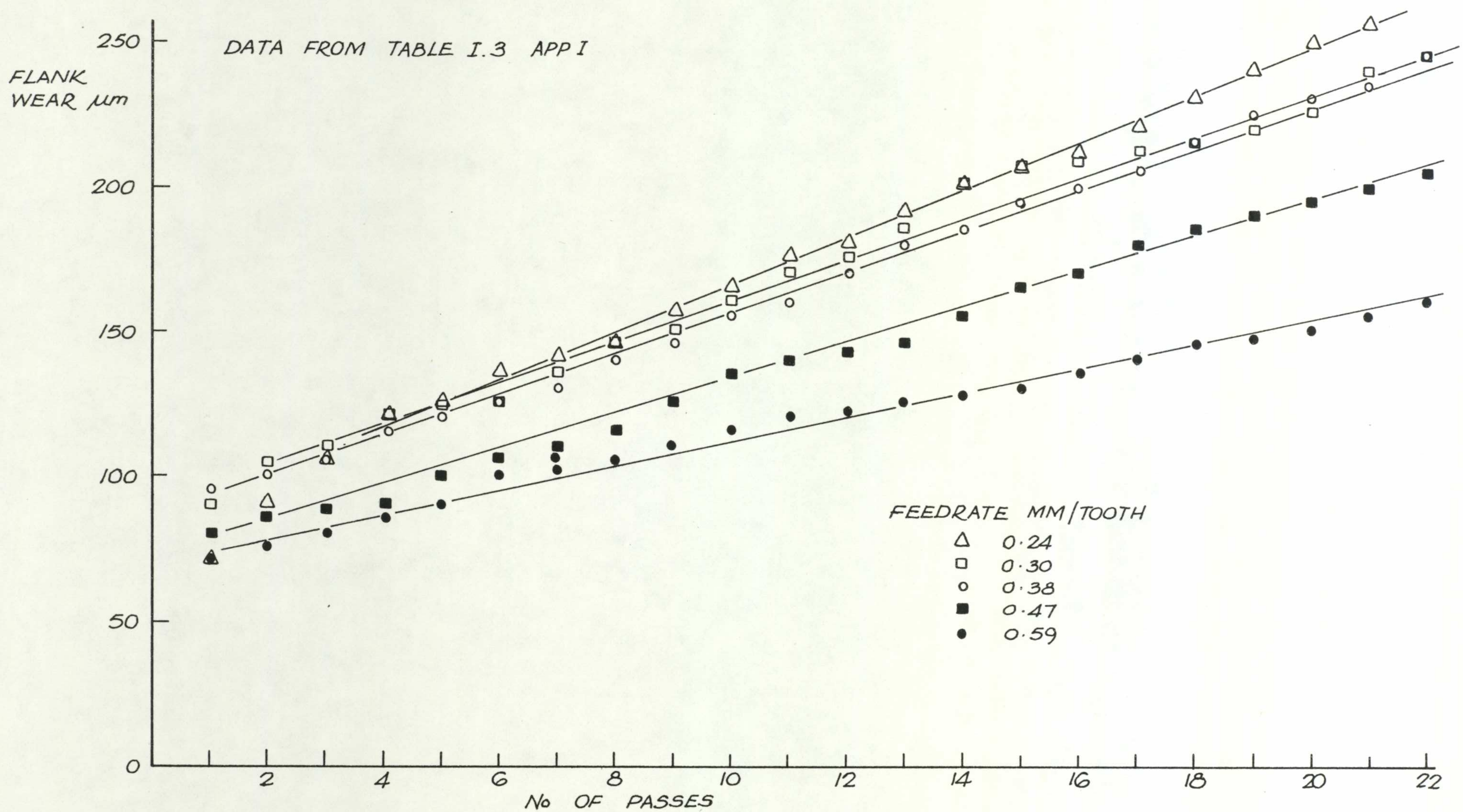


FIG 4.16 NEGATIVE RAKE DOWN-CUT MILLING 370 REV/MIN

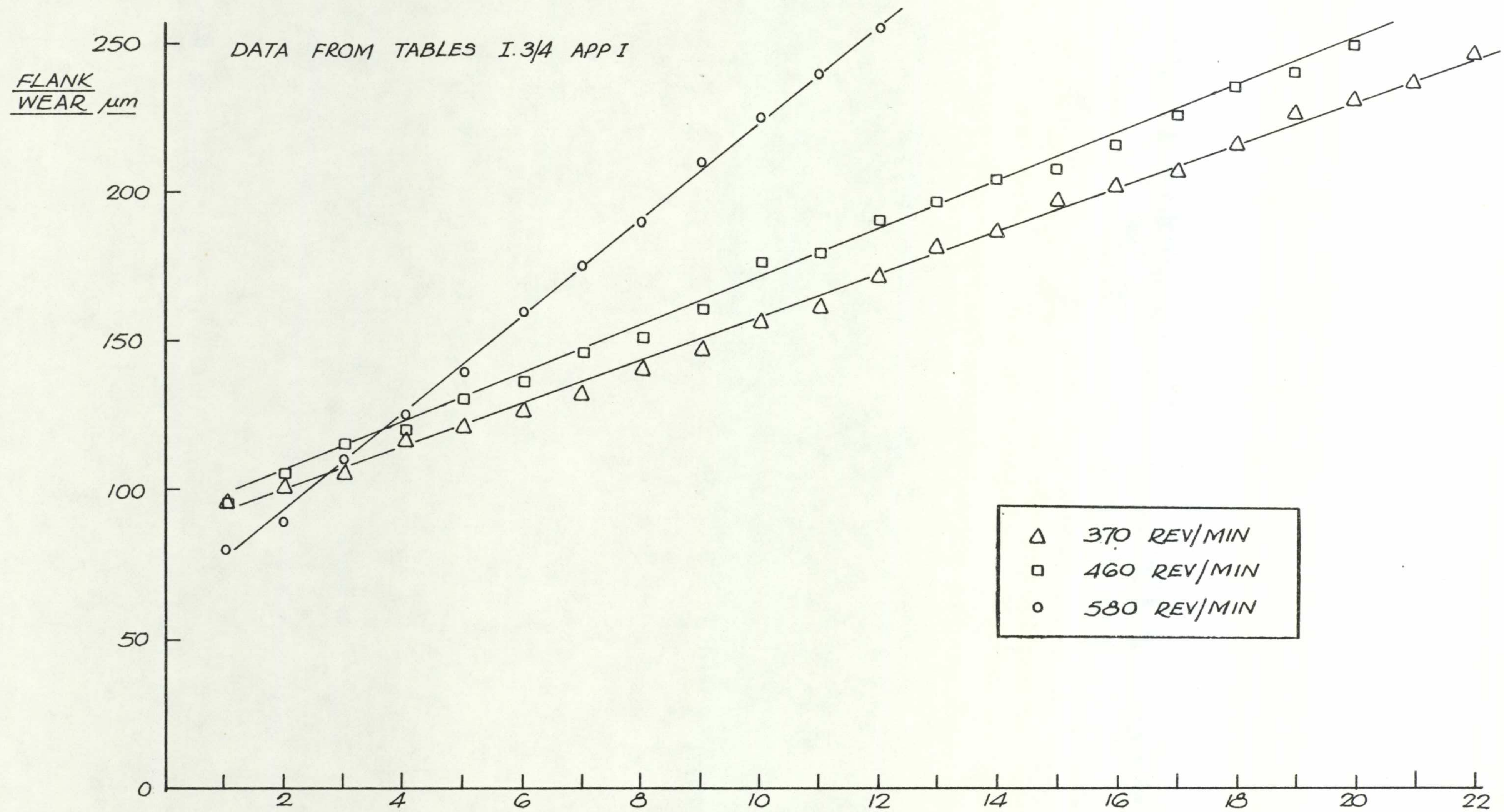


FIG 4.17 NEGATIVE RAKE DOWN-CUT MILLING CONSTANT FEED/MIN = 139 MM

DATA FROM TABLES I.5/6 APP I

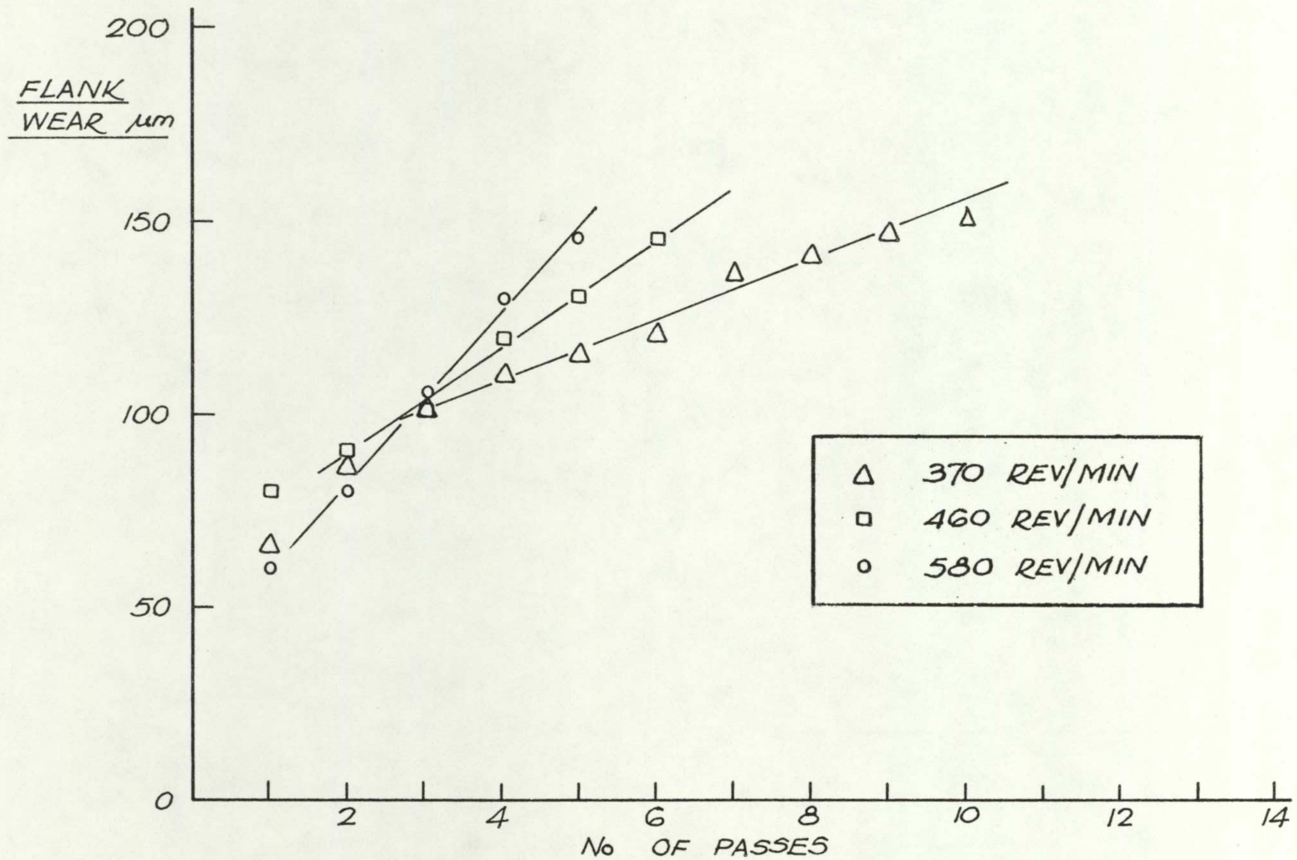


FIG 4.18 NEGATIVE RAKE UP-CUT MILLING FEED/TOOTH 0·24

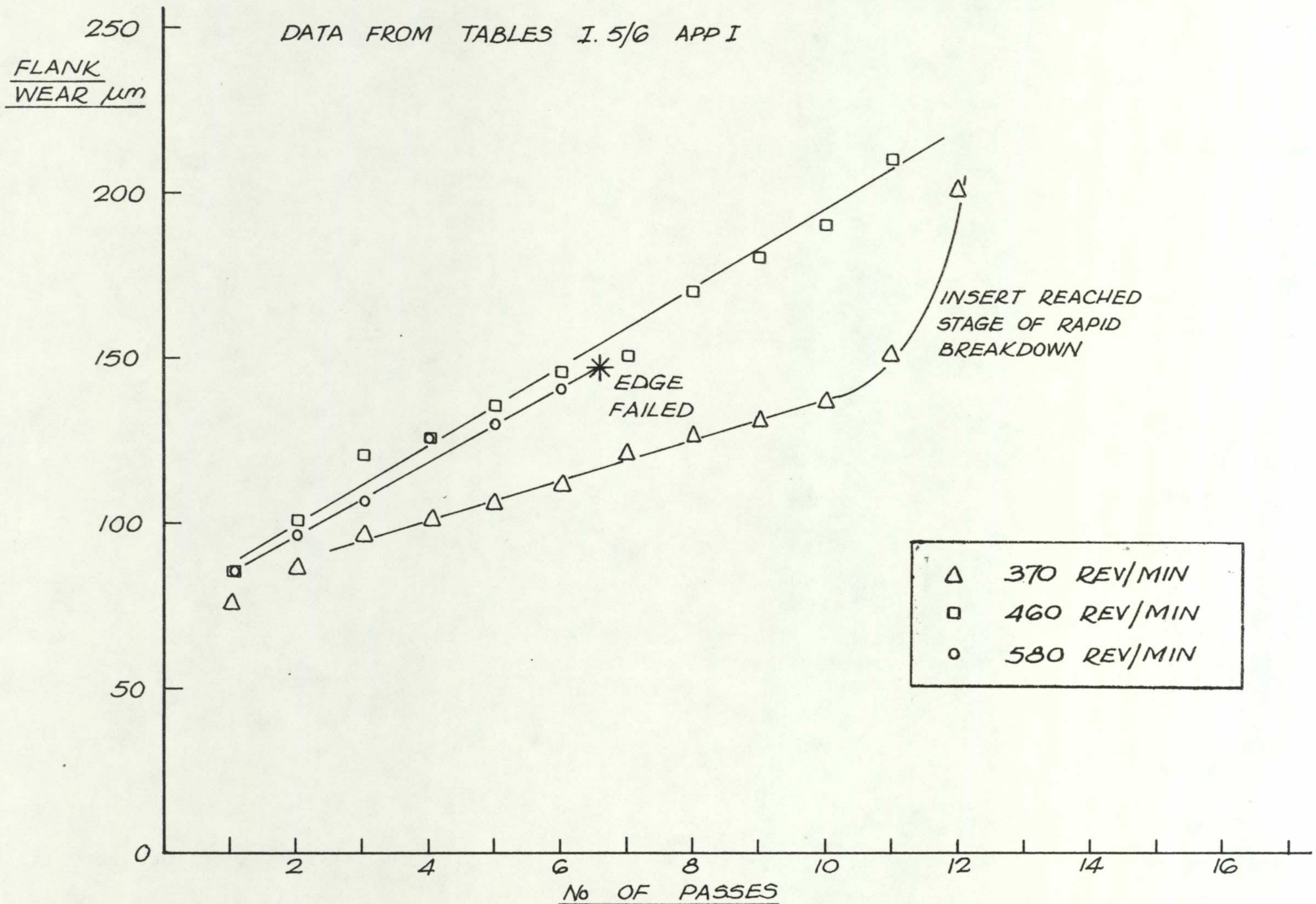


FIG 4.19 NEGATIVE RAKE UP-CUT MILLING FEED/TOOTH 0·30

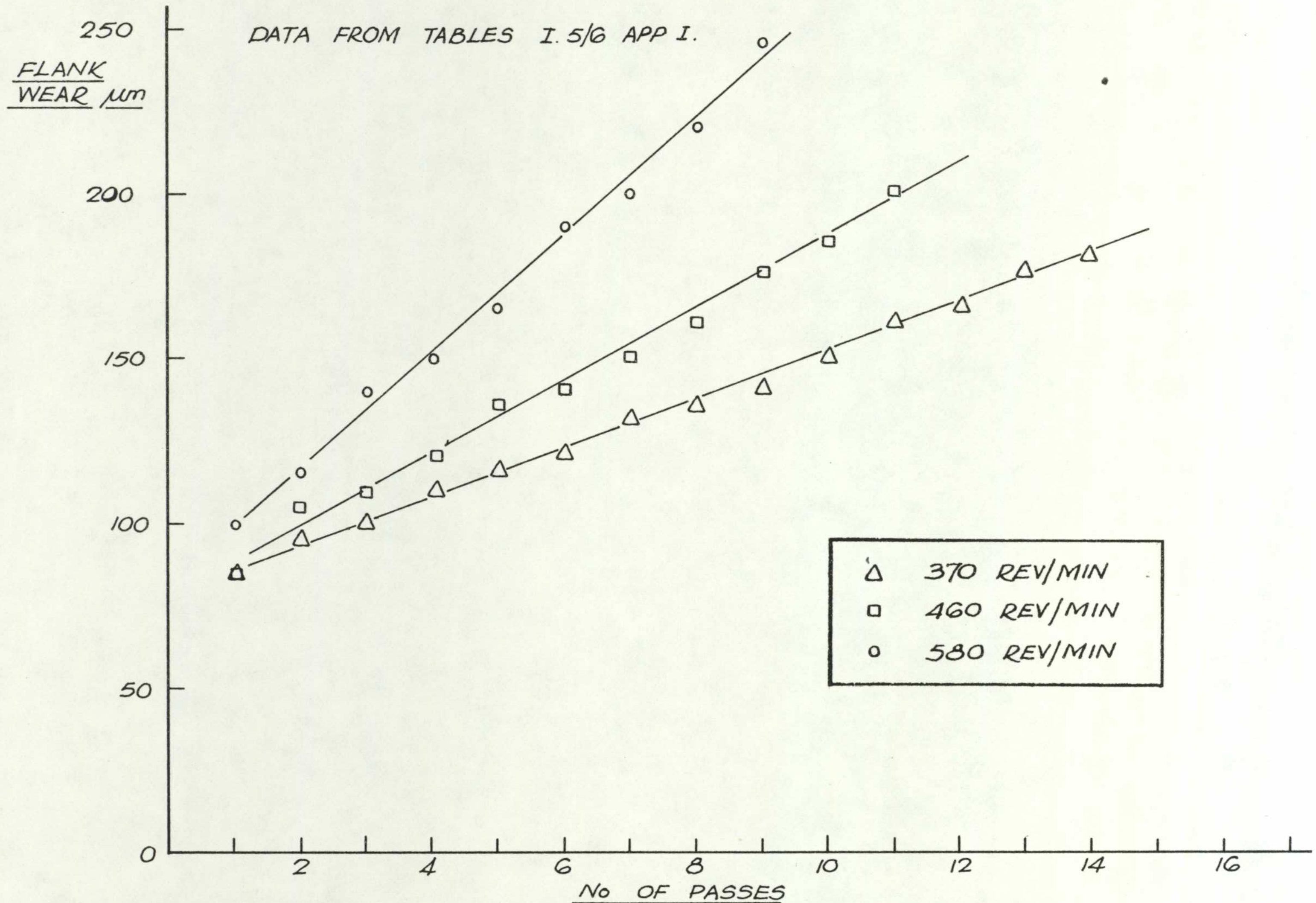


FIG 4.20 NEGATIVE RAKE UP-CUT MILLING FEED/TOOTH 0·38

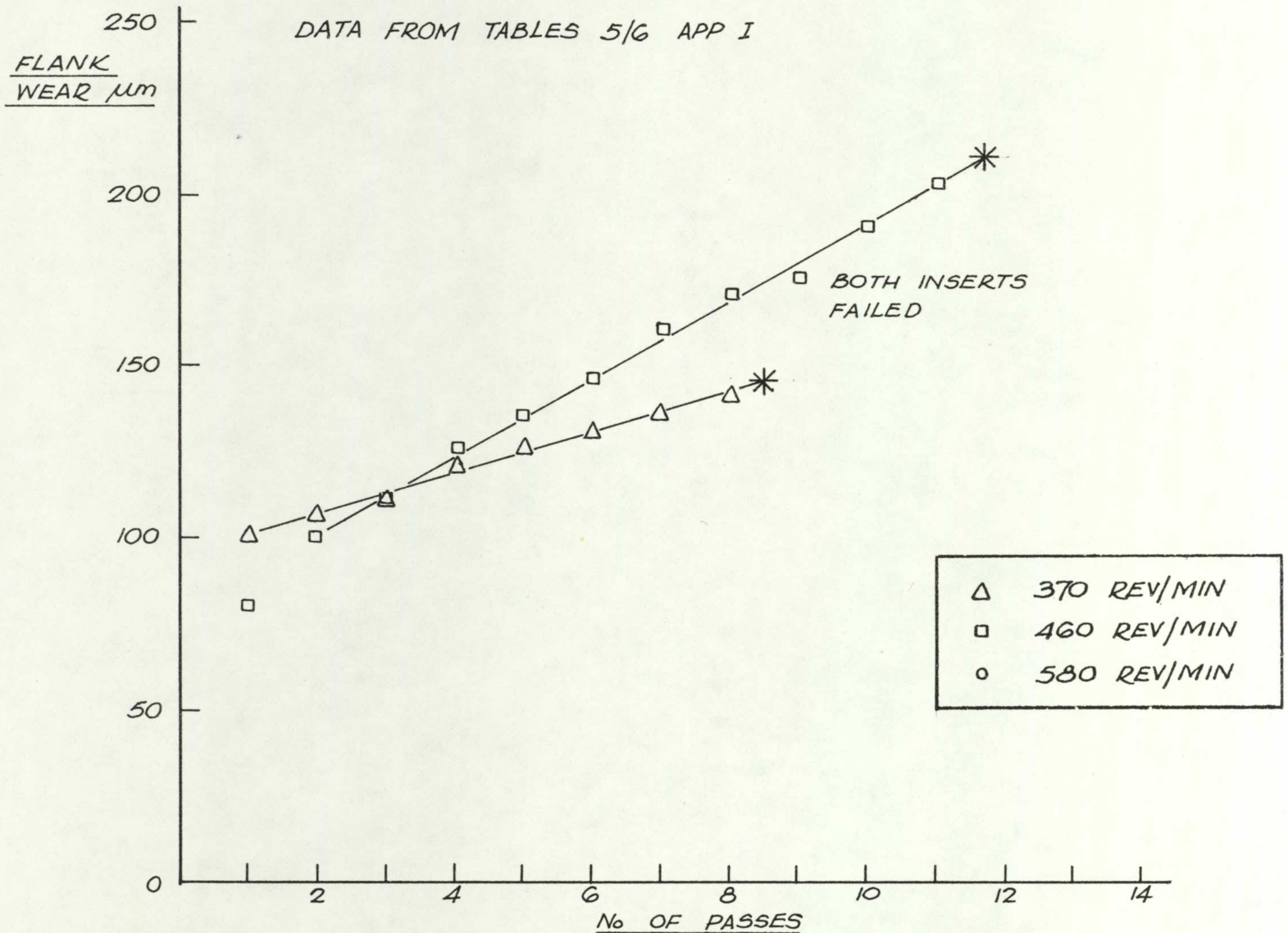


FIG 4.21 NEGATIVE RAKE UP-CUT MILLING FEED/TOOTH 0·47

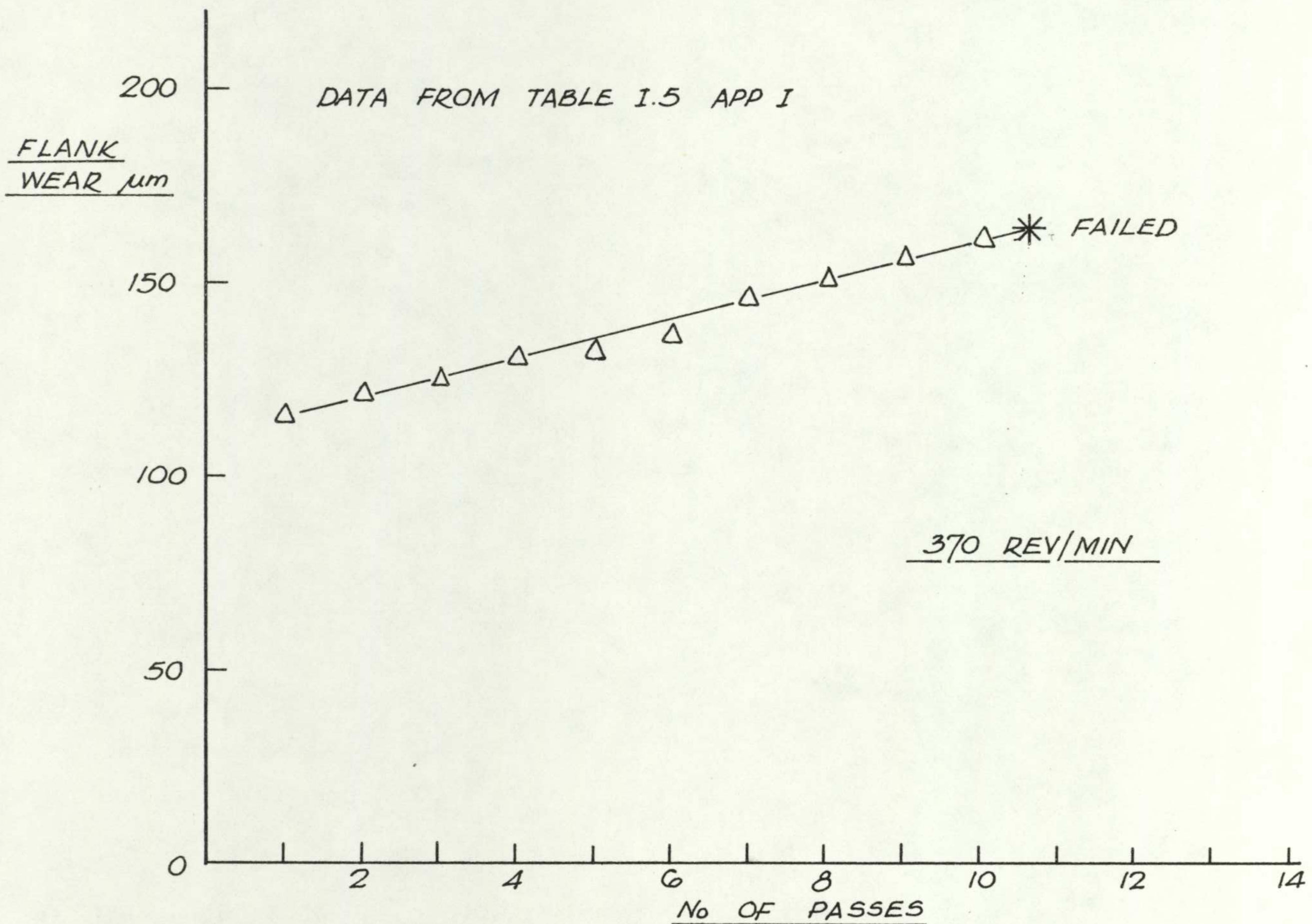


FIG 4.22 NEGATIVE RAKE UP-CUT MILLING FEED/TOOTH 0·59

DATA FROM TABLE I.5 APP I

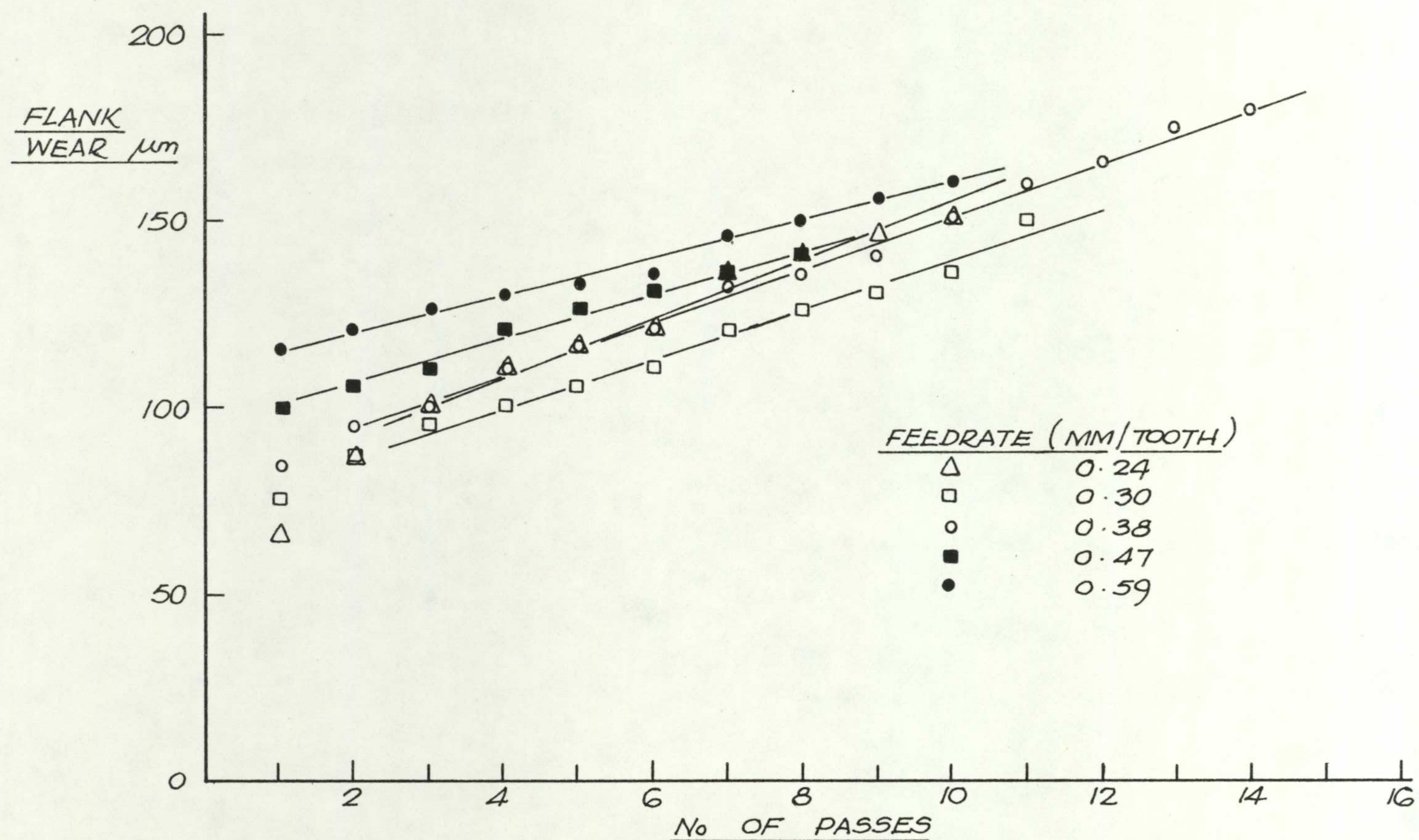


FIG 4.23 NEGATIVE RAKE UP-CUT MILLING 370 REV/MIN

DATA FROM TABLES I.5/6 APP I

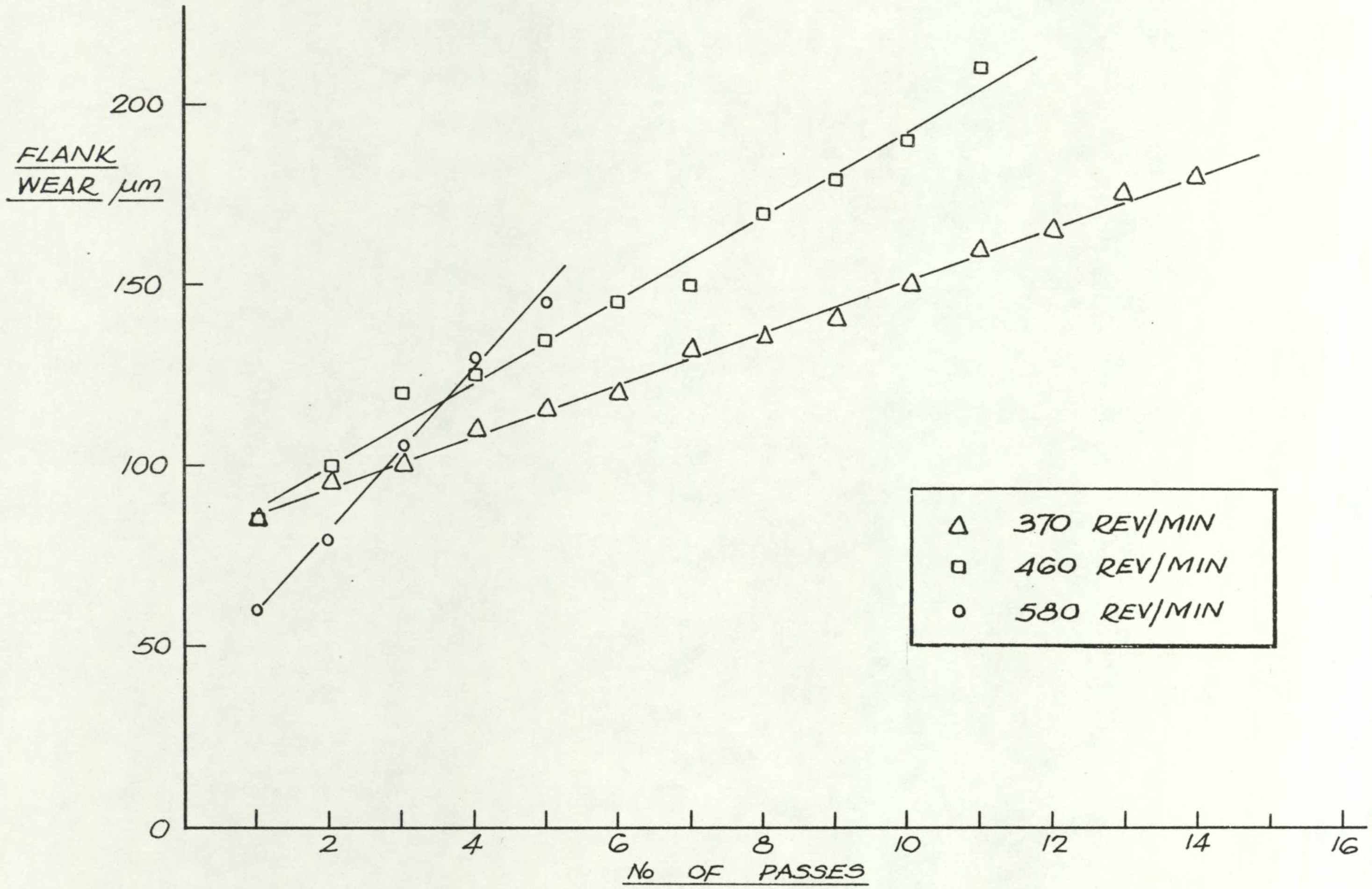


FIG 4.24 NEGATIVE RAKE UP-CUT MILLING CONSTANT FEED/MIN = 139 MM

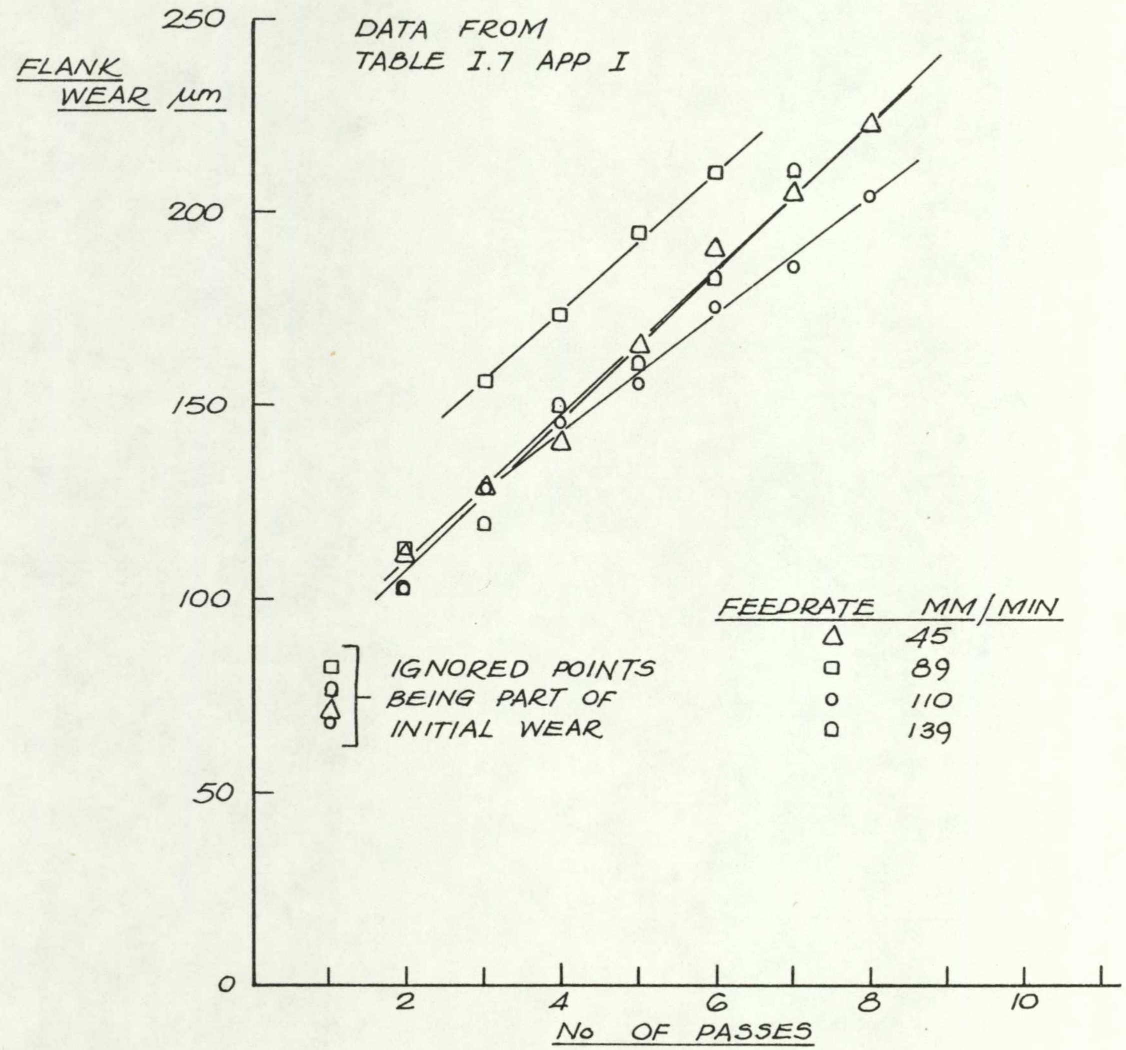


FIG 4.25 POSITIVE RAKE DOWN-CUT MILLING 470 REV/MIN

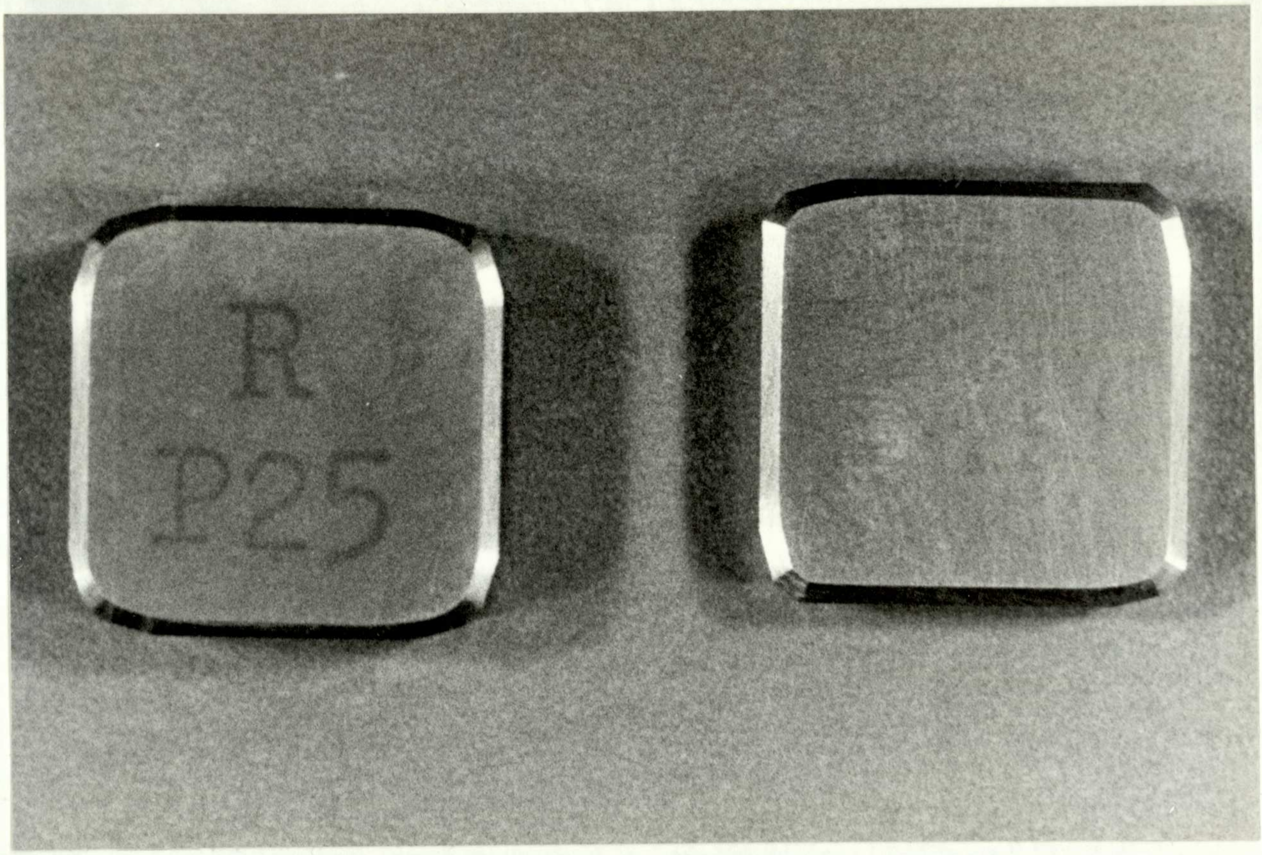


FIG 4.26 CHAMFERED INSERTS

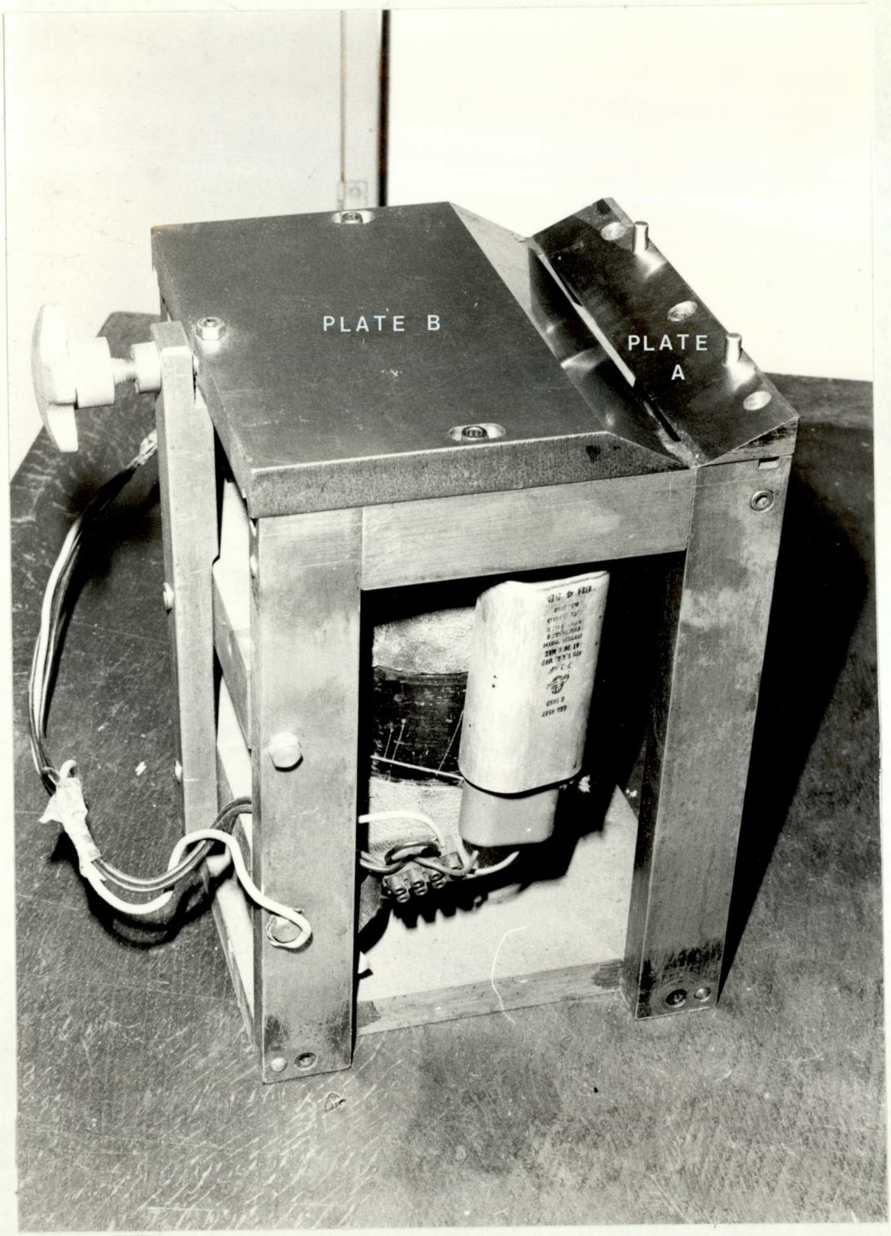


FIG 4.27 GRINDING FIXTURE

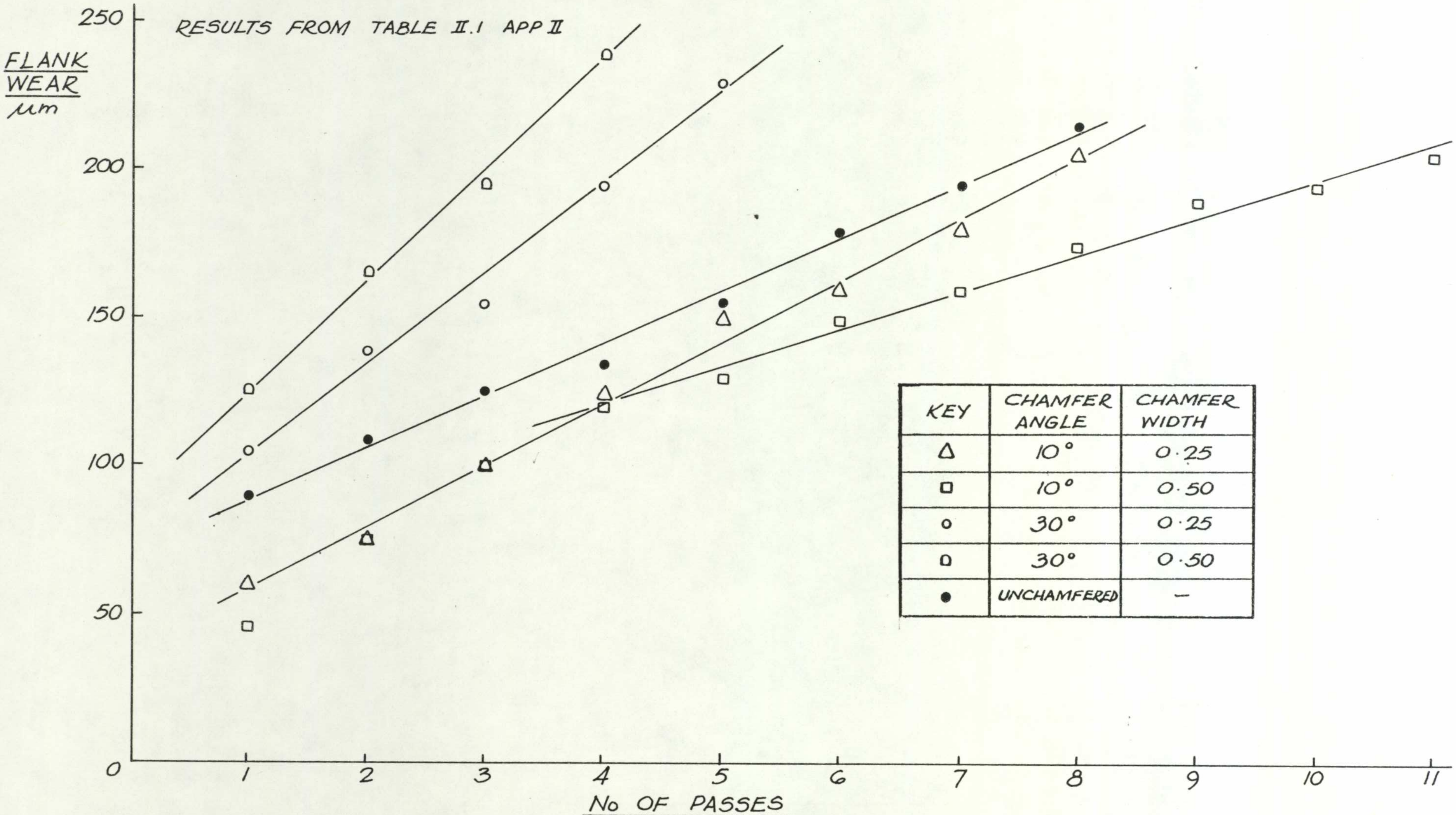


FIG 4.28 NEGATIVE RAKE UP-CUT MILLING 460 REV/MIN FEEDRATE 89 mm/min

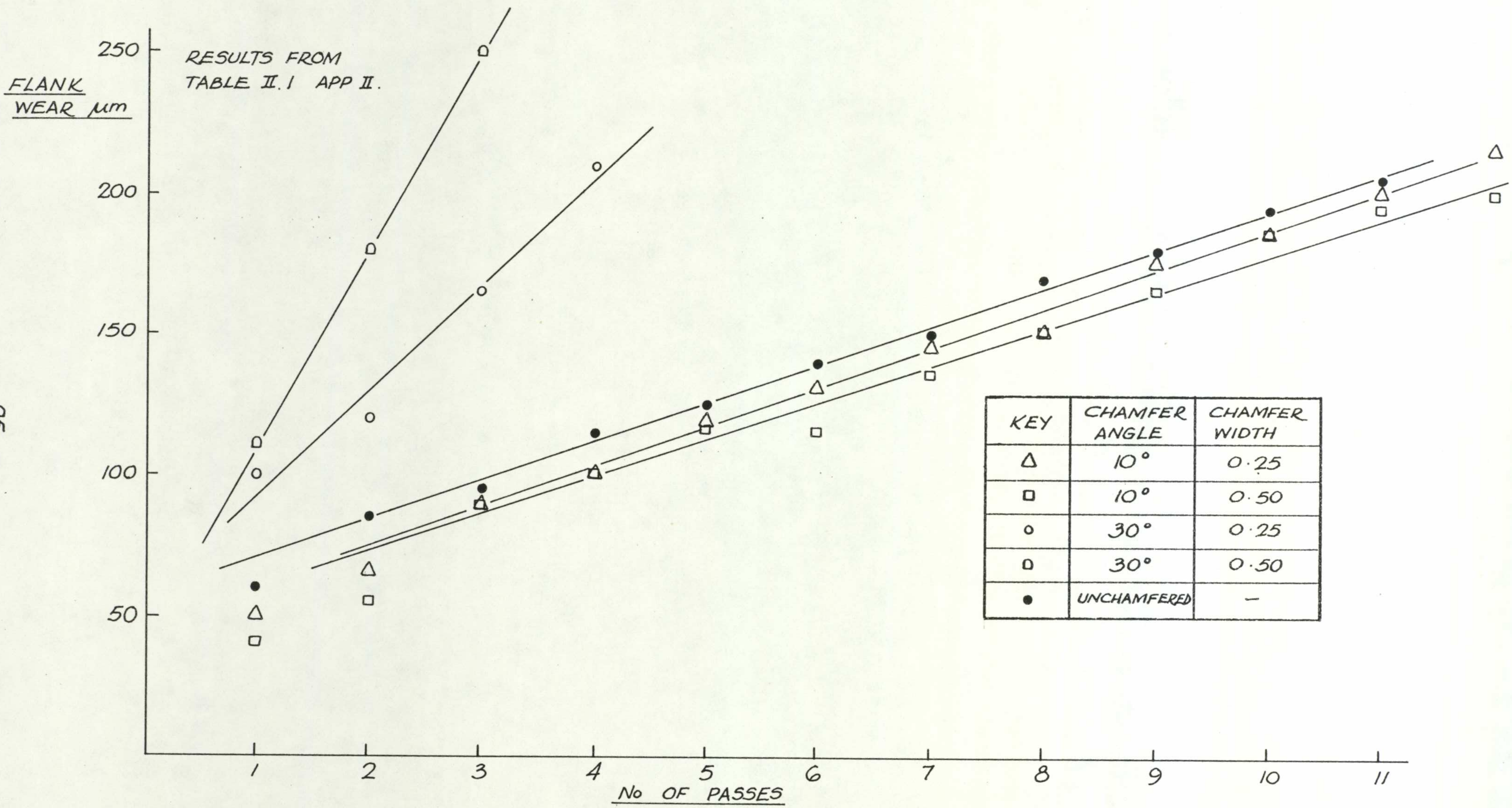


FIG 4.29 NEGATIVE RAKE UP-CUT MILLING 460 REV/MIN FEEDRATE 175 mm/min

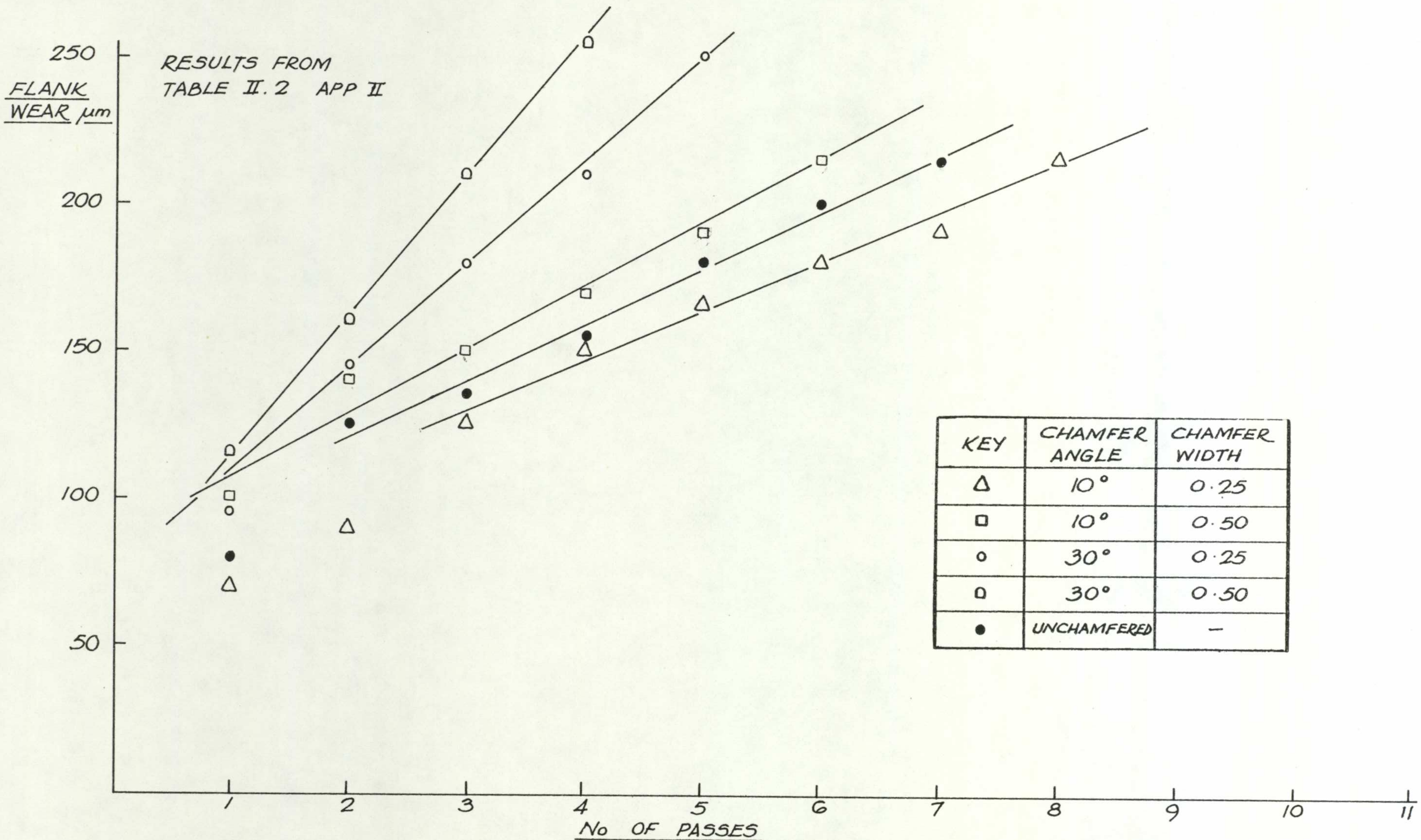


FIG 4.30 NEGATIVE RAKE DOWN-CUT MILLING 460 REV/MIN FEEDRATE 89 mm/min

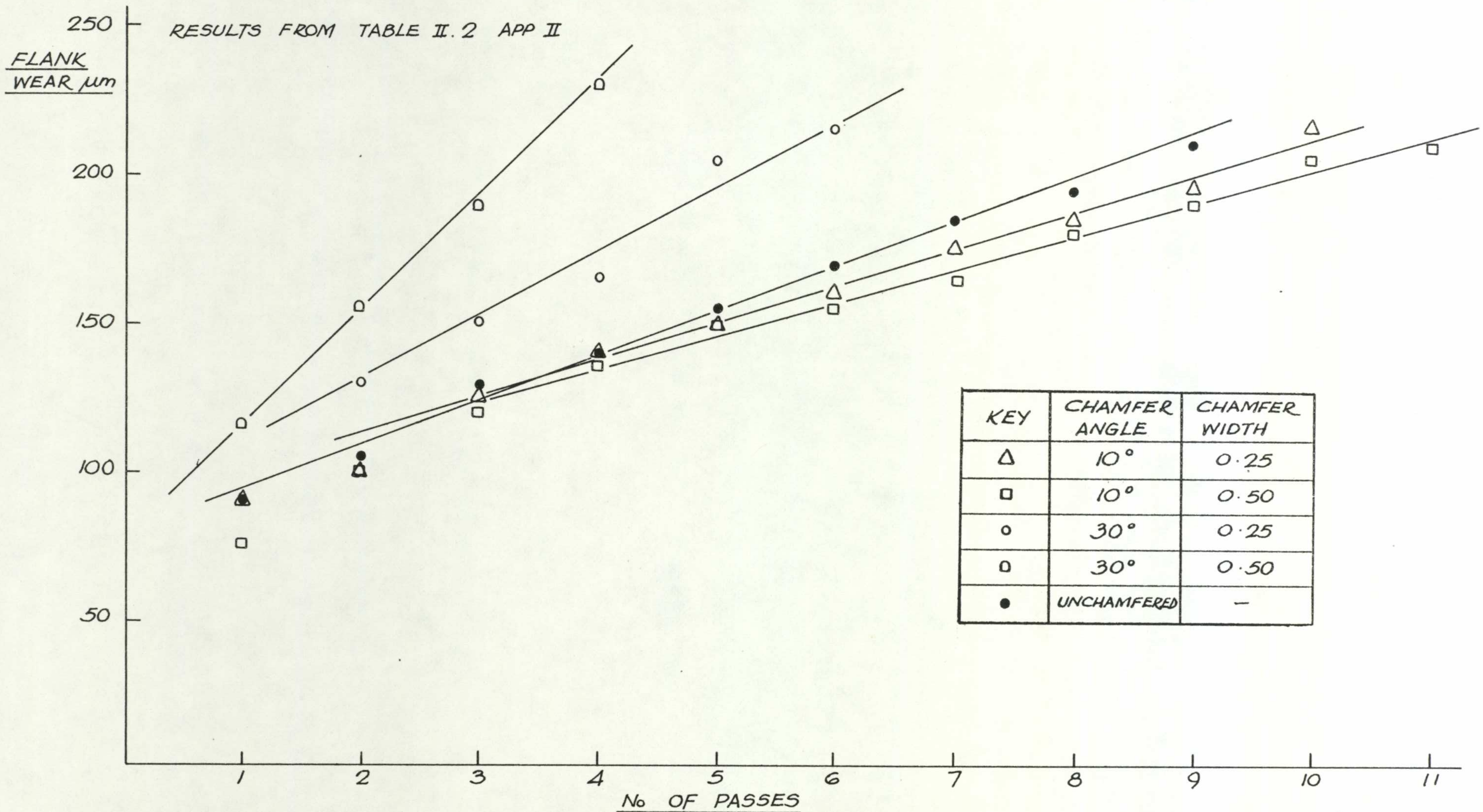


FIG 4.31 NEGATIVE RAKE DOWN-CUT MILLING 460 REV/MIN FEEDRATE 175 mm/min

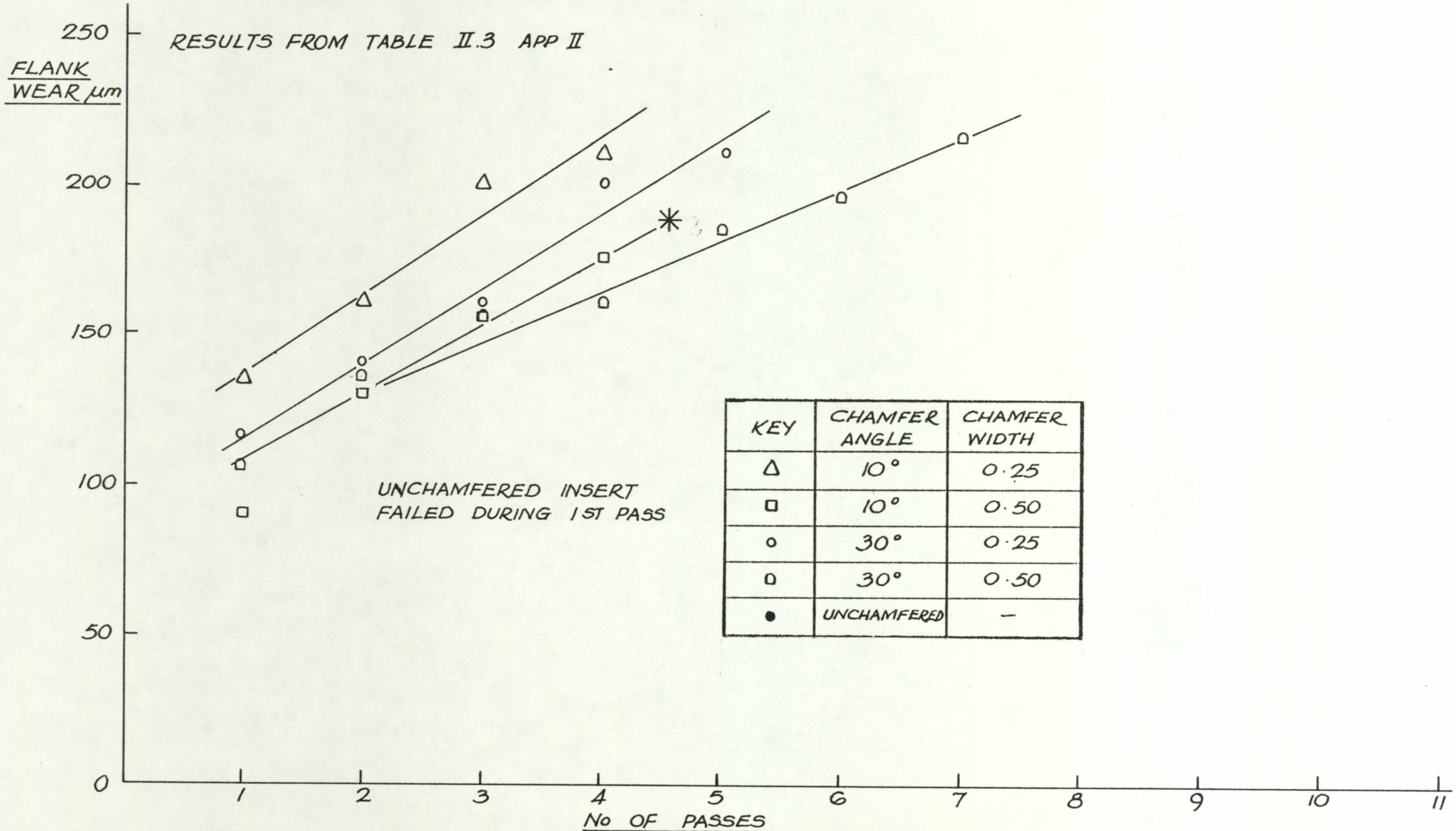


FIG 4.32 POSITIVE RAKE UP-CUT MILLING 460 REV/MIN FEEDRATE 89 mm/min

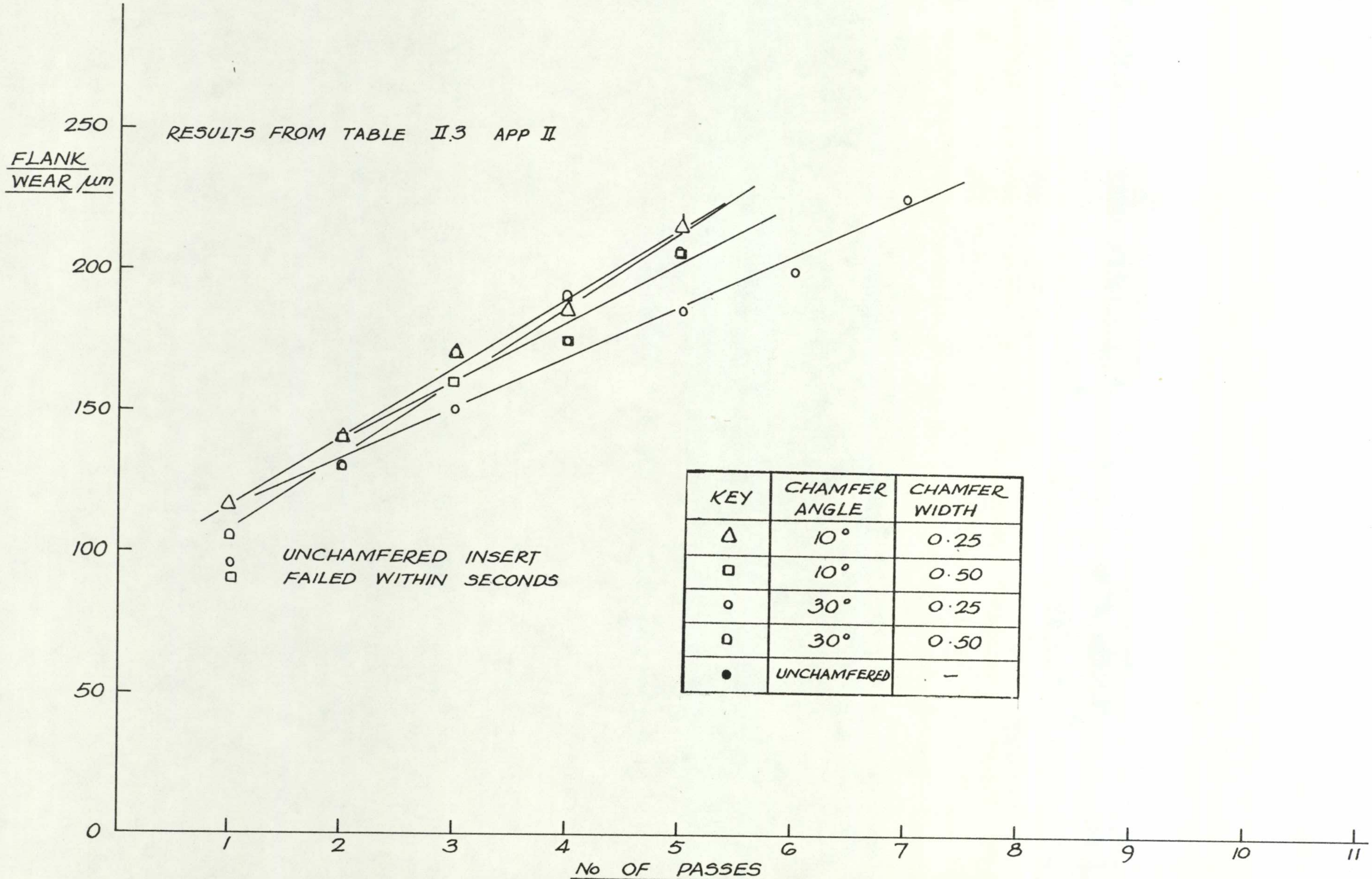


FIG 4.33 POSITIVE RAKE UP-CUT MILLING 460 REV/MIN FEEDRATE 175 mm/min

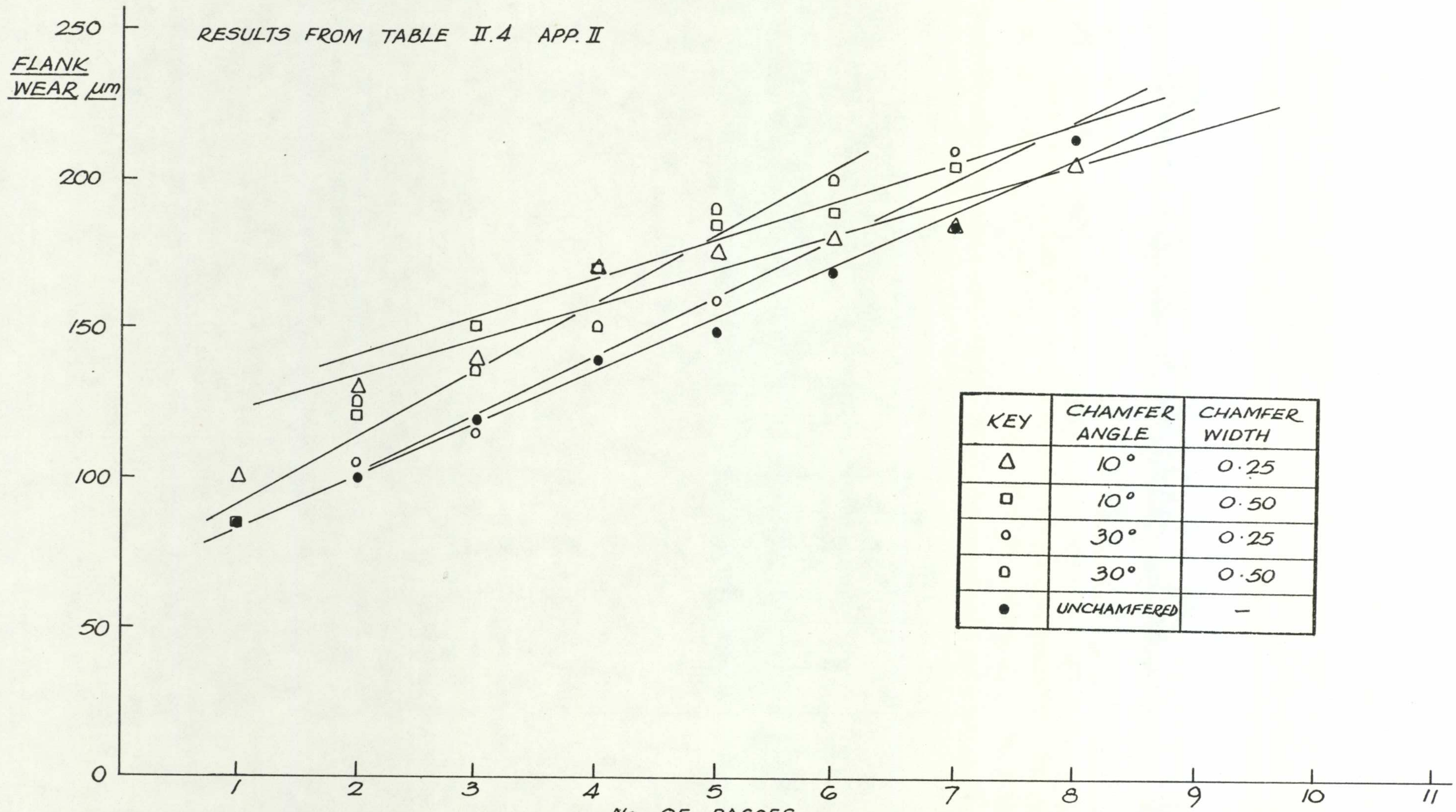


FIG 4.34 POSITIVE RAKE DOWN-CUT MILLING 460 REV/MIN FEEDRATE 89 mm/min

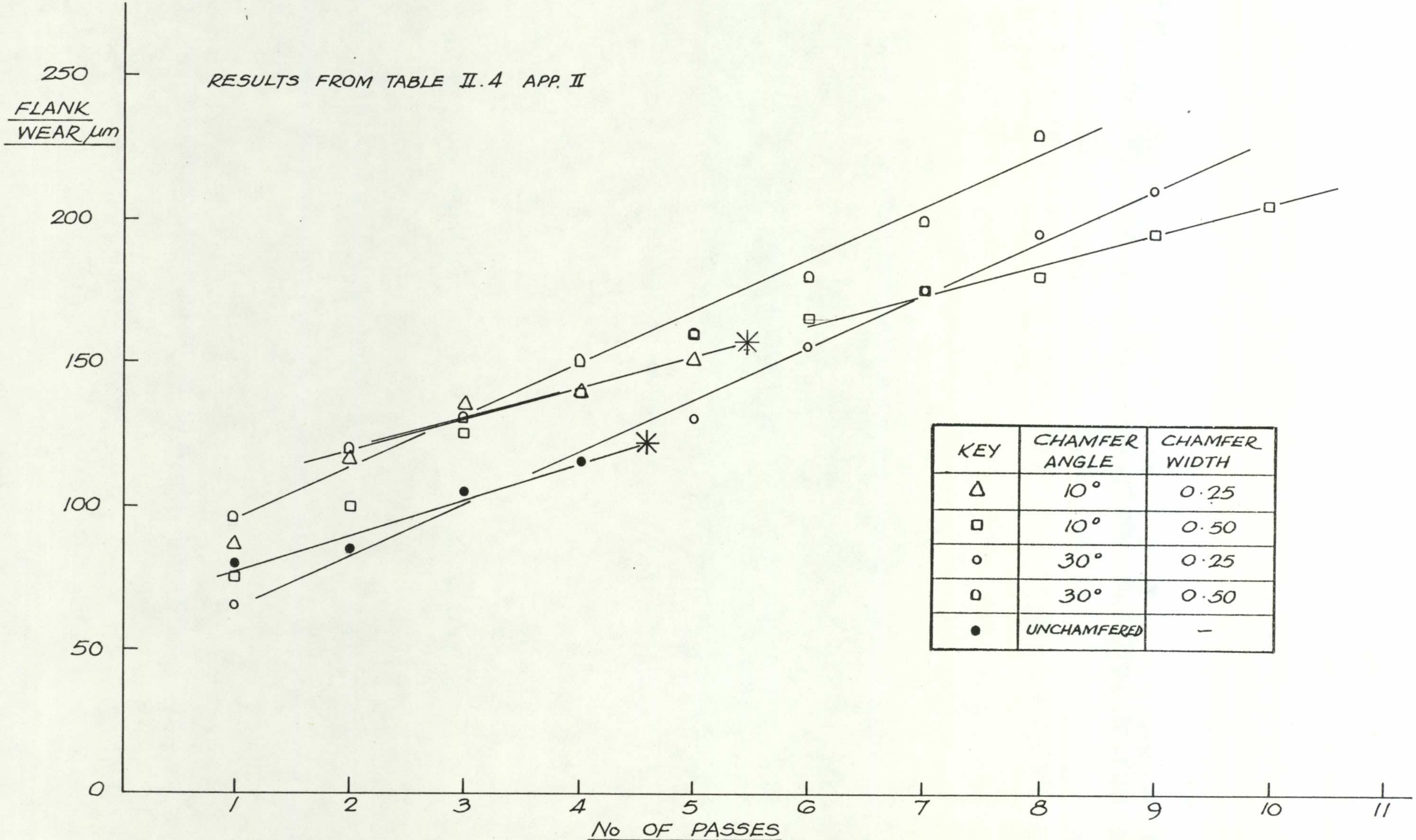


FIG 4.35 POSITIVE RAKE DOWN-CUT MILLING 460 REV/MIN FEEDRATE 175 mm/min

FIG 4.36 NEGATIVE INSERT - 10 SEC USE X360

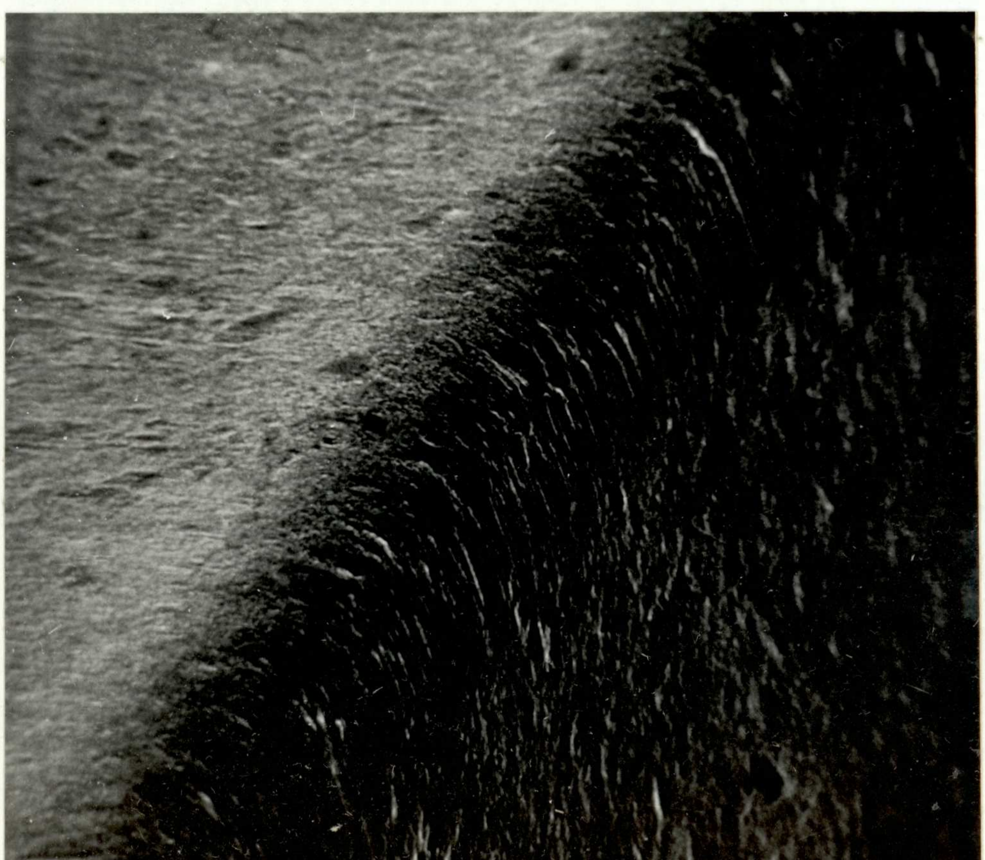


FIG 4.37 NEGATIVE INSERT - 30 SEC USE X360

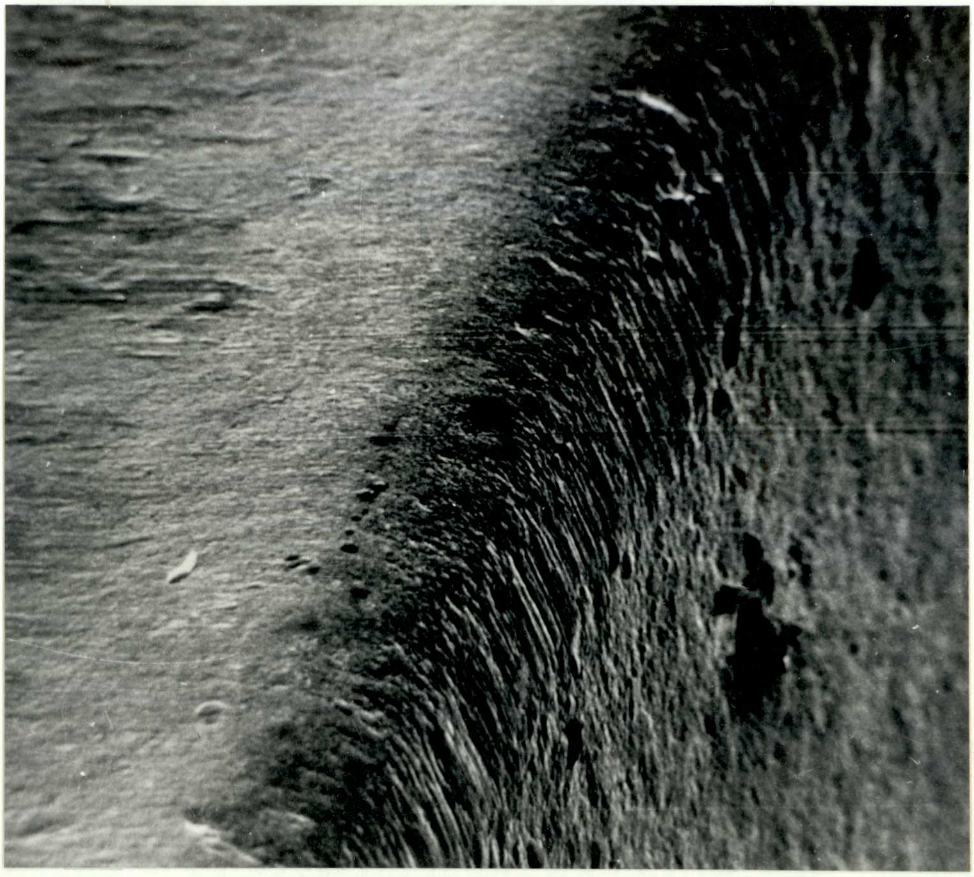


FIG 4.38 NEGATIVE INSERT - 60 SEC USE X360

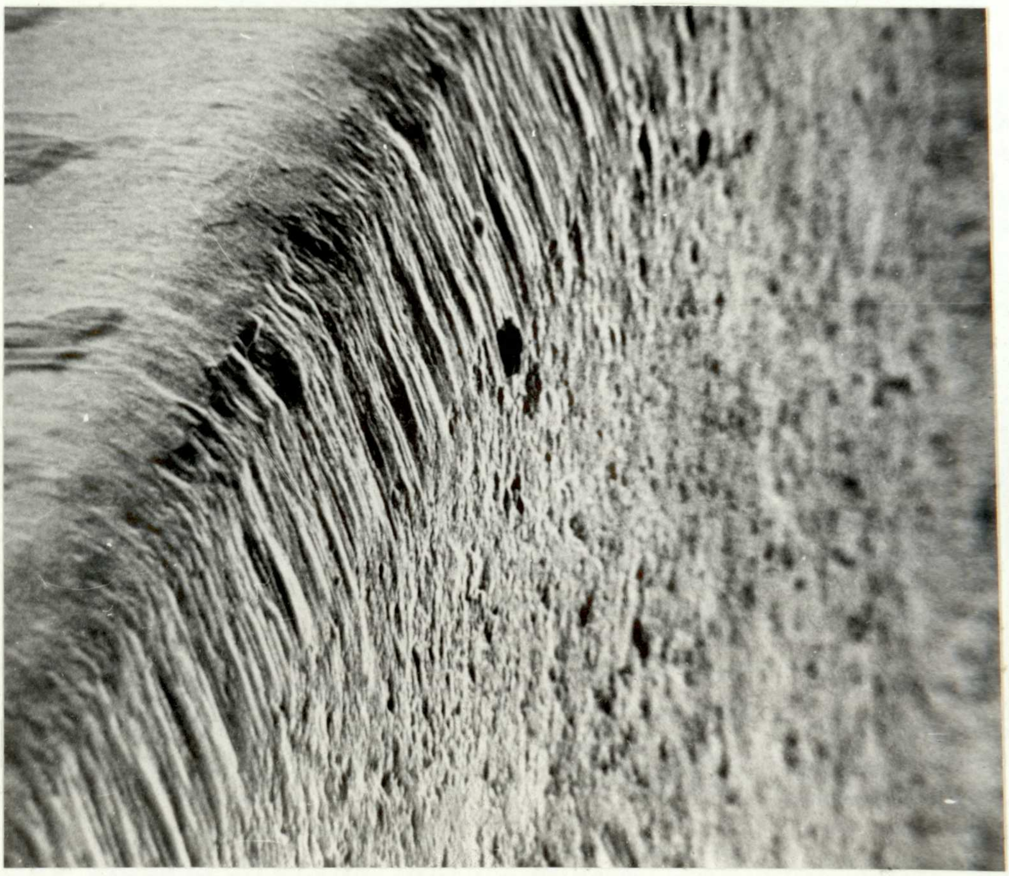


FIG 4.39 NEGATIVE INSERT - 5 MIN USE X360

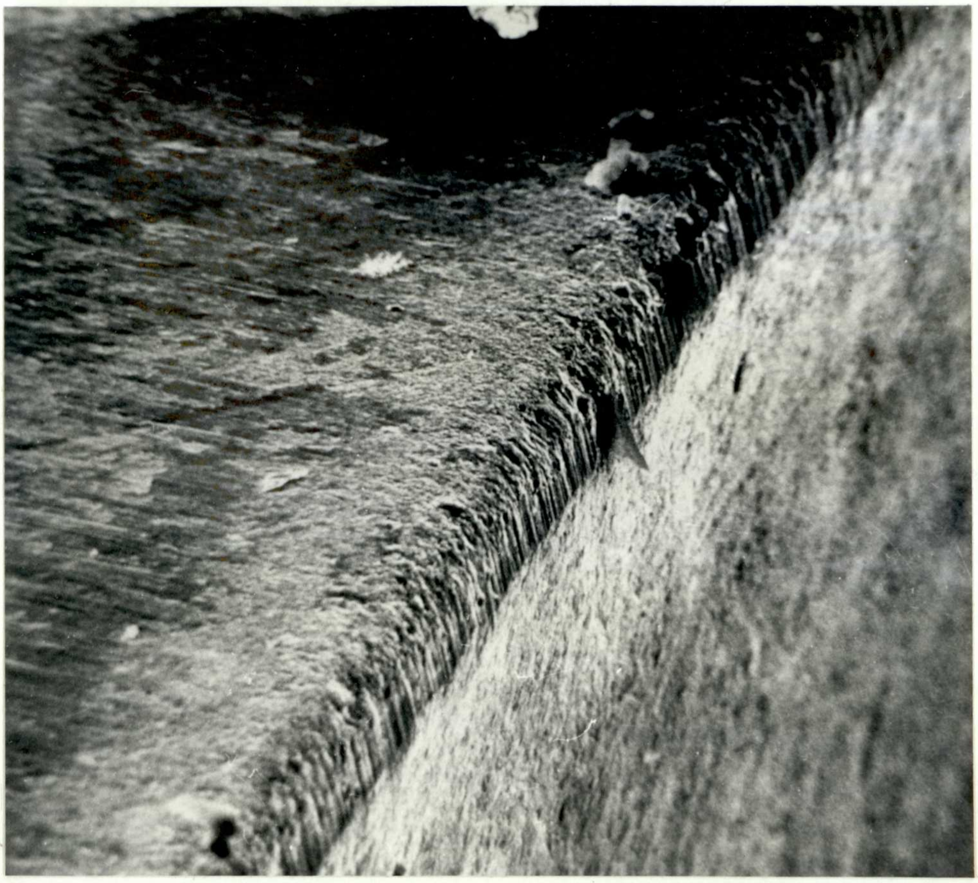


FIG 4.40 POSITIVE INSERT - 10 SEC USE X 360

FIG 4.41 POSITIVE INSERT - 30 SEC USE X 360

FIG 4.42 POSITIVE INSERT - 60 SEC USE X360

FIG 4.43 POSITIVE INSERT - 5 MIN USE X360

FIG 4.44 POSITIVE INSERT - 5 MIN USE X900

FIG 4.45 POSITIVE INSERT - 5 MIN USE X3600

CHAPTER 5

EXTENDED CUTTING TESTS

CHAPTER 5: EXTENDED CUTTING TESTS

The conclusions obtained from the previous cutting tests prompted a fuller investigation, with the object of establishing an optimum chamfer angle, for positive rake and negative rake inserts when face milling EN 8 steel.

The cutting tests were carried out using the procedure developed earlier and detailed in Section 4.1. A single insert was held in the cutter, cuts of 3 mm were taken with the spindle rotating at 460 rev/min, (145 m/min cutting speed) and feedrates of 45, 89 and 110 m/min were used.

Standard unchamfered inserts were used as a control and positive rake and negative rake inserts were chamfered with angles ranging from 5^{o} to 45^{o} in increments of 5^{o}. The widths of chamfer used were 0.25 mm and 0.5 mm as in the previous test.

Each insert was used to take eight, 3 mm cuts or passes along the testpiece, or less if the insert cutting edge failed by chipping or breaking. The flankwear on the insert was measured at the end of each pass and recorded (see Appendix III).

Using linear regression the number of passes to produce a flankwear of 150µm on each insert was determined and the results plotted against the chamfer angle for each combination of feedrate, chamfer width and machining mode (i.e. up-cut or down-cut milling) figs 5.1 to 5.18.

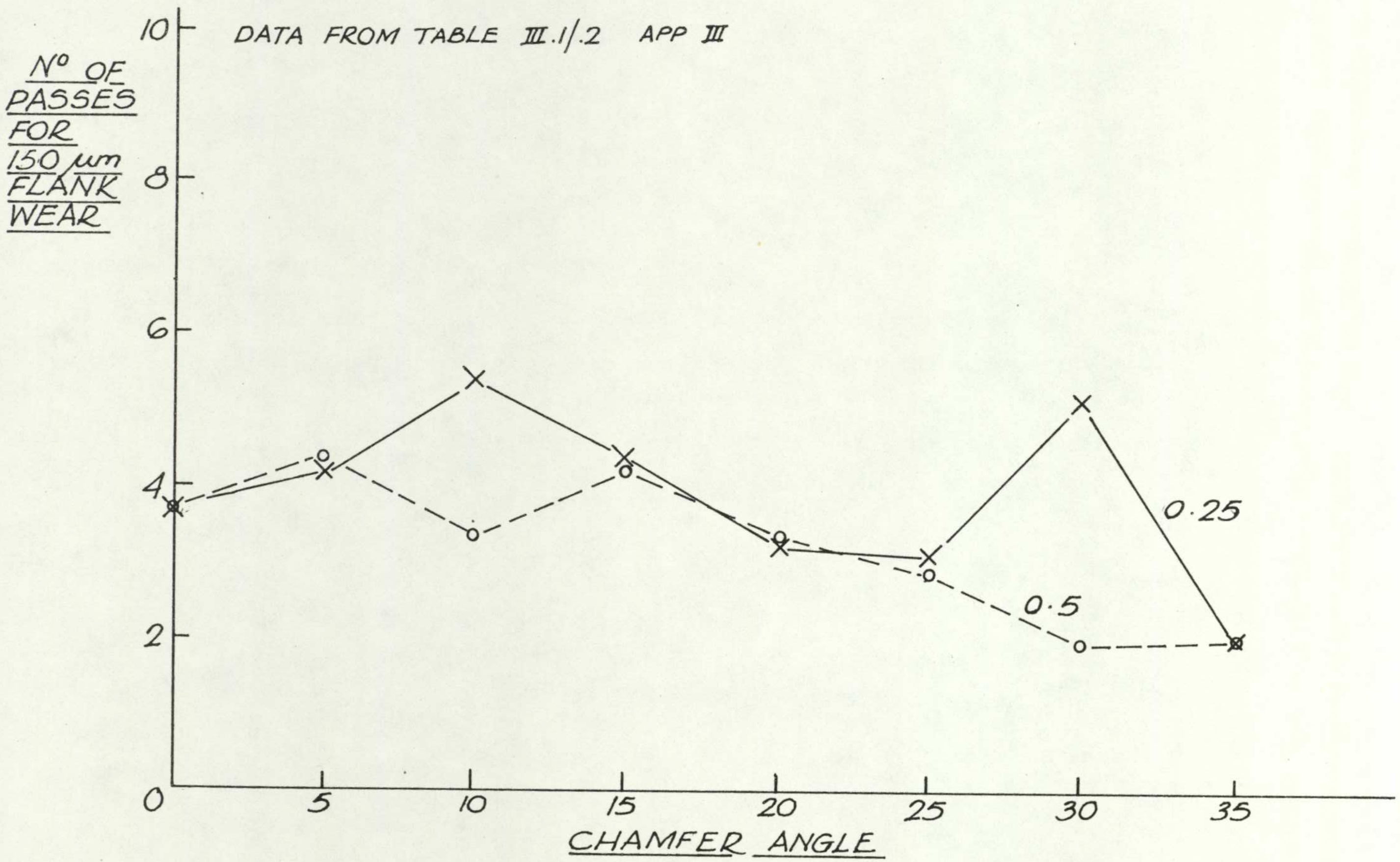
From the graphs obtained for the positive rake inserts it appeared that maximum tool life occurred when the chamfer angle on the insert was in the vicinity of 15^{o} to 25^{o}. As an aid towards establishing the best chamfer angle a computer programme was written (fig 5.19) to fit a polynomial to the points. From the derived equation the turning point for each curve was calculated and hence the chamfer angle, giving the greatest tool life. The figures are shown on the graphs.

5.1 Conclusions

1. The unchamfered positive rake inserts failed when up-cut milling at feedrates in excess of 45 mm/min. At the higher feedrates any chamfer angle produced an improvement in tool life. The improvement was probably due to the chamfer directing the cutting forces into the body of the tool, effectively increasing the strength of the cutting edge. This apparent increase in strength makes the insert capable of withstanding the impact forces.
2. There is no evidence to suggest that a particular chamfer angle on negative rake inserts would maximise tool life. As can be seen in figs 5.1 and 5.2 there is no apparent law relating chamfer angle and tool life. It can be claimed however, that in the majority of cases an improvement in tool life was obtained by chamfering the cutting

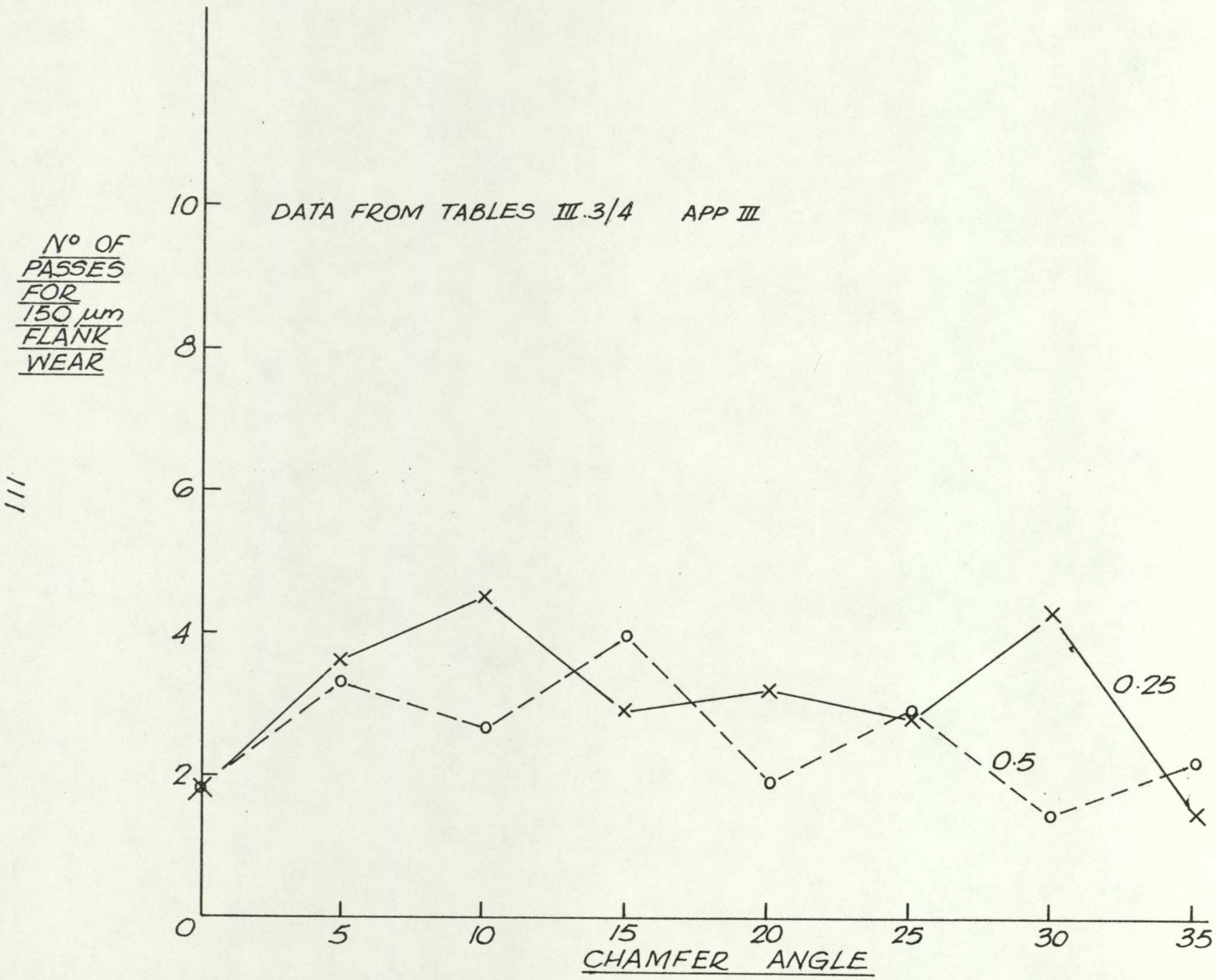
edge, probably due to a slight increase in strength because of the modified edge geometry.

3. When considering figs 5.3 to 5.14 with a few exceptions the best chamfer angle for positive rake inserts lay between 15^{o} and 25^{o}. This suggested that an optimum angle exists for the positive rake inserts whatever chamfer width was ground on the tool. It also appears to be true for any of the feedrates used.
4. Generally the inserts having a chamfer width of 0.5 mm performed better than those with a 0.25 mm chamfer.
5. Down-cut milling produced longer tool life than up-cut milling when using positive rake inserts, but the negative rake tools performed better when up-cut milling.
6. The tool life increased as the feedrate increased for a given cutting speed. This confirmed earlier findings but it must be considered in the context of using only one insert in the facemill. See Section 4.1.1.



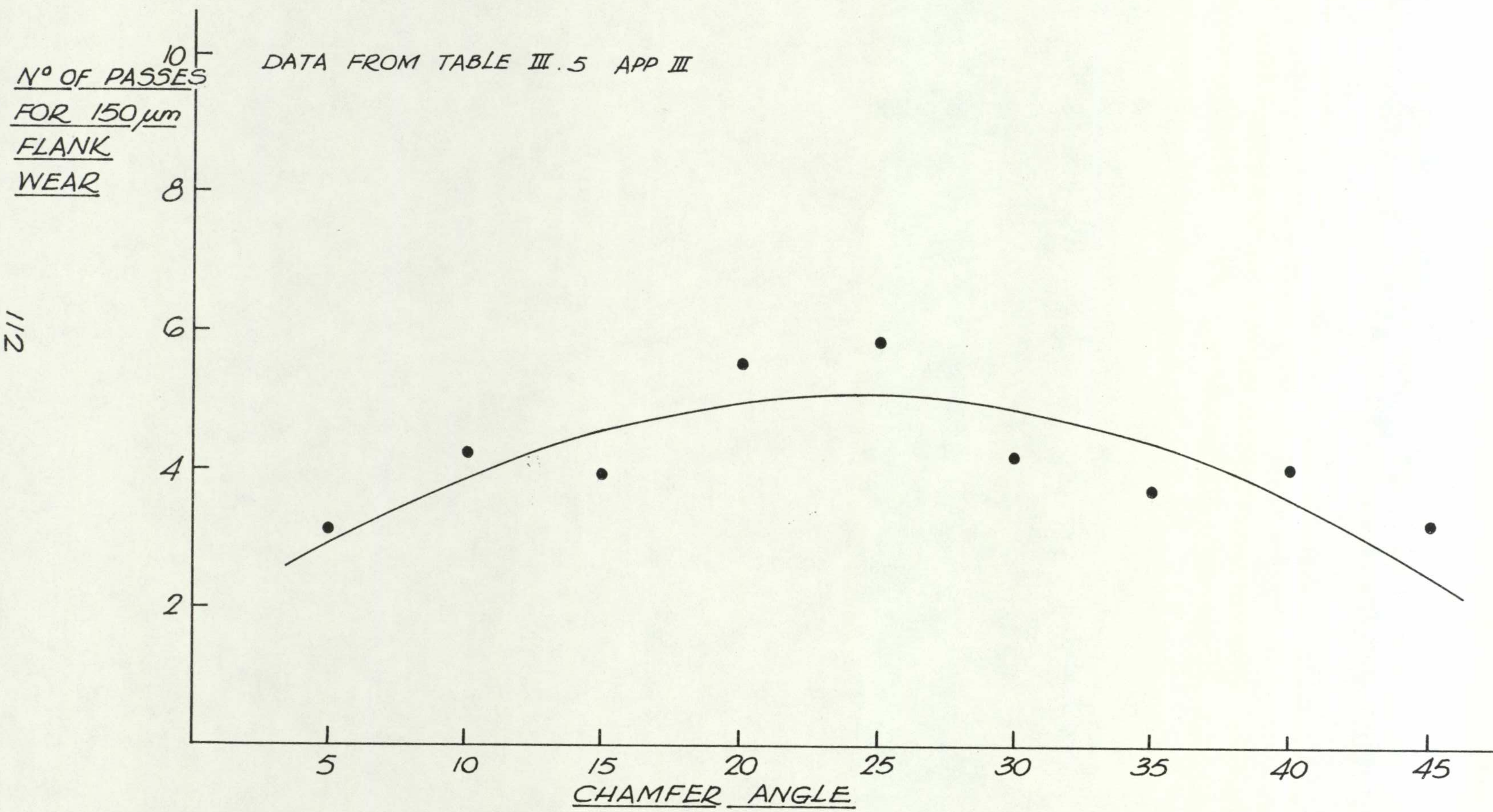
CHAMFER ANGLE	TOOL LIFE 0·25	0·50
0	3·7	3·7
5	4·2	4·4
10	5·4	3·3
15	4·4	4·2
20	3·2	3·3
25	3·1	2·8
30	5·1	1·9
35	2·0	2·0

FIG 5.1 NEGATIVE RAKE UP-CUT MILLING 460 REV/MIN 89 mm/MIN FEED



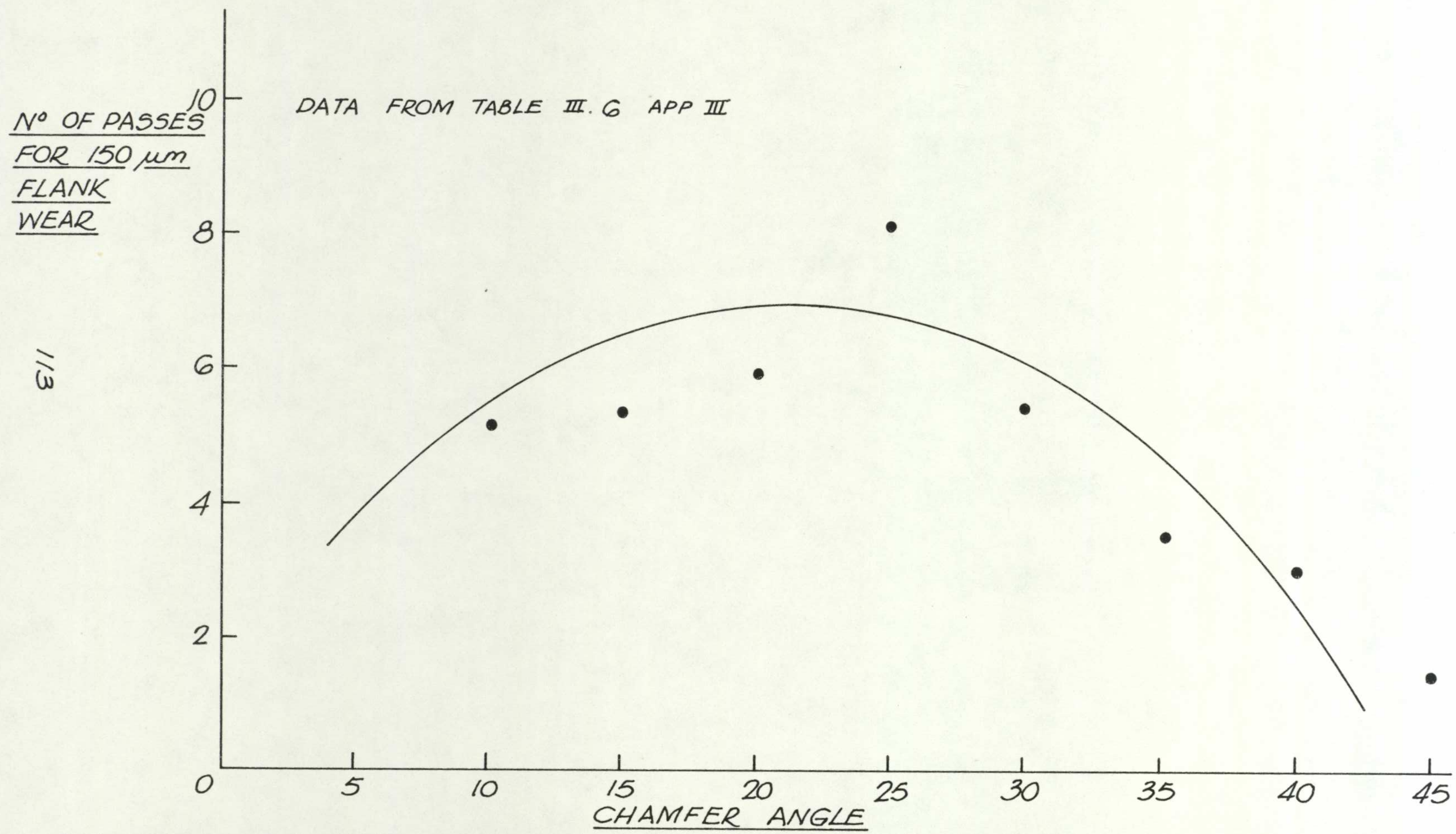
CHAMFER ANGLE	TOOL LIFE 0.25	0.50
0	1.8	1.8
5	3.6	3.3
10	4.5	2.7
15	2.9	4.0
20	3.2	1.9
25	2.8	2.9
30	4.3	1.5
35	1.5	2.2

FIG 5.2 NEGATIVE RAKE DOWN-CUT MILLING 460 REV/MIN 89 mm/MIN FEED



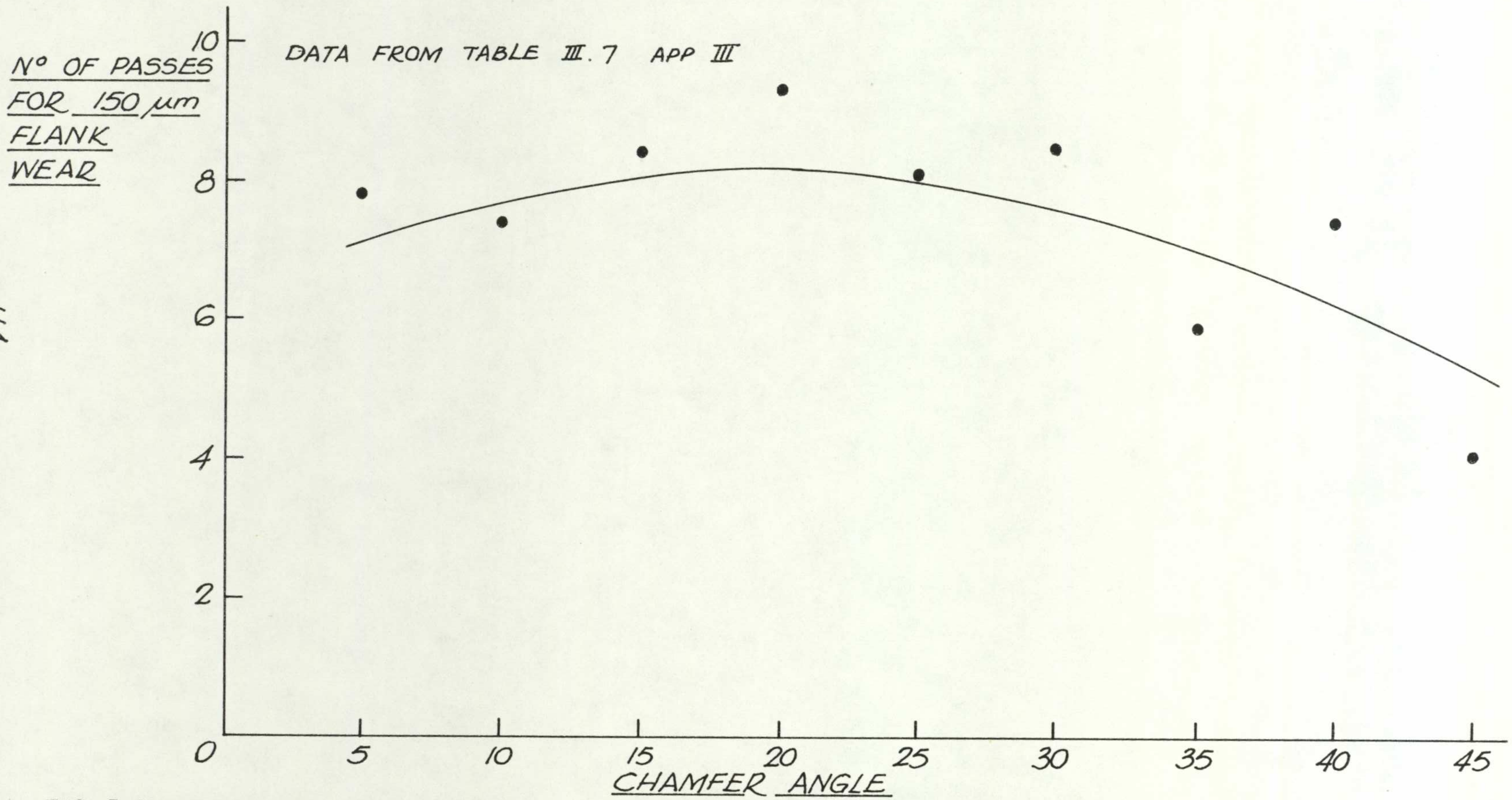
CHAMFER ANGLE	TOOL LIFE
0	FAILED <1
5	3·1
10	4·2
15	3·9
20	5·5
25	5·8
30	4·2
35	3·7
40	4·0
45	3·2

FIG 5.3 POSITIVE RAKE UP-CUT MILLING 0·25 CHAMFER 460 REV/MIN 89 mm/MIN FEED



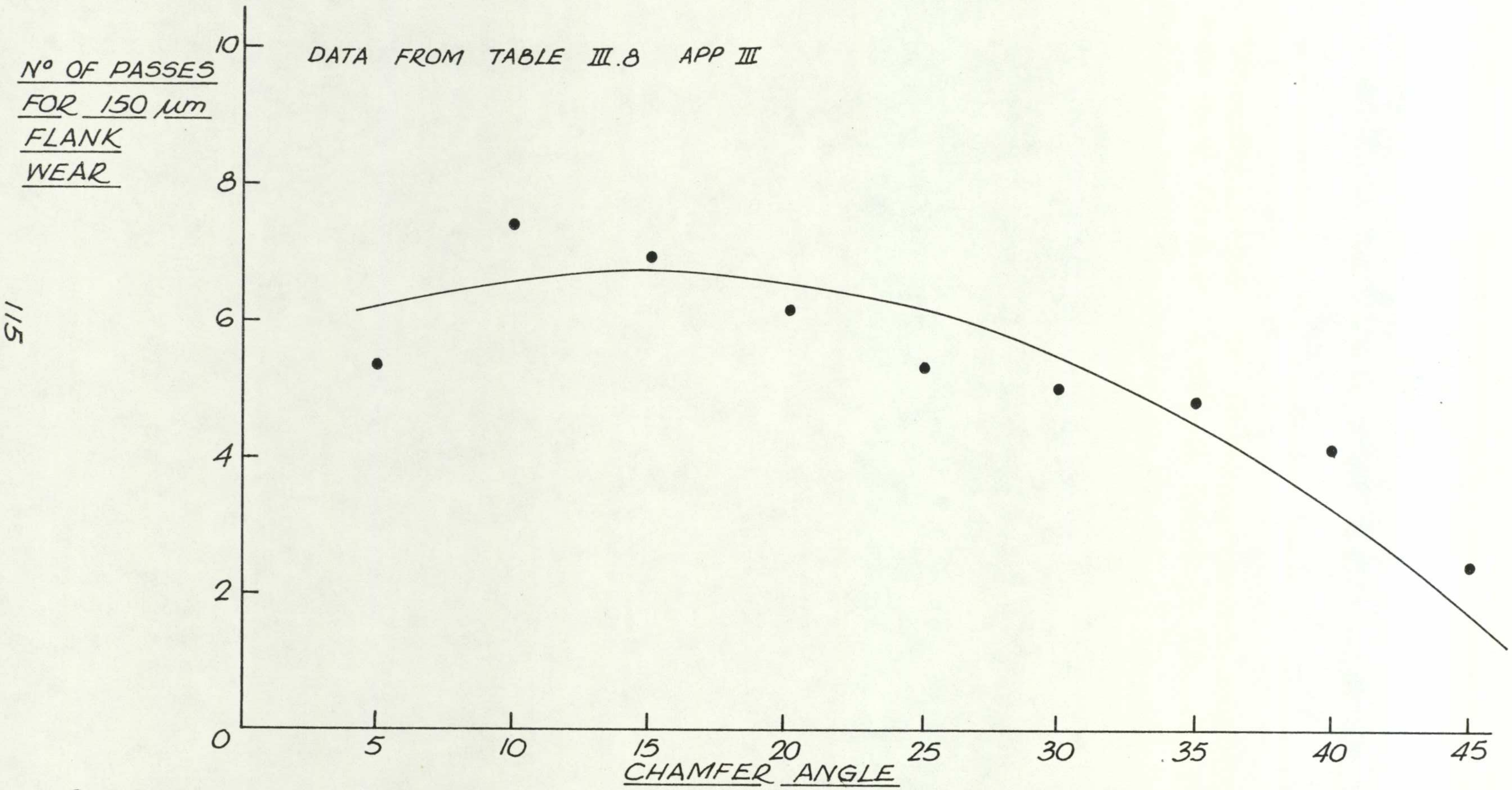
CHAMFER ANGLE	TOOL LIFE
0	F
5	F
10	5·1
15	5·3
20	5·9
25	8·1
30	5·4
35	3·5
40	3·0
45	1·4

FIG 5.4 POSITIVE RAKE UP-CUT MILLING 0·5 CHAMFER 460 REV/MIN 89 mm/MIN FEED



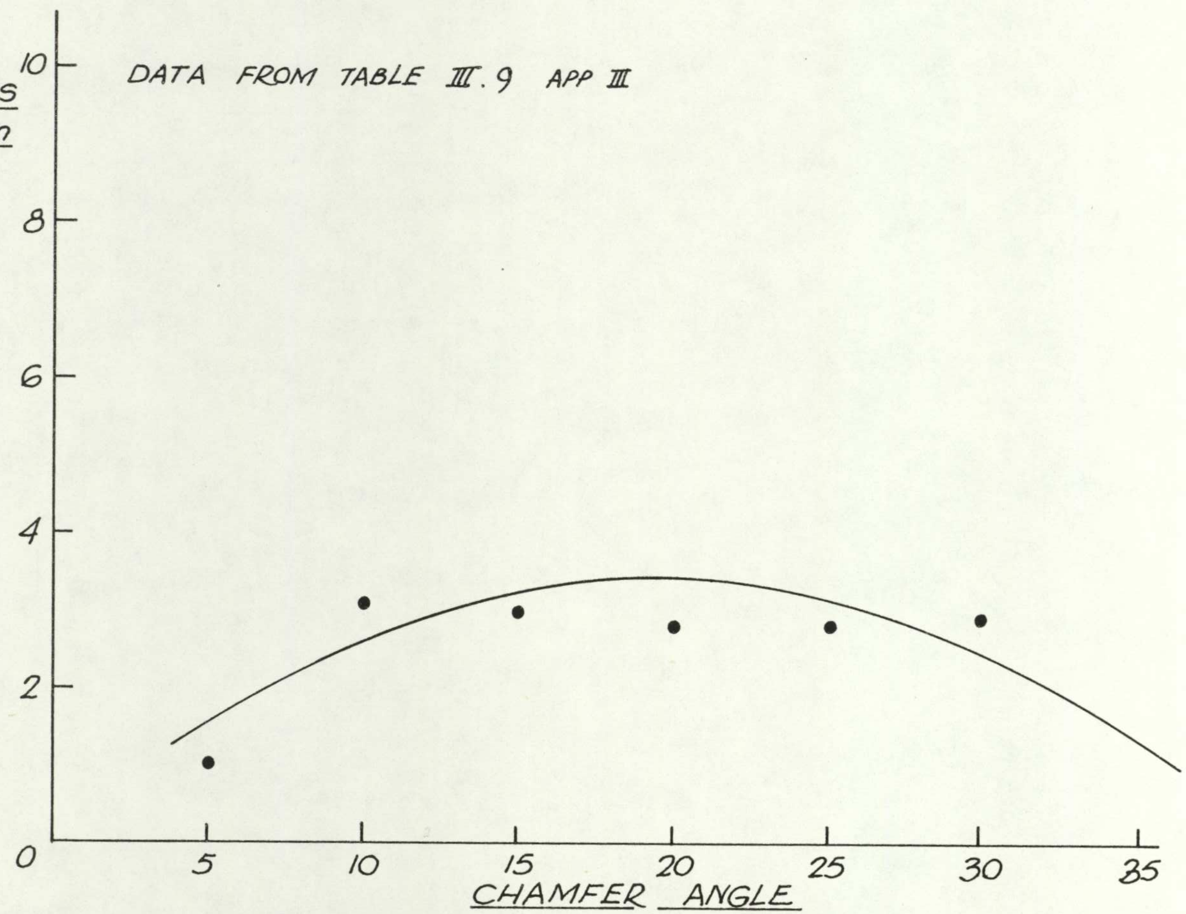
CHAMFER ANGLE	TOOL LIFE
0	8·4
5	7·8
10	7·4
15	8·4
20	9·3
25	8·1
30	8·5
35	5·9
40	7·4
45	4·0

FIG 5.5 POSITIVE RAKE DOWN-CUT MILLING 0·25 CHAMFER 460 REV/MIN 89mm/MIN FEED



CHAMFER ANGLE	TOOL LIFE
0	8.4
5	5.3
10	7.4
15	6.9
20	6.1
25	5.3
30	5.0
35	4.8
40	4.1
45	2.4

FIG 5.6 POSITIVE RAKE DOWN CUT MILLING 0.5 CHAMFER 460 REV/MIN 89 mm/MIN FEED



CHAMFER ANGLE	TOOL LIFE
0	2·9
5	1·0
10	3·1
15	3·0
20	2·8
25	2·8
30	2·9

FIG 5.7 POSITIVE RAKE UP-CUT MILLING 0·25 CHAMFER 460 REV/MIN 45 mm/MIN FEED

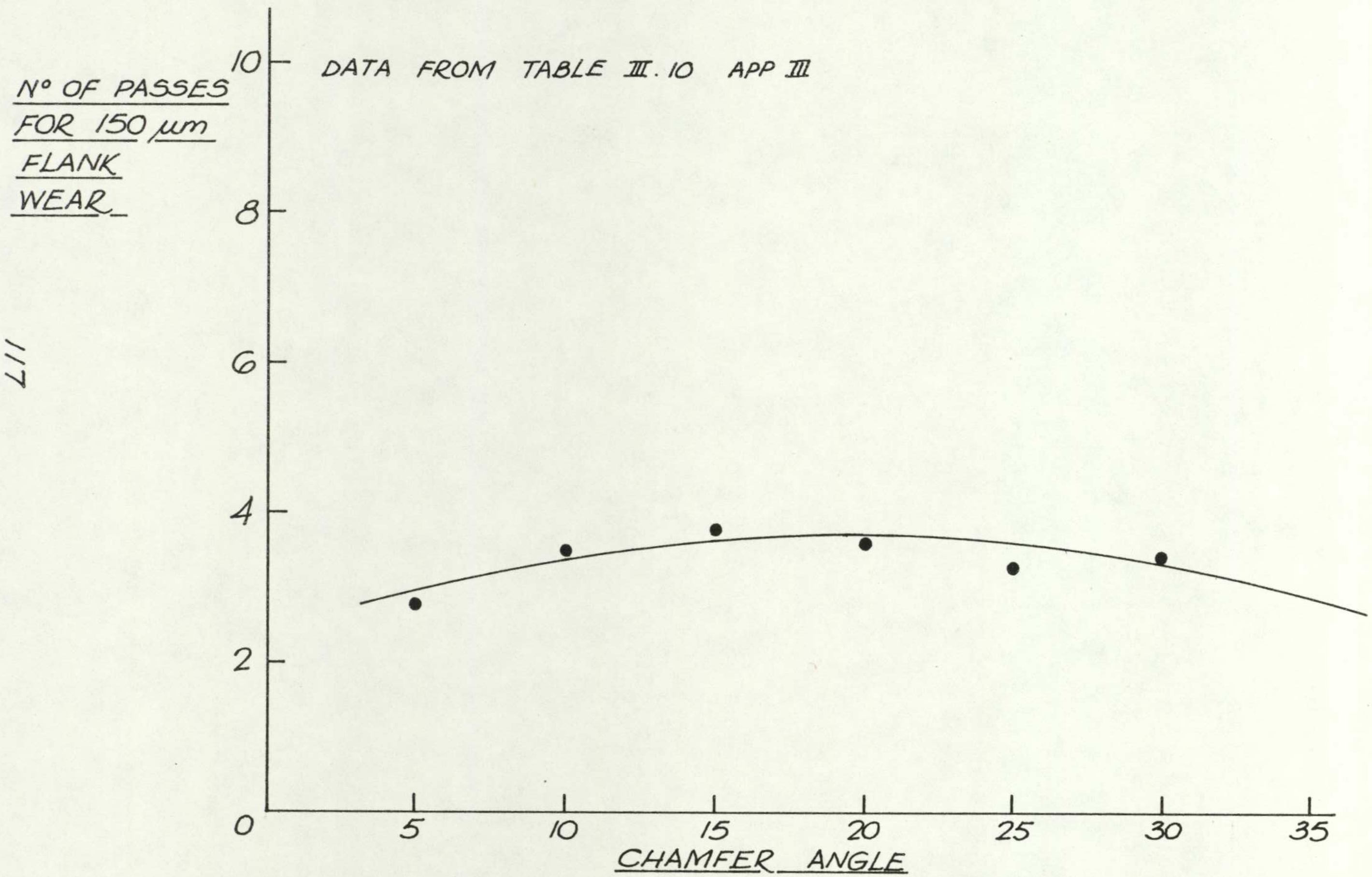
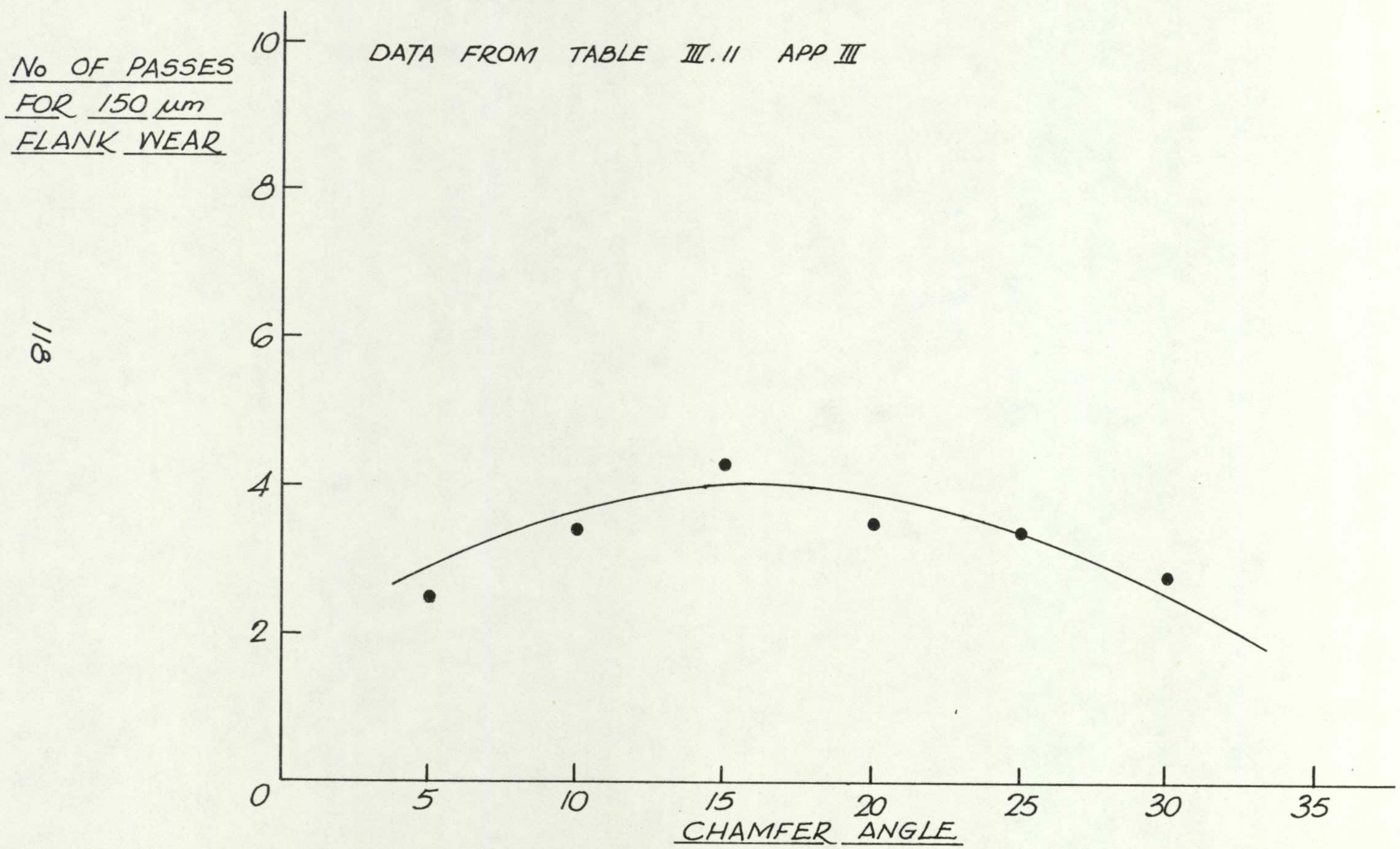


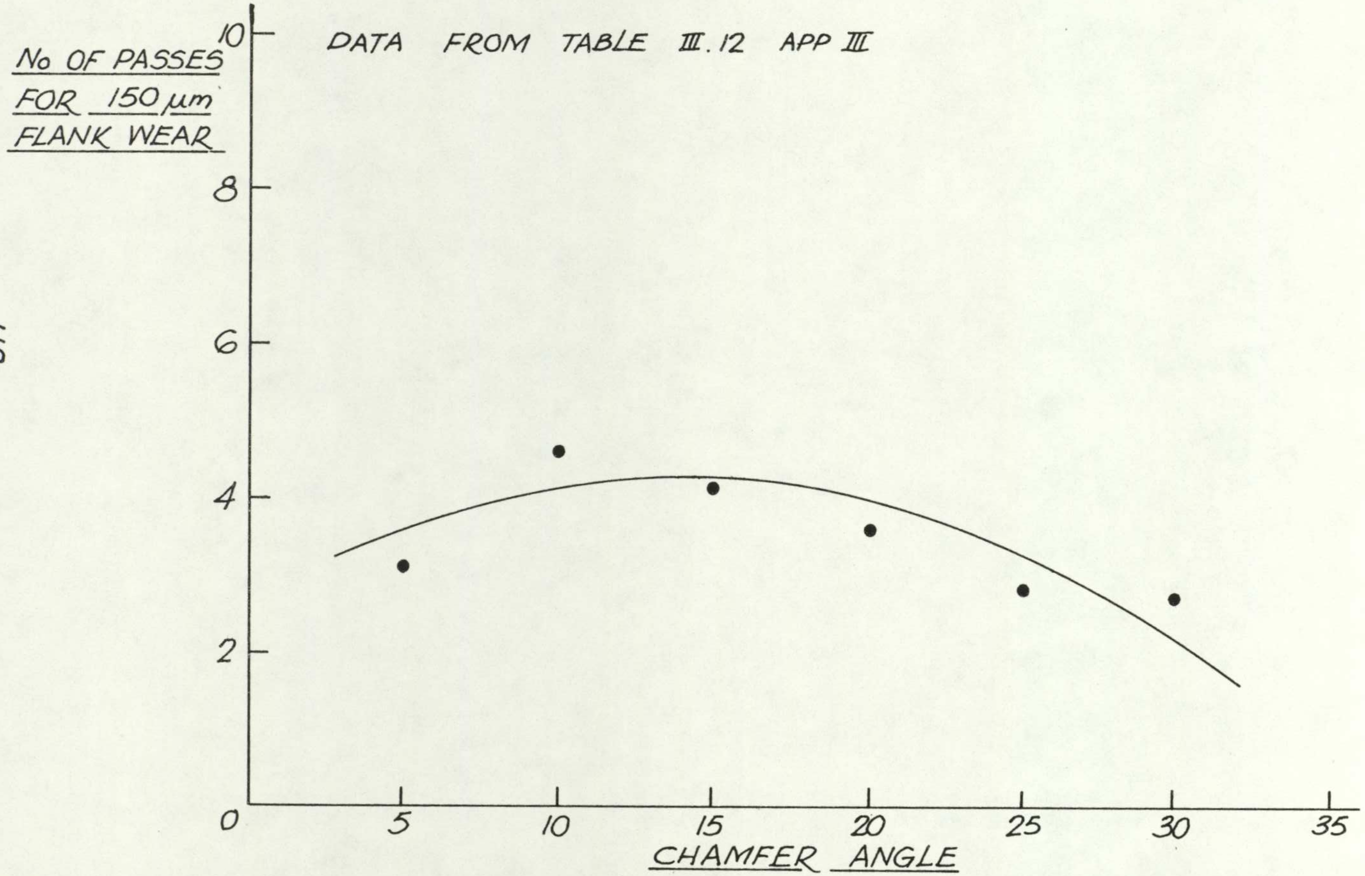
FIG 5.8 POSITIVE RAKE UP-CUT MILLING 0·5 CHAMFER 460 REV/MIN 45 mm/MIN FEED

CHAMFER ANGLE	TOOL LIFE
0	2·9
5	2·8
10	3·5
15	3·8
20	3·6
25	3·3
30	3·4



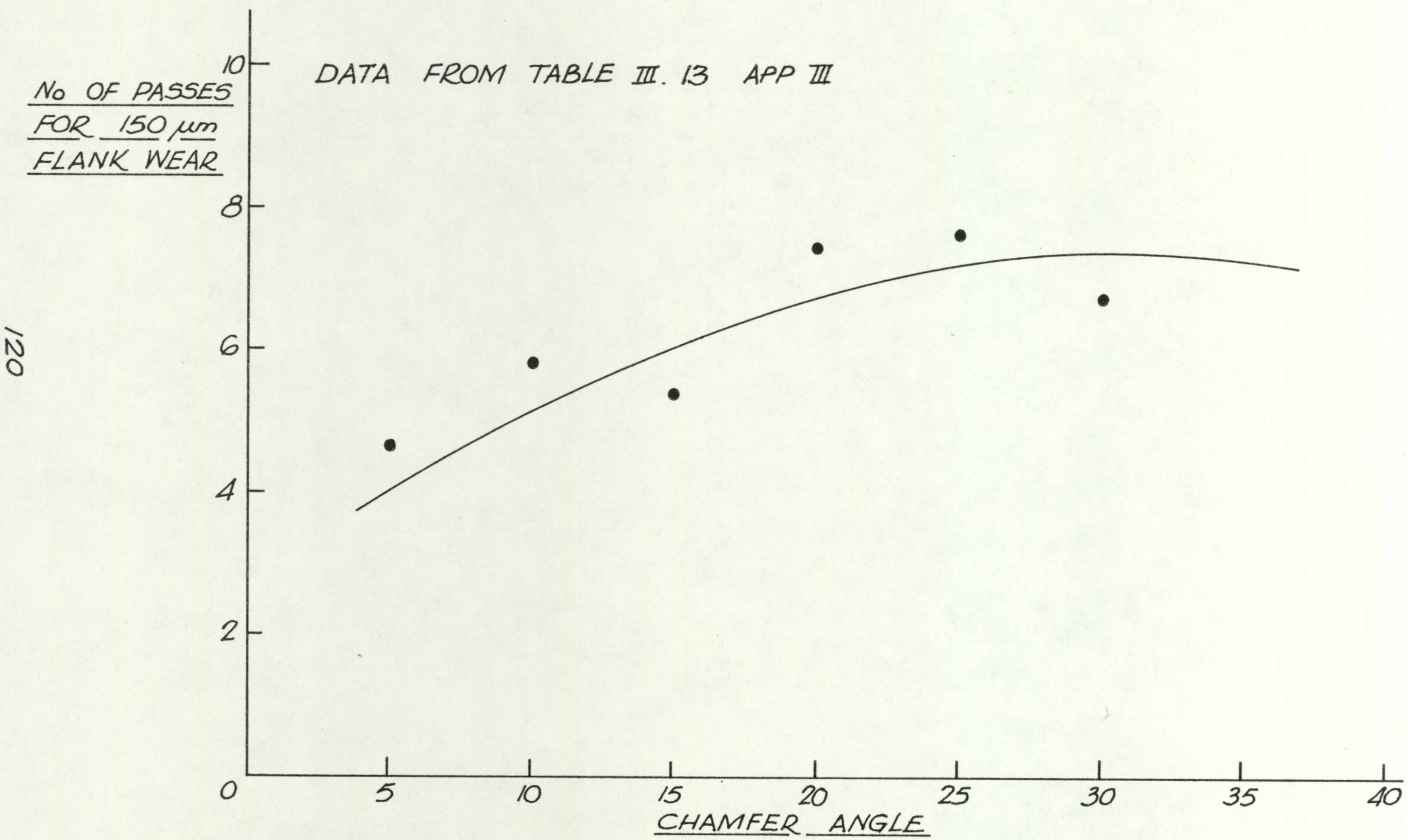
CHAMFER ANGLE	TOOL LIFE
5	2·5
10	3·4
15	4·3
20	3·5
25	3·4
30	2·8

FIG 5.9 POSITIVE RAKE DOWN-CUT MILLING 0·25 CHAMFER 460 REV/MIN 45 mm/MIN FEED



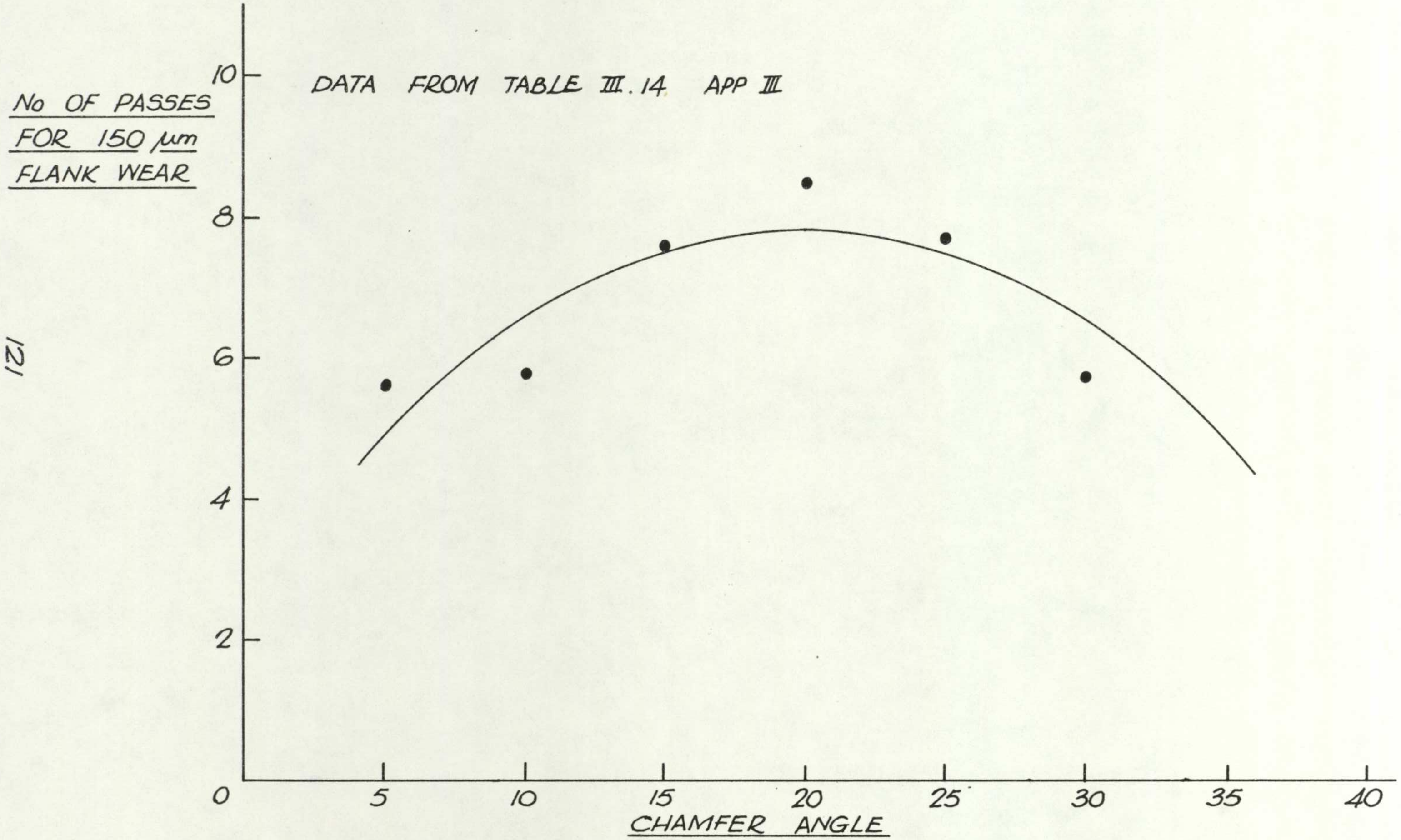
CHAMFER ANGLE	TOOL LIFE
0	4·3
5	3·1
10	4·6
15	4·1
20	3·6
25	2·8
30	2·7

FIG 5.10 POSITIVE RAKE DOWN-CUT MILLING 0·5 CHAMFER 460 REV/MIN 45 mm/MIN FEED



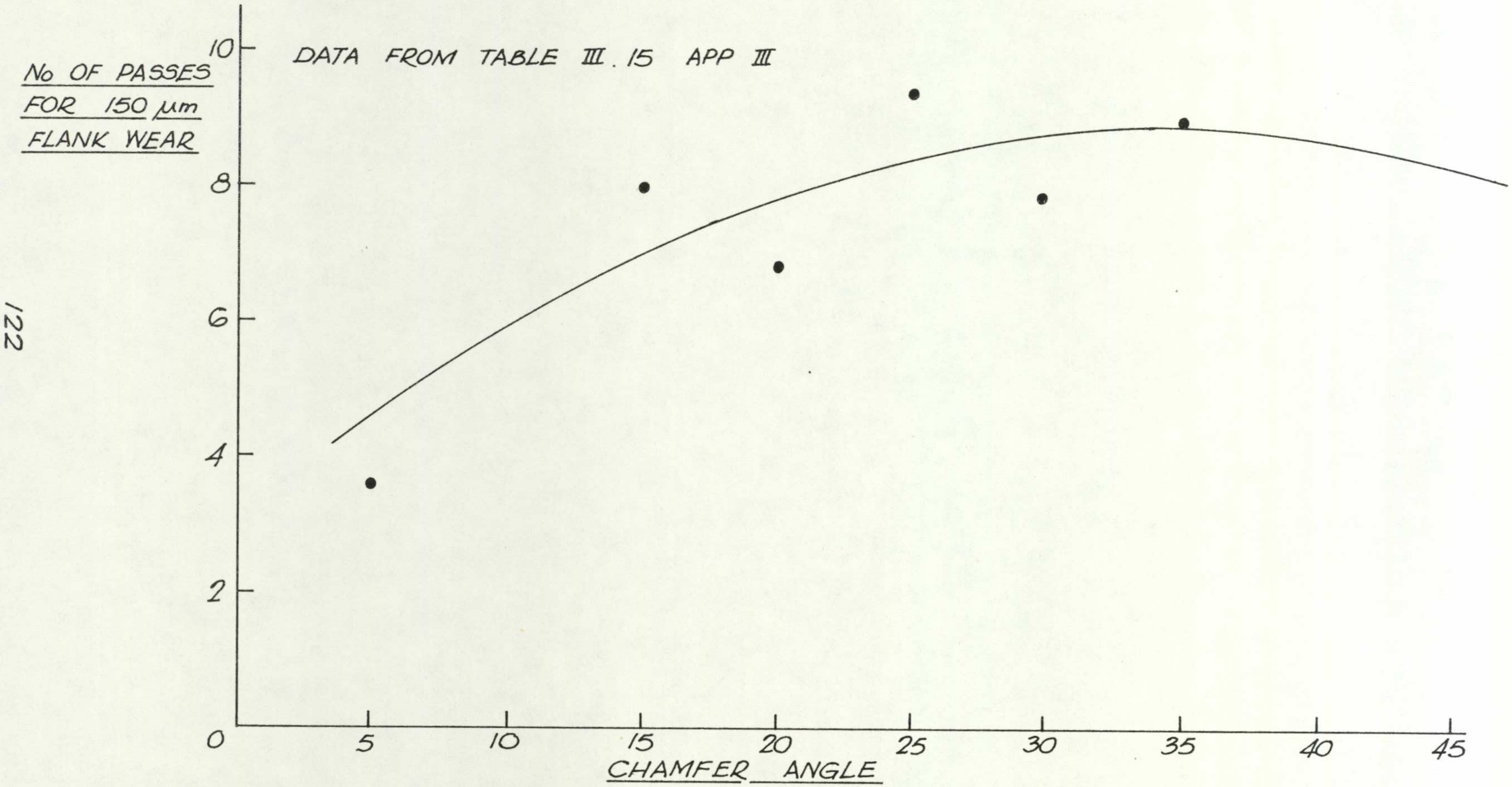
CHAMFER ANGLE	TOOL LIFE
0	FAILED
5	4·6
10	5·8
15	5·4
20	7·4
25	7·6
30	6·7

FIG 5.11 POSITIVE RAKE UP-CUT MILLING 0·25 CHAMFER 460 REV/MIN 175 mm/MIN FEED



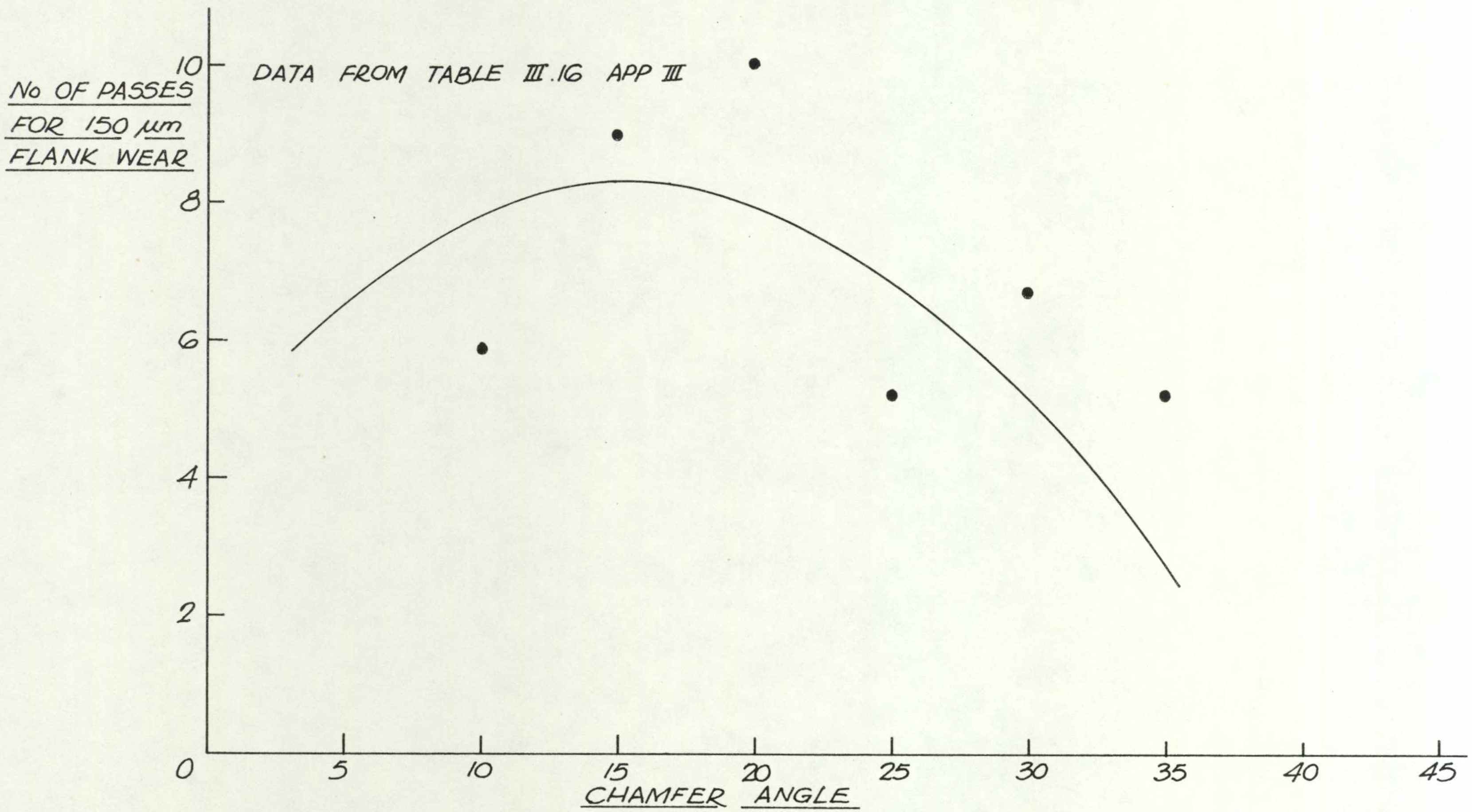
CHAMFER ANGLE	TOOL LIFE
0	FAILED
5	5·6
10	5·8
15	7·6
20	8·5
25	7·7
30	5·7

FIG 5.12 POSITIVE RAKE UP-CUT MILLING 0·5 CHAMFER 460 REV/MIN 175 mm/MIN FEED



CHAMFER ANGLE	TOOL LIFE
0	6·9
5	3·6
10	FAILED
15	8·0
20	6·8
25	9·4
30	7·8
35	8·9

FIG 5.13 POSITIVE RAKE DOWN-CUT MILLING 0·25 CHAMFER 460 REV/MIN 175 mm/MIN FEED



CHAMFER ANGLE	TOOL LIFE
0	6·9
5	FAILED
10	5·9
15	9·0
20	10·0
25	5·2
30	6·7
35	5·2

FIG 5.14 POSITIVE RAKE DOWN-CUT MILLING 0·5 CHAMFER 460 REV/MIN 175 mm/MIN FEED

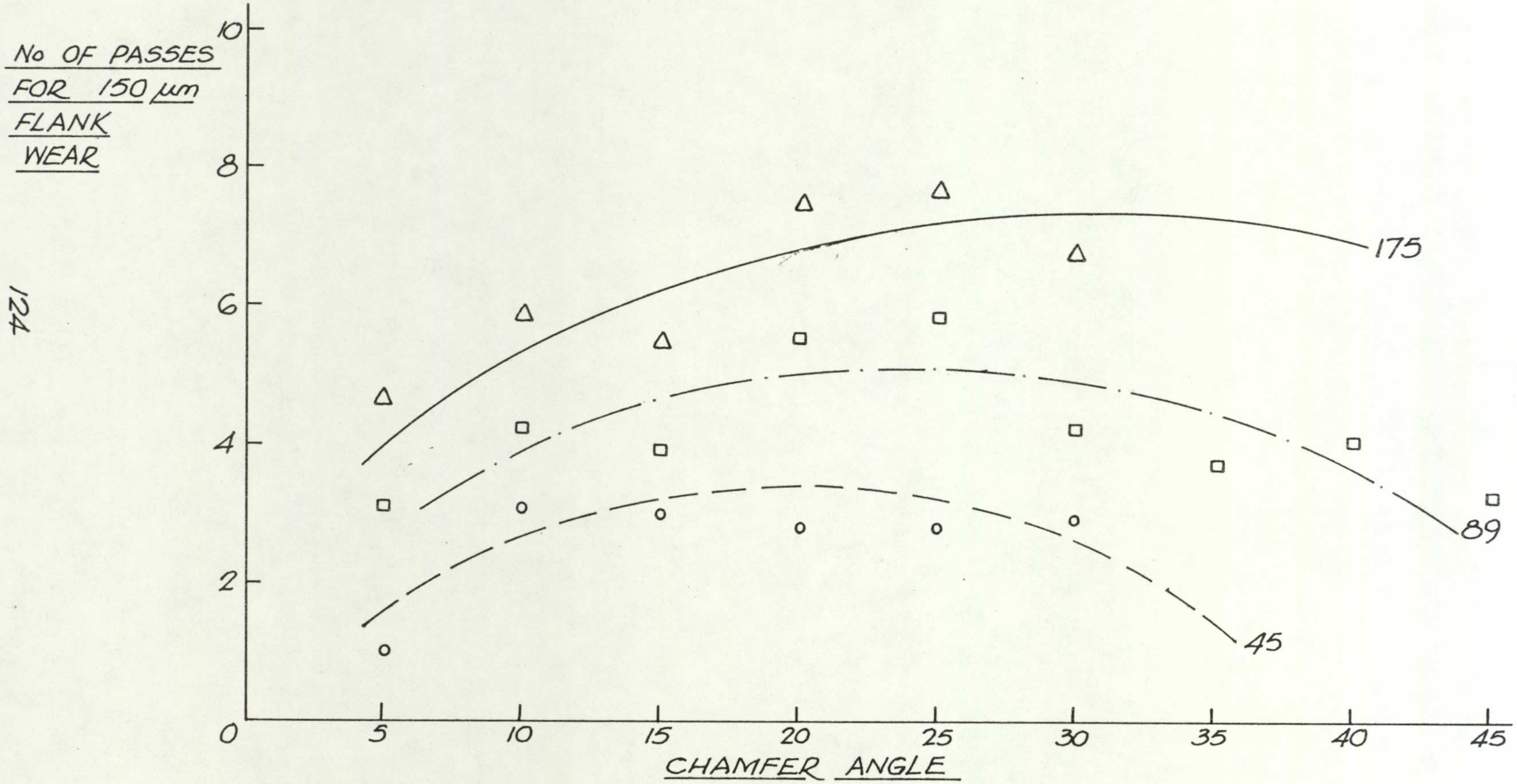


FIG 5.15 POSITIVE RAKE UP-CUT MILLING 0·25 CHAMFER 460 REV/MIN VARYING FEEDRATE

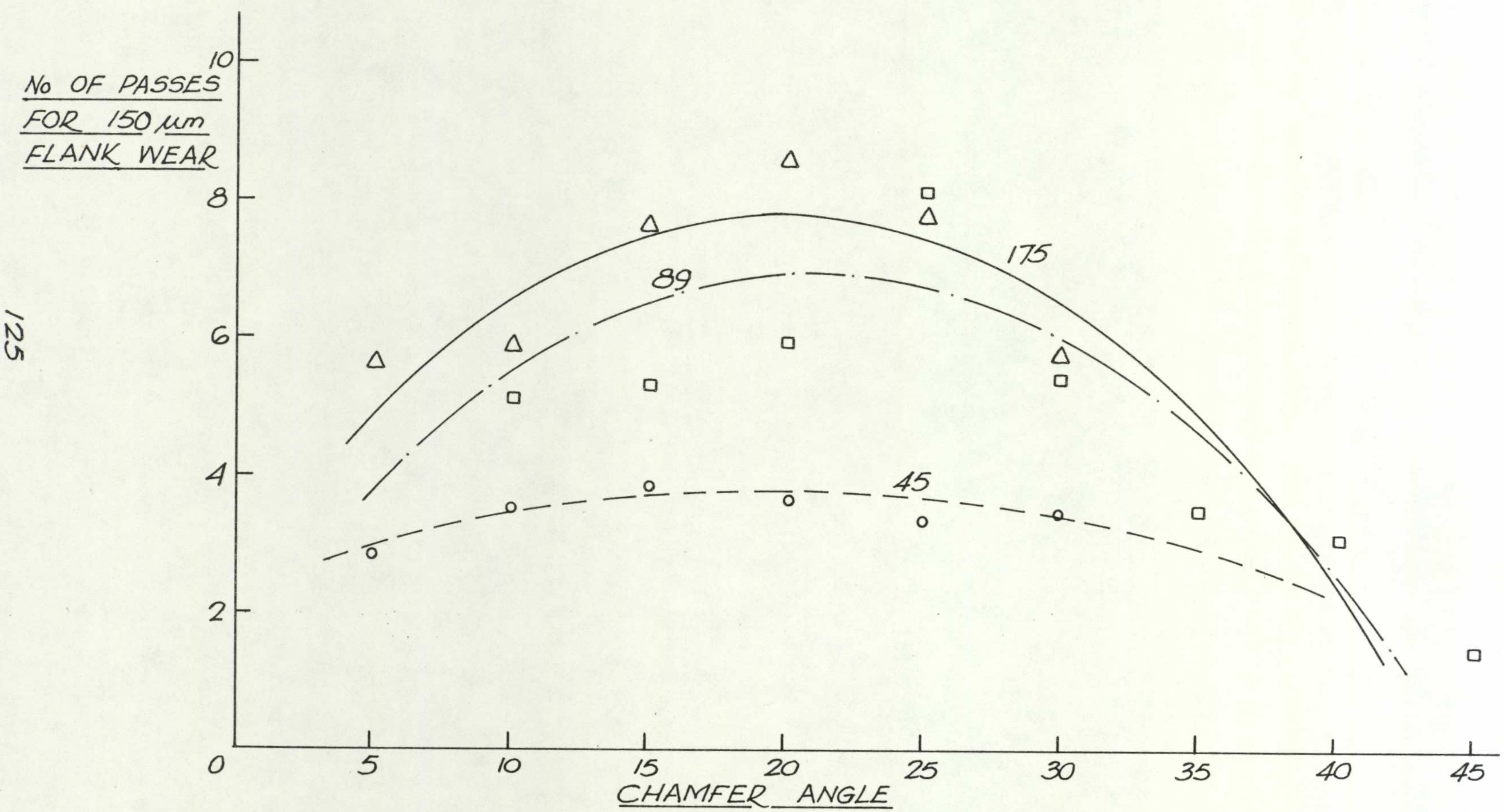


FIG 5.16 POSITIVE RAKE UP-CUT MILLING 0·5 CHAMFER 460 REV/MIN VARYING FEEDRATE

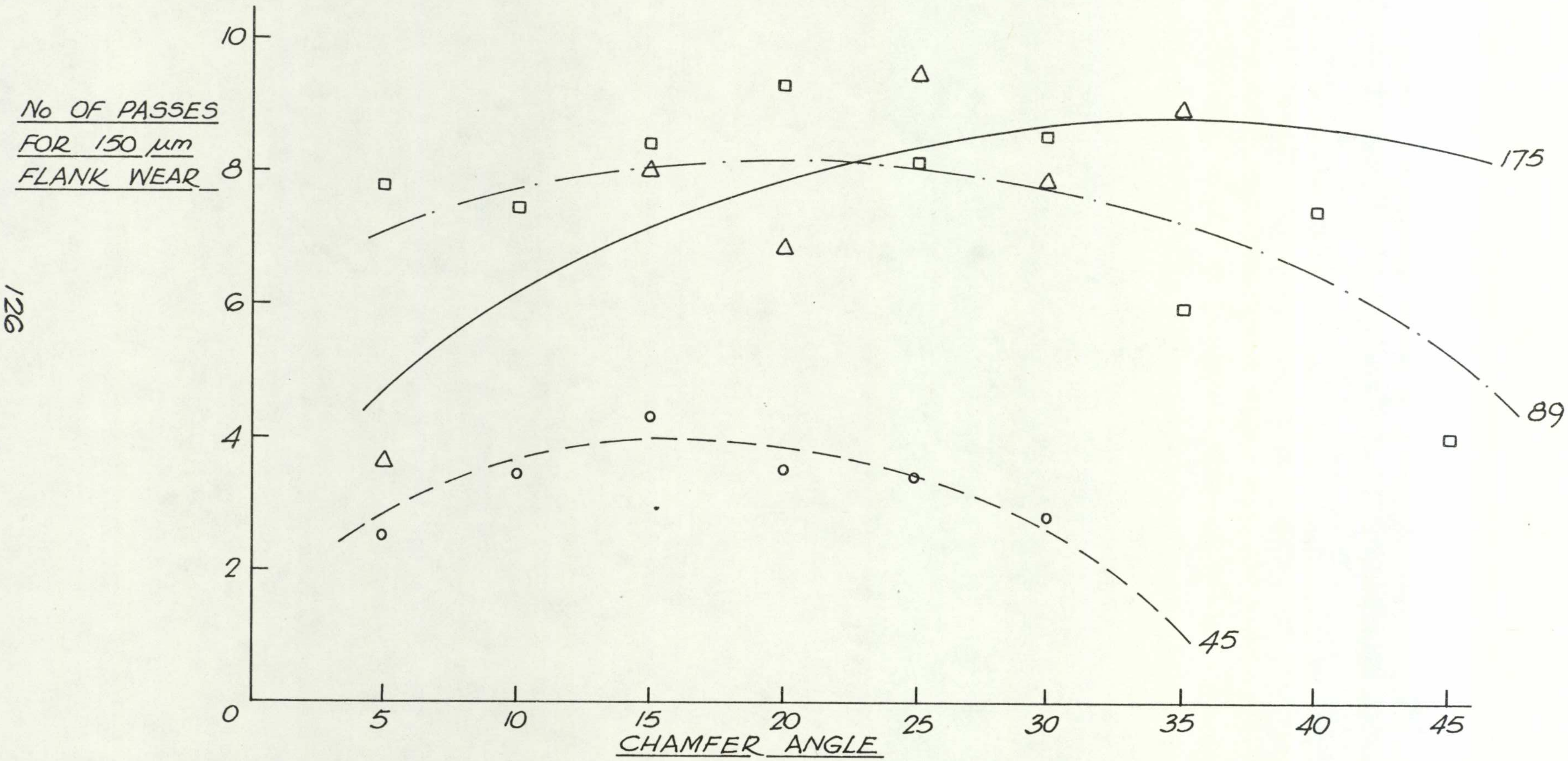


FIG 5.17 POSITIVE RAKE DOWN-CUT MILLING 0·25 CHAMFER 460 REV/MIN VARYING FEEDRATE

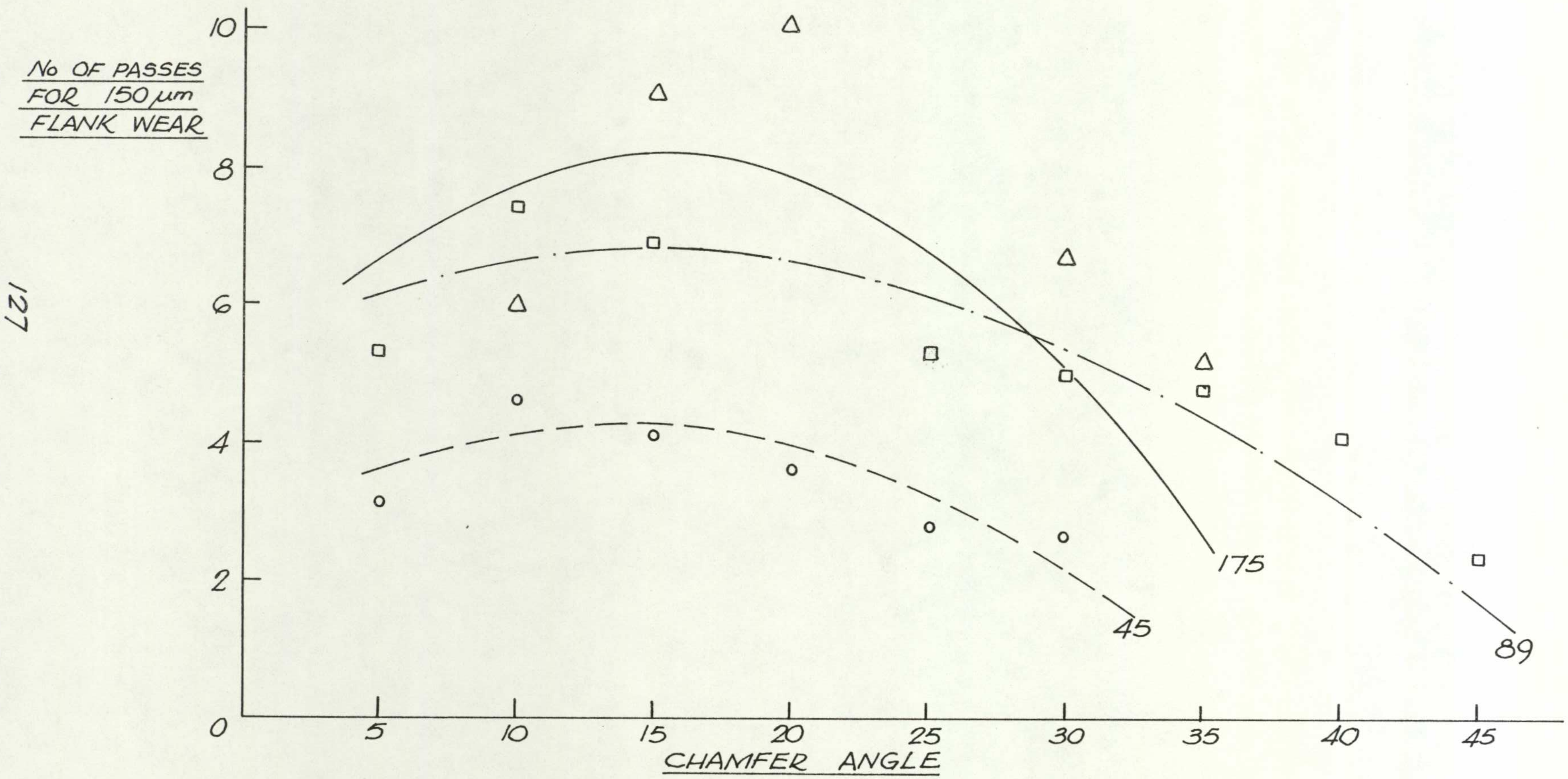


FIG 5.18 POSITIVE RAKE DOWN-CUT MILLING 0·5 CHAMFER VARYING FEEDRATE

CHAPTER 6

EFFECTS OF CHAMFER ANGLE, CHAMFER WIDTH AND FEEDRATE

CHAPTER 6: EFFECTS OF CHAMFER ANGLE, CHAMFER WIDTH AND FEEDRATE

6.1 THE CUTTING TEST

Having established that a chamfered insert could give an improvement in tool life, particularly when using positive rake inserts, it was decided to run a series of cutting tests to reaffirm that an optimum chamfer angle on the cutting edge of the insert existed and at the same time find out if the feedrate and chamfer width had any effect on tool life, as measured by flank wear. If there was a change in tool life attributable to the feed or chamfer width it was intended to establish the relationship between the variables to maximise the life of the insert.

Five values for each variable were chosen, the chamfer angles being 5°, 15°, 25°, 35° and 45°, the chamfer widths were 0.2, 0.4, 0.6, 0.8 and 1.0 mm. The five feedrates were governed by the feeds available on the milling machine and the five chosen were 89, 110, 139, 175 and 217 mm/min. It was decided to use a single cutting speed because it had been confirmed during earlier cutting tests that the cutting speed had a major effect on tool life. A speed of 460 rev/min (145 m/min) was chosen as being a suitable practical cutting speed for the grade of insert being used when machining EN 8 steel. This speed produced the following feeds/tooth when associated with the above feedrates 0.19, 0.24, 0.30, 0.38 and 0.47 mm/tooth. Anything less than these values would be undesirable for a carbide cutting tool and higher values could make excessive power demands or cause the insert to fail due to massive shock cutting forces.

To carry out a full factorial test using 5 values of 3 variables would require $5^3 = 125$ positive rake inserts for up-cut milling and a similar number for down-cut milling and if each insert was used on average to take 8 cuts of 3 mm depth from the testpieces it was estimated that over 1 tonne of testpiece material would be required. It was therefore decided to employ a statistical analysis technique and a Latin Square method was adopted. This method requires 25 tests for down-cut milling and a further 25 for up-cut milling.

The chamfer angles were denoted A to E, A being the smallest value and 5 inserts were ground for each angle, one for each chamfer width. The inserts were used for machining as shown in the following matrix, (Table 6.I). (i.e. * indicates insert No.19 having a chamfer of 25°, 0.8 mm wide and used with a feed of 0.38 mm/tooth).

It is essential that each chamfer angle appears once only in each row and column.

		Feedrate (mm/rev)				
		0.19	0.24	0.30	0.38	0.47
Chamfer Width (mm)	0.2	C 1	B 2	A 3	D 4	E 5
	0.4	D 6	C 7	B 8	E 9	A 10
	0.6	B 11	E 12	C 13	A 14	D 15
	0.8	A 16	D 17	E 18	* C 19	B 20
	1.0	E 21	A 22	D 23	B 24	C 25

Table 6.I

Each insert was used to machine the testpiece, using the methods established for earlier tests, until a flankwear in excess of 200μm was obtained. One series of tests as in the above matrix was carried out for up-cut milling and another for down-cut milling and the results for the flankwear are shown in Appendix IV.

The flankwear on each insert was plotted against the number of passes made by the cutter (figs 6.1 to 6.10) and using linear regression the equation for the straight portion of the graph was derived and the number of passes across the testpiece to produce 200μm flank-wear was determined and shown in tables 6.II and 6.III.

		Feedrate (mm/rev)				
		0.19	0.24	0.30	0.38	0.47
Chamfer Width (mm)	0.2	C: 6.1	B:12.2	A: 4.7	D: 8.7	E: 6.1
	0.4	D: 6.1	C: 5.1	B:13.6	E: 3.7	A: 4.1
	0.6	B:10.1	E: 1.9	C: 7.2	A: 9.3	D: 6.0
	0.8	A: 5.6	D: 6.5	E: 2.8	C:10.9	B:13.8
	1.0	E: 3.4	A: 4.6	D: 6.5	B:13.4	C: 9.9

Table 6.II Down-cut milling

		Feedrate (mm/rev)				
		0.19	0.24	0.30	0.38	0.47
Chamfer Width (mm)	0.2	C: 6.9	B: 7.2	A: 1.7	D: 3.0	E: 5.0
	0.4	D: 5.4	C: 9.3	B: 6.8	E: 2.5	A: 5.7
	0.6	B: 9.0	E: 2.1	C: 6.6	A: 3.4	D: 4.6
	0.8	A: 4.5	D: 4.8	E: 2.0	C: 7.6	B:10.4
	1.0	E: 2.3	A: 3.8	D: 4.4	B: 7.4	C: 7.5

Table 6.III Up-cut milling

The statistical analysis of the results produced the analysis of variance tables shown in tables 6.IV and 6.V. (See Appendix IV for the calculations.

Source of variance	d.f.	s.s	m.s.	F
Total	25	1622.91		
Mean	1	1329.33		
Due to chamfer width	4	6.44	1.61	0.74
Due to feed	4	34.04	8.51	3.92
Due to chamfer angle	4	227.07	56.77	26.16
Error	12	26.03	2.17	

Table 6.IV Analysis of variance for down-cut milling

Source of variance	d.f.	s.s.	m.s.	F
Total	25	861.97		
Mean	1	717.17		
Due to chamfer width	4	5.36	1.34	1.55
Due to feed	4	15.86	3.97	4.62
Due to chamfer angle	4	113.21	28.30	32.91
Error	12	10.37	0.86	

Table 6.V Analysis of variance for up-cut milling

The analysis of variance for both down-cut and up-cut milling indicated that the variation in tool life is due to the chamfer angle. The chamfer angle is significant at the 0.1% level.

The values from tables 6.II and 6.III were plotted against the chamfer angles for each feedrate and it suggested that each graph was following a similar pattern. To fit a curve through the points a computer programme was written (fig 6.11). The output plots from the computer are shown in figs 6.12 to 6.21. From these curves it can be seen that a chamfer angle in the vicinity of 15^{o} produced the best results.

6.2 THE SWARF PRODUCED DURING CUTTING

During the cutting tests samples of the swarf were collected to study the effects that the variables produced. The swarf was grouped for comparison as shown in figs 6.22 to 6.25.

It was noticed that each sample of swarf from a particular set-up was consistent in shape and colour. Often the swarf was distorted due to contact with either the testpiece or the cutter.

Group A (fig 6.22) up-cut milling

Swarf collected from inserts having a chamfer angle of 25^{o} and using different feedrates.

All the swarf had a polished side generally associated with good machining conditions. As the feedrate increased the swarf became more compressed.

Group B (fig 6.23) up-cut milling

Similar to group A but using 45^{o} chamfer angle. It can be seen that the swarf exhibits the normal characteristics of having been cut in the accepted sense of metal cutting, i.e. one side of the swarf is highly polished due to its progress across the face of the tool and the other side being dull due to compression. The swarf is generally distorted to a greater extent than that produced by conventional unchamfered inserts.

Group C (fig 6.24) up-cut milling

Collected from positive rake inserts milling at a constant feedrate of 0.3 mm/rev, using the five chamfer angles.

As the chamfer angle increased so the chip was more distorted and there was a tendency for the chip to be shortened.

Group D (fig 6.25) down-cut milling

Produced by positive rake inserts having a chamfer angle of 5^{o} and using various feedrates.

The swarf has a more conventional appearance because of the small chamfer angle which caused little distortion. As the feedrate increased the chip curled less probably due to its increased strength.

6.3 EXAMINATION OF INSERTS

Examination of the inserts by low powered magnification, after cutting, revealed several defects such as chipped edges and what appeared to be attrition wear on the chamfered edge.

> Attrition wear is when parts of the cutting tool are plucked out due to interfacial welds taking place between the tool and workpiece. The tool material is carried away by the chip and/or workpiece.

To verify the findings several inserts were prepared and mounted for viewing under a scanning electron microscope (figs 6.26 to 6.37). It should be noted that some of the figures show the inserts in a viewing position different from normal. This was due to the method of mounting the inserts and using the best viewing angle to obtain the greatest detail.

Fig 6.26 shows a positive rake insert (inverted) where the edge has broken. The breakage had occurred early on when taking a cut along a testpiece and a secondary flankwear has started to form. A higher magnification (fig 6.27) shows the presence of test-piece material in the damaged area.

Another positive rake insert having failed after a few seconds when attempting up-cut milling is shown in fig 6.28 and again at a higher magnification in fig 6.29.

Fig 6.30 shows an insert with flankwear and a crack running parallel to the cutting edge. This crack is due to the high cutting loads imposed on the tool and would have soon lead to mechanical failure of the insert, (Section 2.2.3). This type of crack is difficult to obtain and photograph because it rapidly develops and leads to failure.

A thermal crack is shown in fig 6.31, the view being from the rake face looking down the flankwear.

Figs 6.32 and 6.33 show inserts numbered 15 and 18 respectively (see table 6.I), two of the inserts that gave the impression that attrition wear had occurred and both inserts were examined at higher magnifications.

Fig 6.34 is a magnified view of part of the chamfer on insert No.15 and it can be seen that there is a deposit of testpiece material similar to a built-up-edge on the chamfer. The feature in the centre of the figure has a different structure than the sintered structure of the insert itself and forms an addition to the insert rather than part of the insert being plucked away. This is illustrated by the photographs at higher magnification of insert No.18 shown in the series of figures 6.35 to 6.36. These figures suggest that the material deposited on the insert is quite stable, unlike a built-up-edge which is much more active. Usui et al[71] suggest that with high negative rake angles it is probable that some form of flow zone or possibly dead zone would be present adjacent to the tool face even in the region of natural contact. These figures tend to confirm their view.

To ensure that the material on the chamfer was part of the testpiece an analysis was made of the deposit and the surrounding area using an energy dispensive x-ray analyser attached to the electron microscope. The traces obtained from the analyser are shown in figs 6.37 to 6.38 and they clearly confirm that the deposited material was steel and the granular structure onto which it is attached was the original insert material. It was therefore concluded that no attrition wear had taken place.

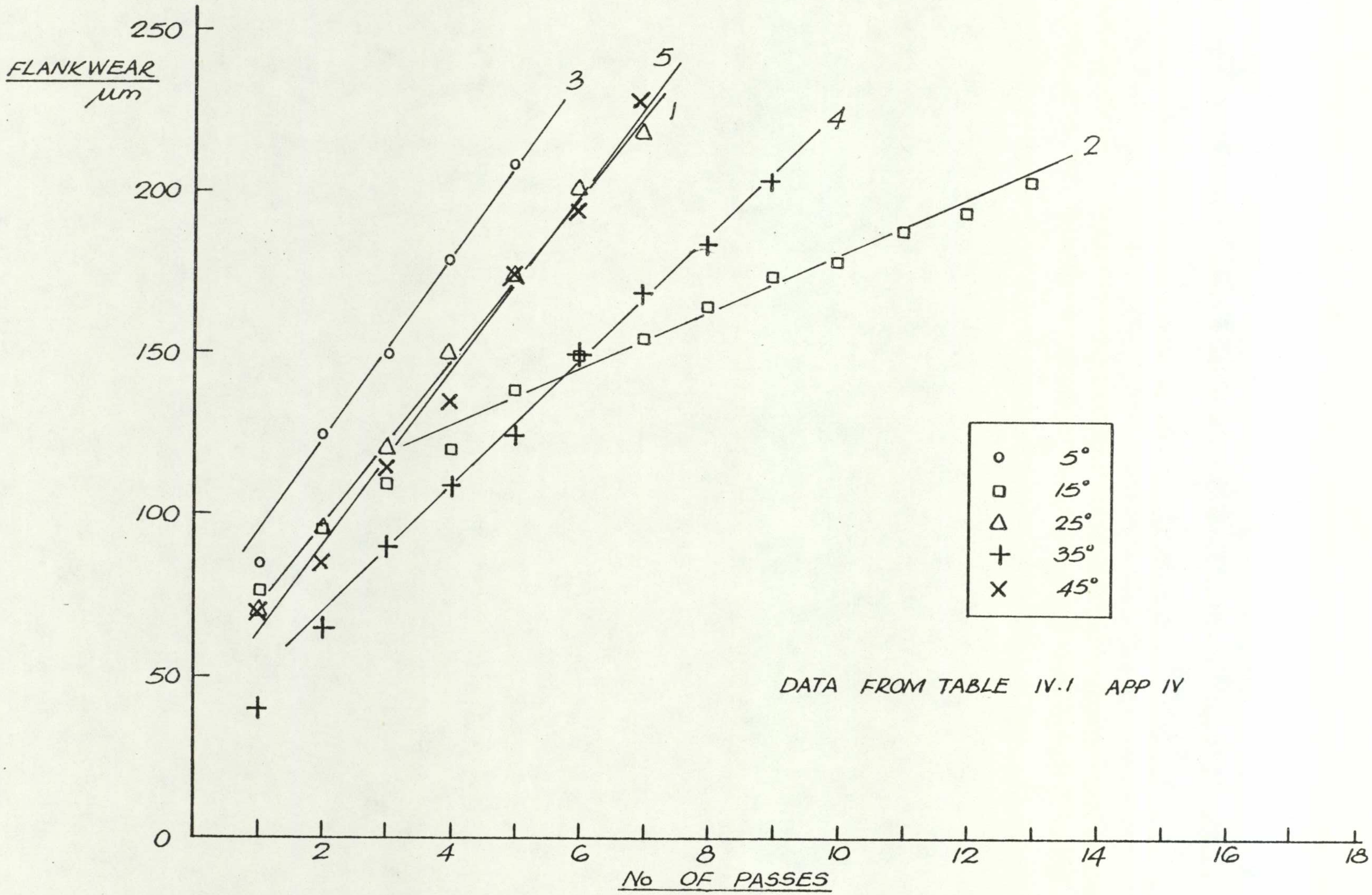


FIG 6.1 FLANKWEAR ON INSERTS 1 TO 5 (DOWN-CUT MILLING)

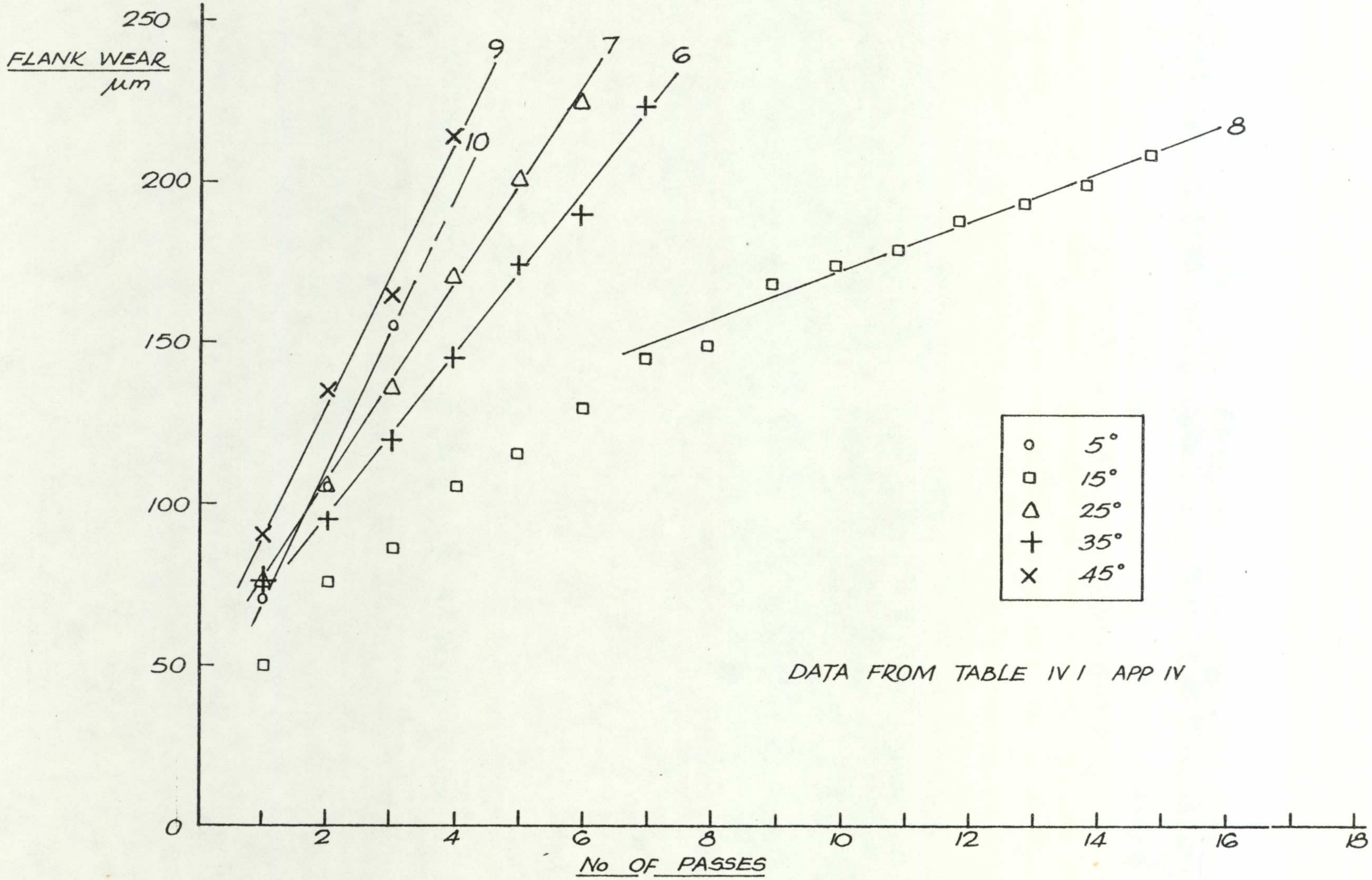


FIG 6.2 FLANKWEAR ON INSERTS 6 TO 10 (DOWN-CUT MILLING)

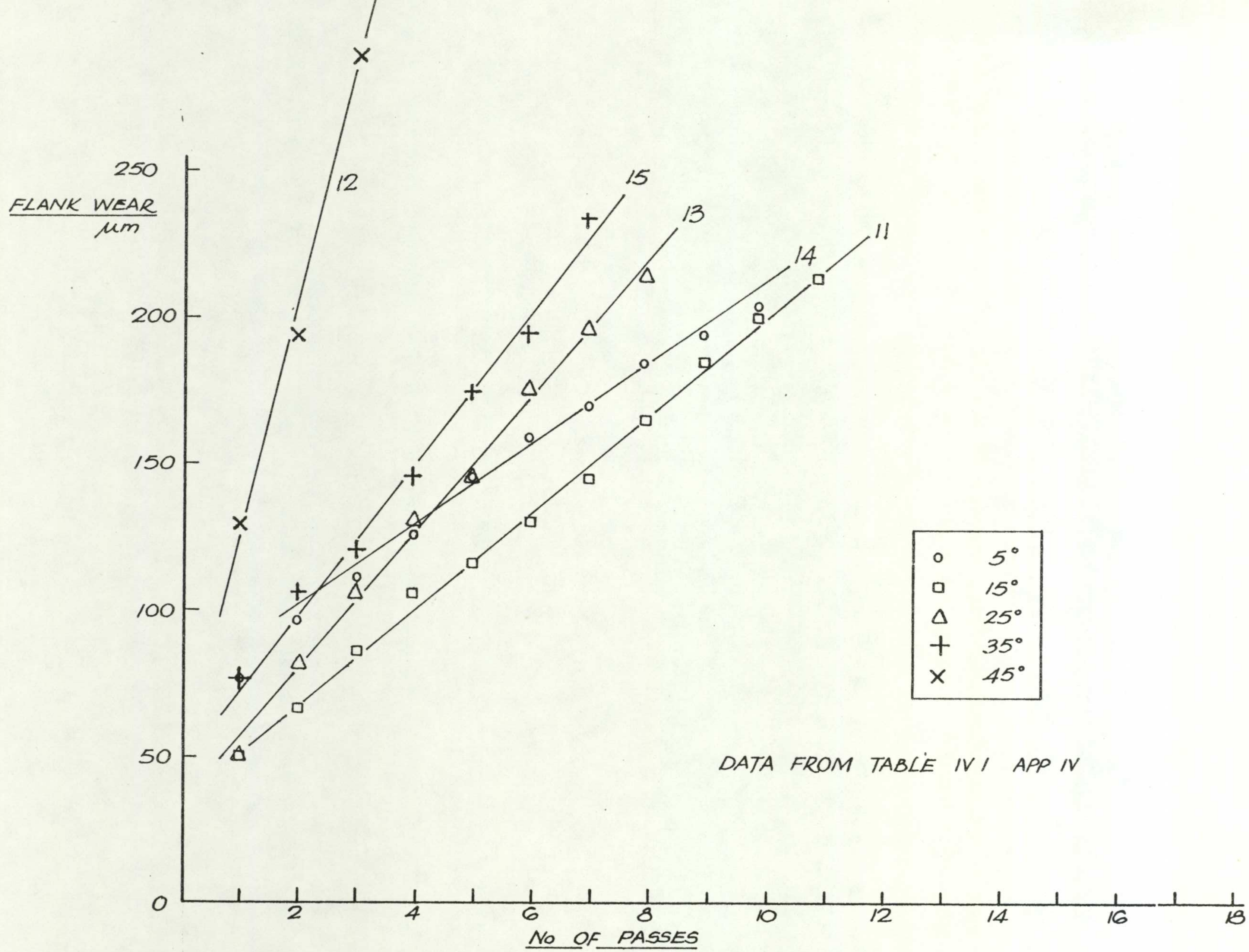


FIG 6.3 FLANKWEAR ON INSERTS 11 TO 15 (DOWN-CUT MILLING)

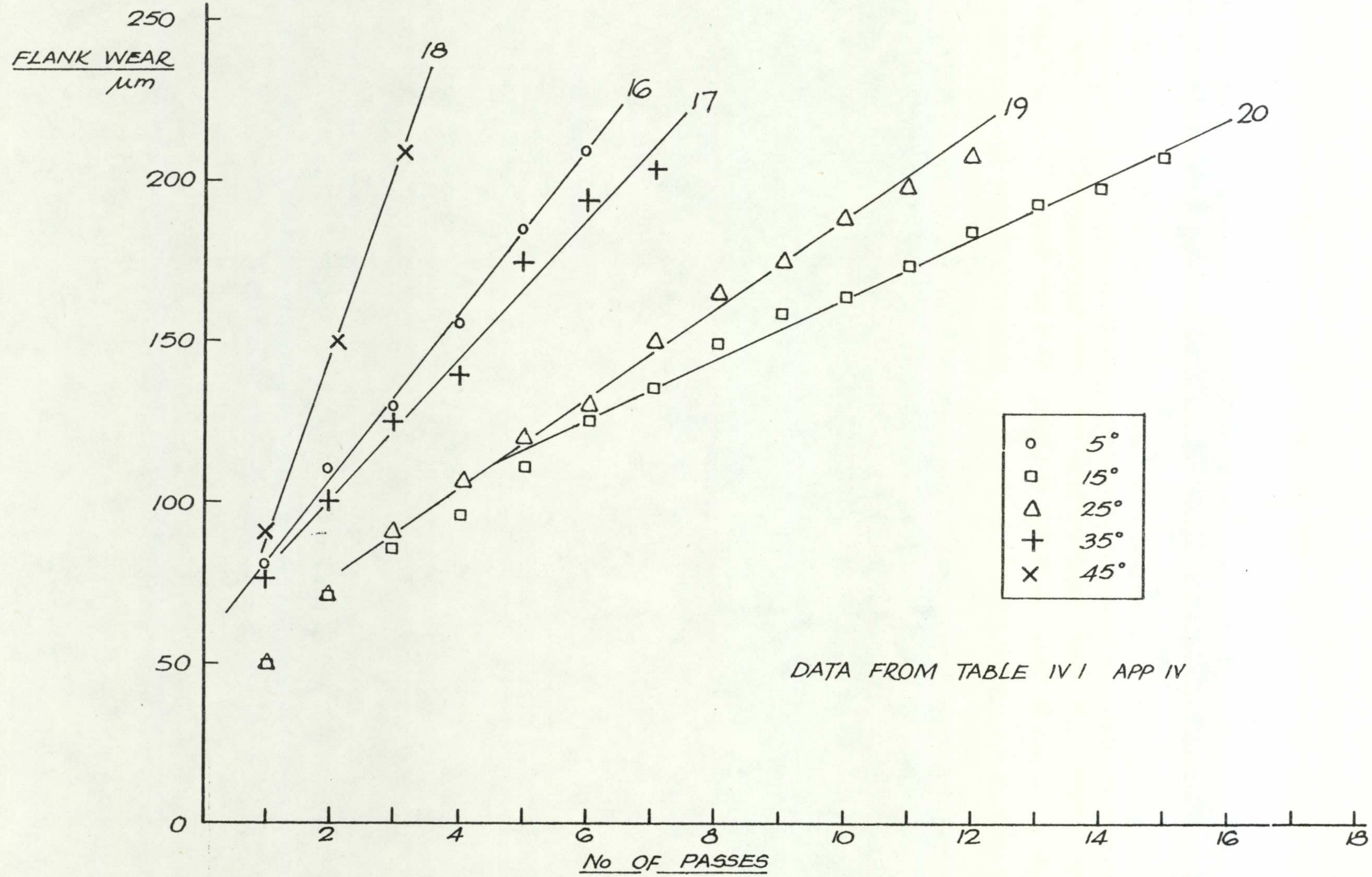


FIG 6.4 FLANKWEAR ON INSERTS 16 TO 20 (DOWN-CUT MILLING)

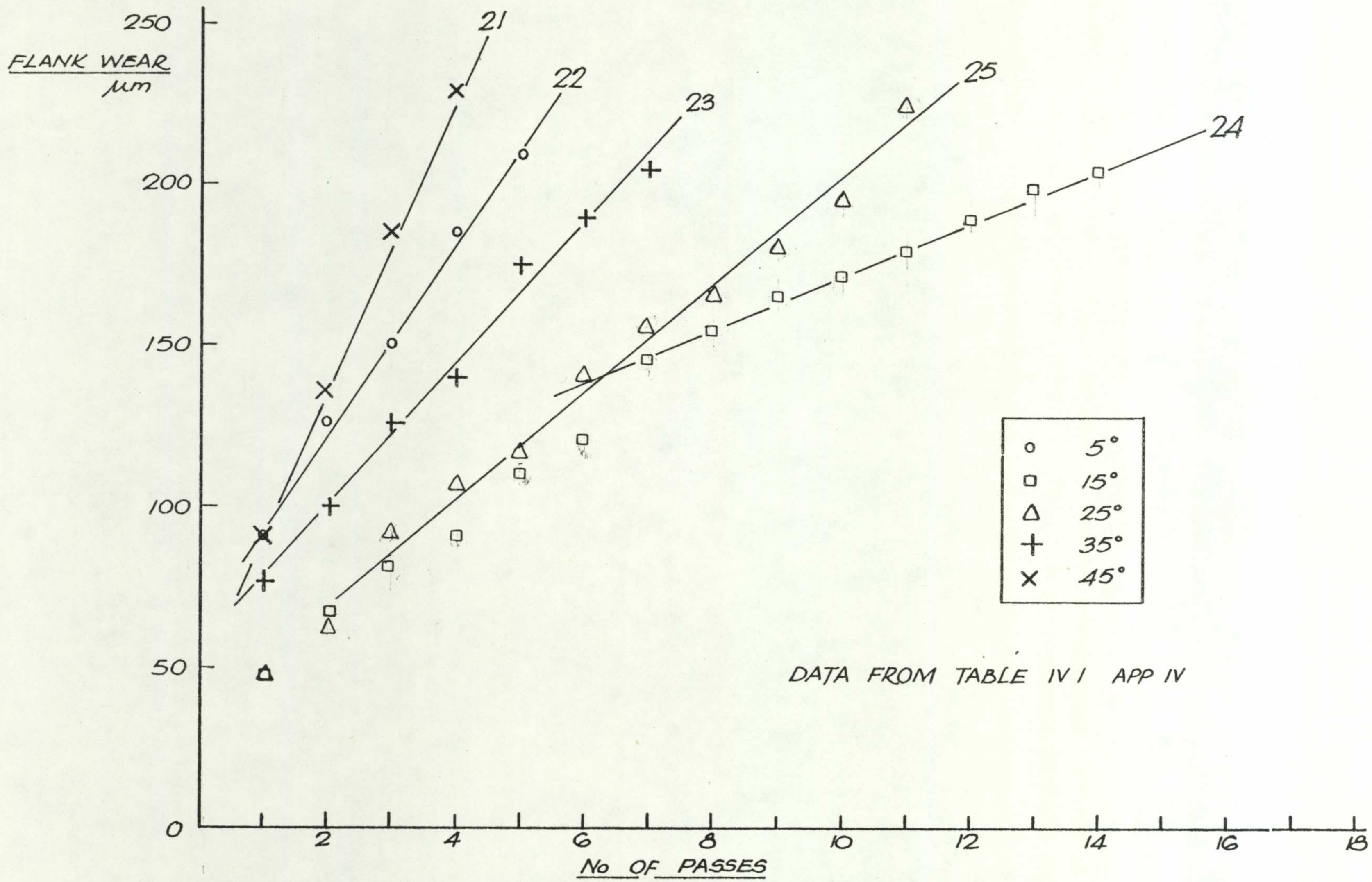


FIG 6.5 FLANKWEAR ON INSERTS 21 TO 25 (DOWN-CUT MILLING)

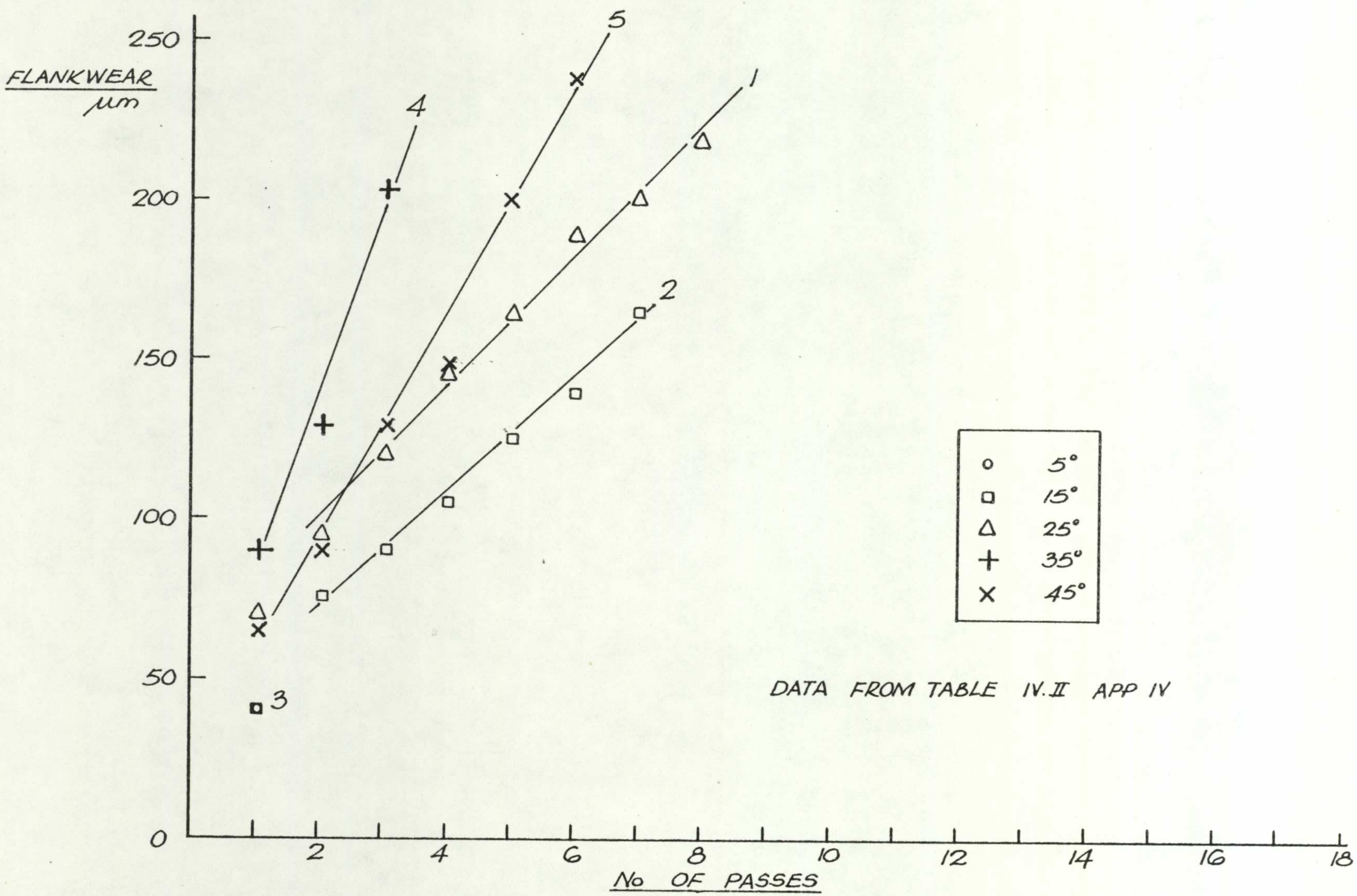


FIG 6.6 FLANKWEAR ON INSERTS 1 TO 5 (UP-CUT MILLING)

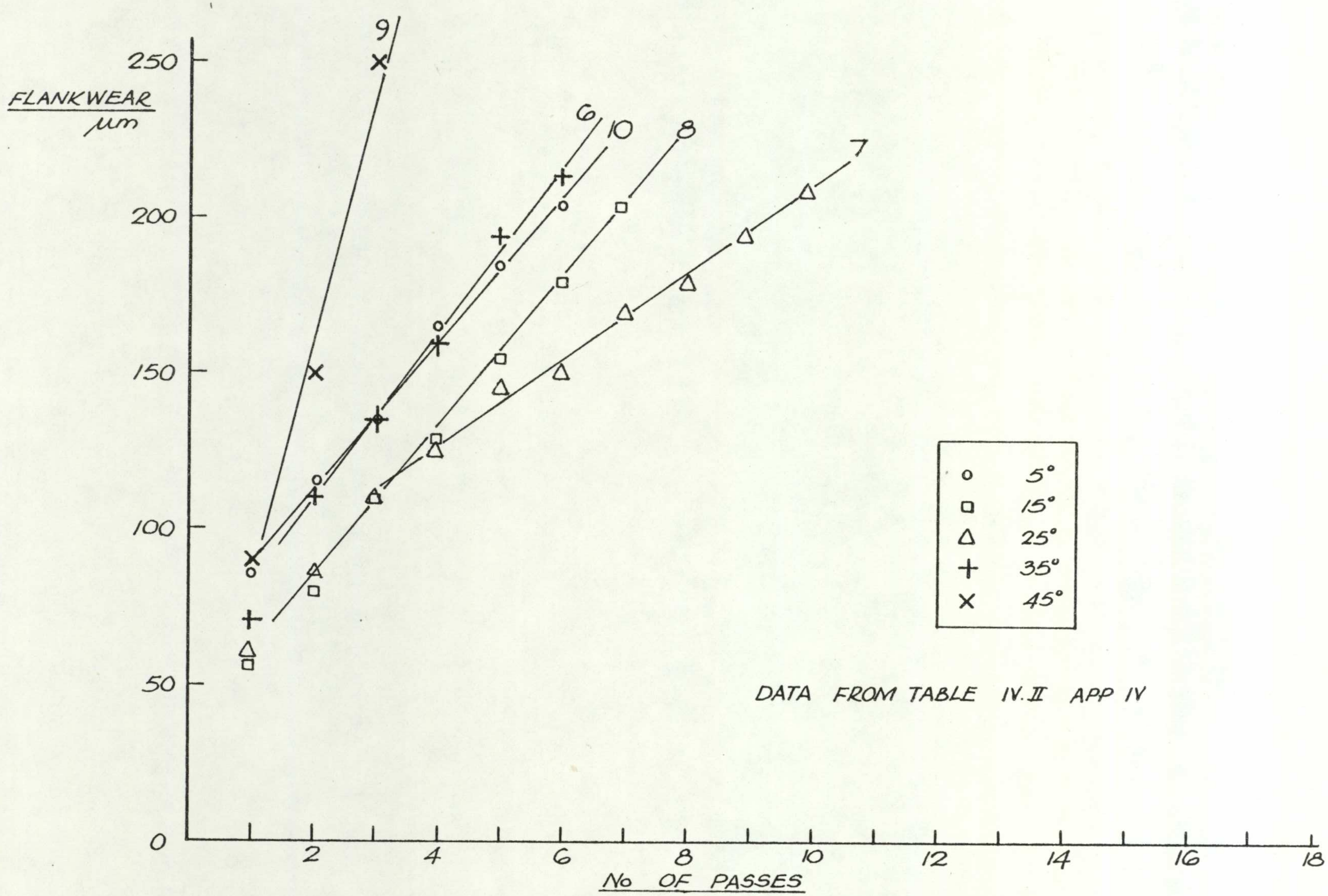


FIG 6.7 FLANKWEAR ON INSERTS 6 TO 10 (UP-CUT MILLING)

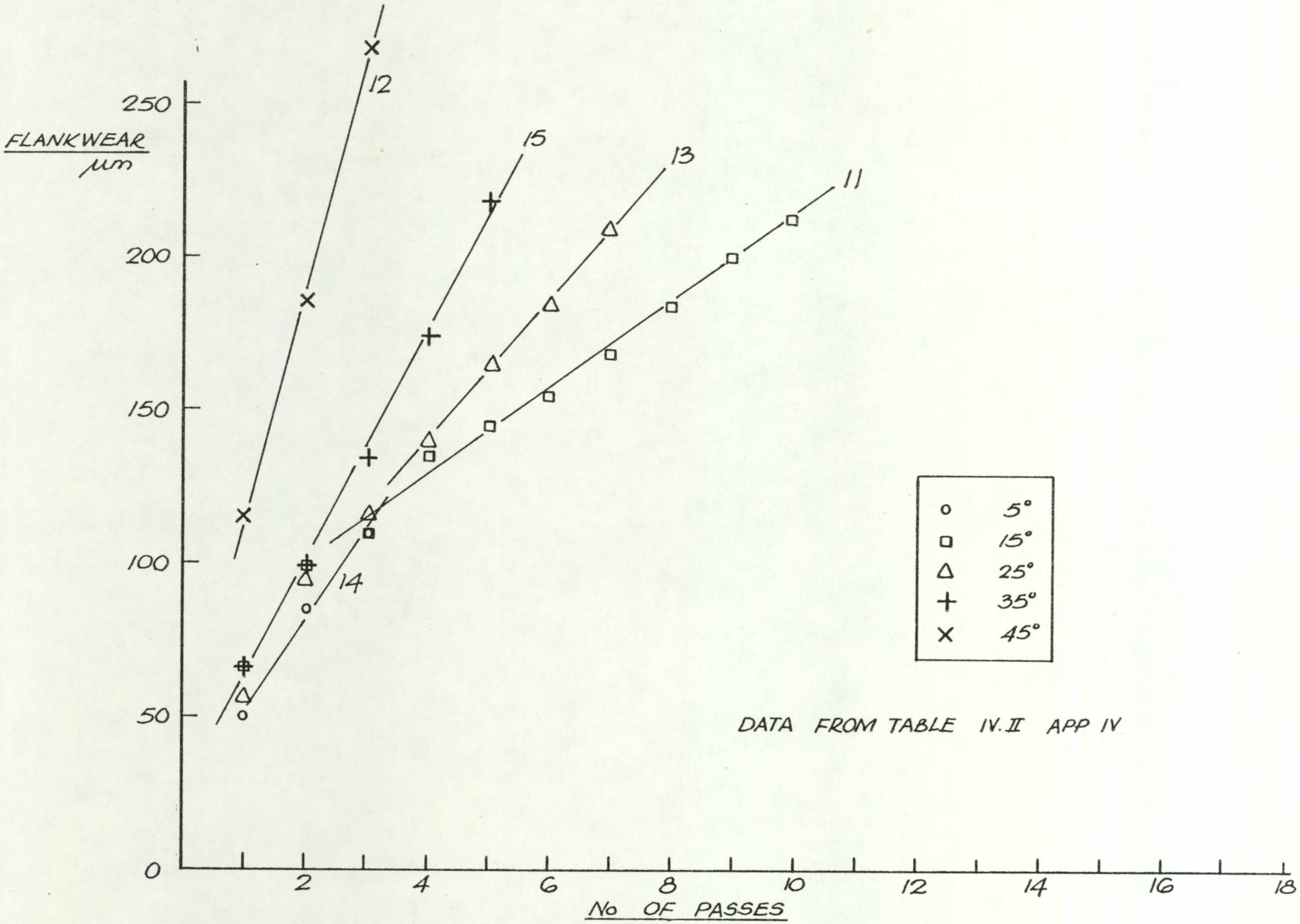


FIG 6.8 FLANKWEAR ON INSERTS 11 TO 15 (UP-CUT MILLING)

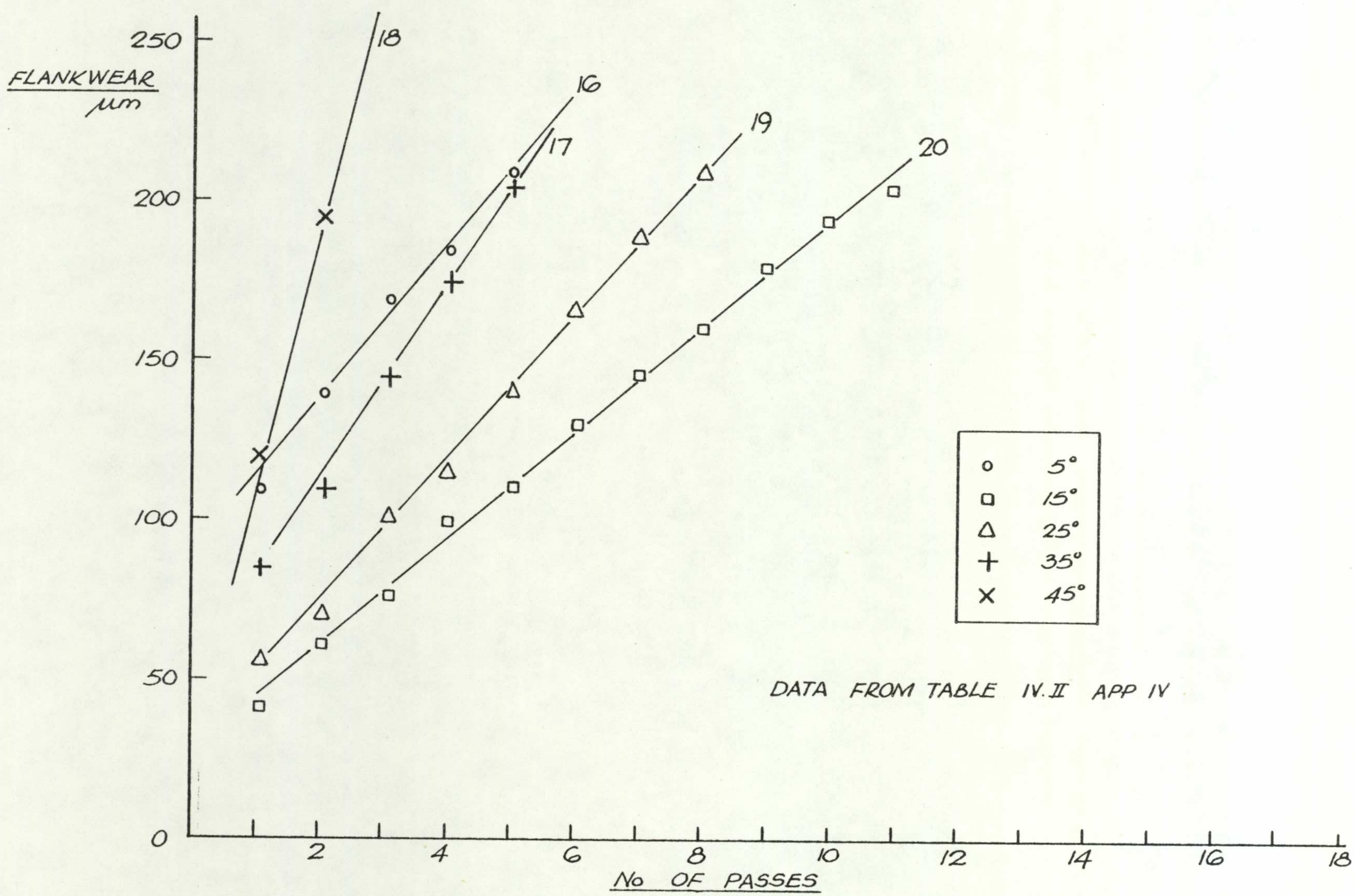


FIG 6.9 FLANKWEAR ON INSERTS 16 TO 20 (UP-CUT MILLING)

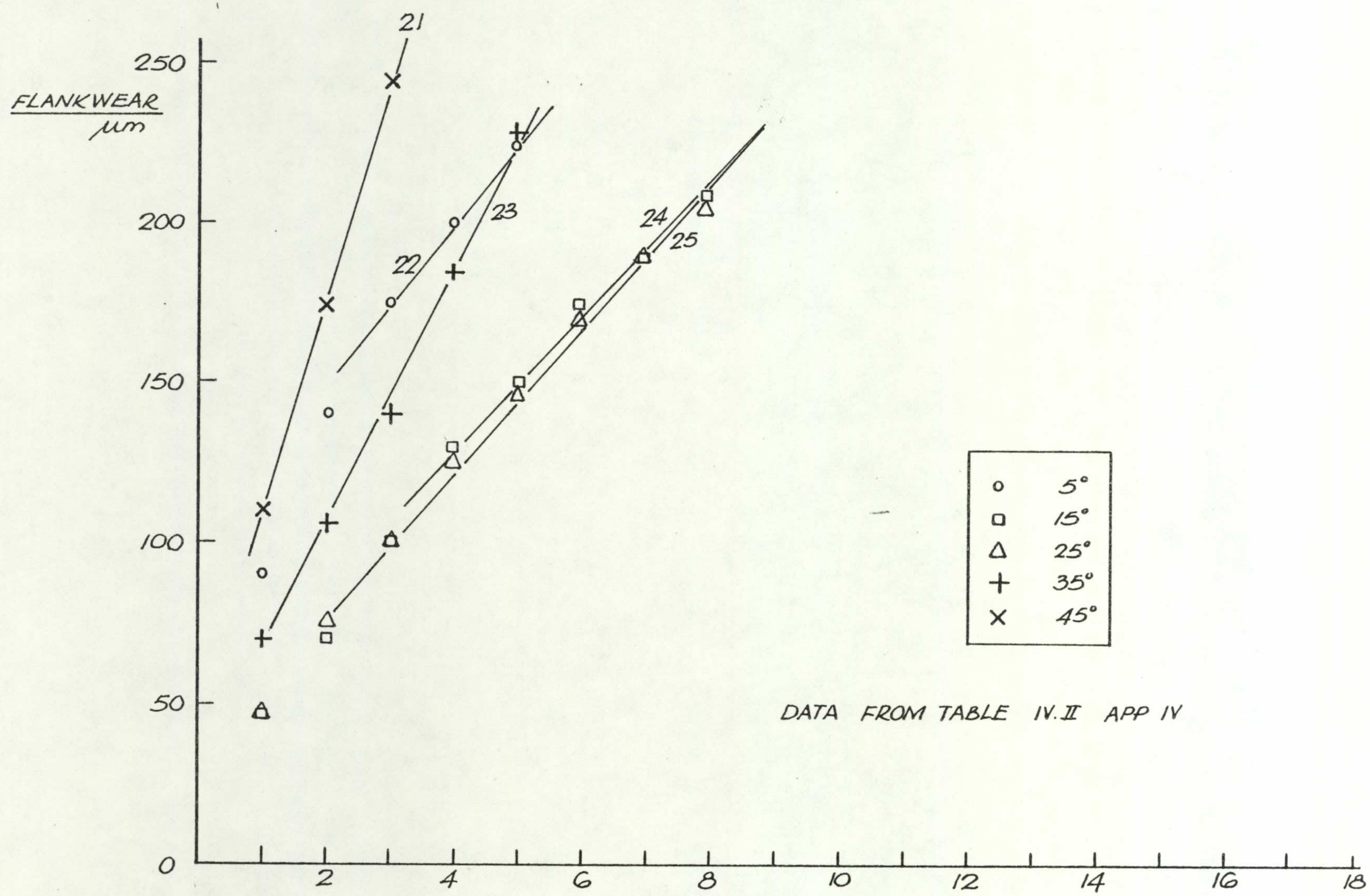


FIG 6.10 FLANKWEAR ON INSERTS 21 TO 25 (UP-CUT MILLING)

```
*************************************************************************
PE1908   NEW.CURVE                          Wed, Apr 01 1981      16:19
*************************************************************************

C       CURVE FITTING ROUTINE
$INSERT SYSCOM>A$KEYS
        REAL*8 X(5),Y(5),A(5),REF,Z(5)
        DIMENSION XX(5),YY(5),ZZ(5)
        INTEGER H(40)
        DATA X/5.,15.,25.,35.,45./
        CALL OPEN$A(A$WRIT+A$SAMF,'CURVPRINT',9,2)
        CALL TNOU('INPUT HEADING FOR GRAPH',23)
        READ(1,10)H
10      FORMAT(40A1)
        WRITE(6,10)H
        CALL TNOU('ENTER 5 VALUES FOR PASSES',25)
        N=5
        M=4
        DO 20 I=1,5
        READ(1,*)Y(I)
20      CONTINUE
        CALL E02ACF(X,Y,5,A,4,REF)
        DO 2 J=1,4
        WRITE(6,50)A(J)
2       CONTINUE
50      FORMAT(F20.3)
        DO 100 J=1,5
        Z(J)=A(1)+A(2)*X(J)+A(3)*X(J)*X(J)+A(4)*X(J)**3
        WRITE(6,51)X(J),Y(J),Z(J)
100     CONTINUE
51      FORMAT(3F15.3)
        CALL CILS4N
        CALL WINDOW(2)
        CALL SHIFT2(20.,20.)
        CALL CHASWI(1)
        CALL CHASIZ(2.,2.)
        CALL AXIPOS(1,0.0,0.0,150.,1)
        CALL AXIPOS(1,0.0,0.0,100.,2)
        CALL AXISCA(3,10,0.,50.,1)
        CALL AXISCA(3,10,0.,15.,2)
        CALL AXIDRA(1,1,1)
        CALL AXIDRA(-1,-1,2)
        CALL MOVTO2(50.,-15.)
        CALL CHASIZ(3.,3.)
        CALL CHASWI(0)
        CALL CHAHOL('CHAMFER ANGLE*.')
        CALL MOVTO2(0.,120.)
        CALL CHAA1(H,40)
        CALL MOVTO2(-15.,20.)
        CALL CHAHAR(3,1)
        CALL CHAHOL('NO. OF PASSES*.')
        CALL CHAHAR(3,0)
        DO 1 J=1,5
        XX(J)=X(J)
        YY(J)=Y(J)
1       ZZ(J)=Z(J)
        CALL GRACUR(XX,ZZ,5)
        CALL GRASYM(XX,YY,5,4,0)
        CALL DEVEND
        CALL CLOS$A(1)
        CALL CLOS$A(2)
        CALL EXIT
        END
```

FIG 6.11 COMPUTER PROGRAMME
CURVE FITTING ROUTINE

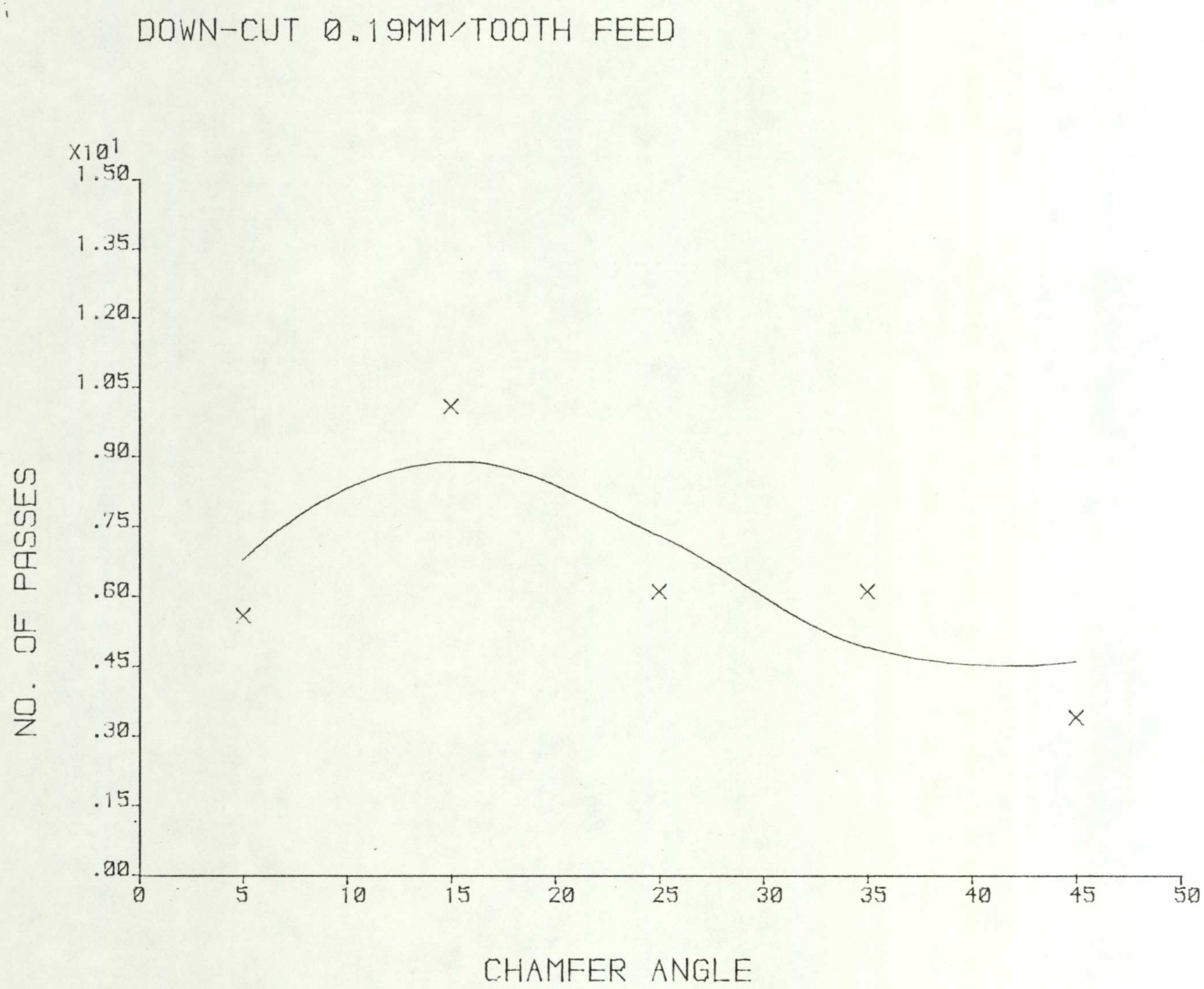


FIG 6.12 TOOL LIFE 0.19 FEED (DOWN-CUT)

8

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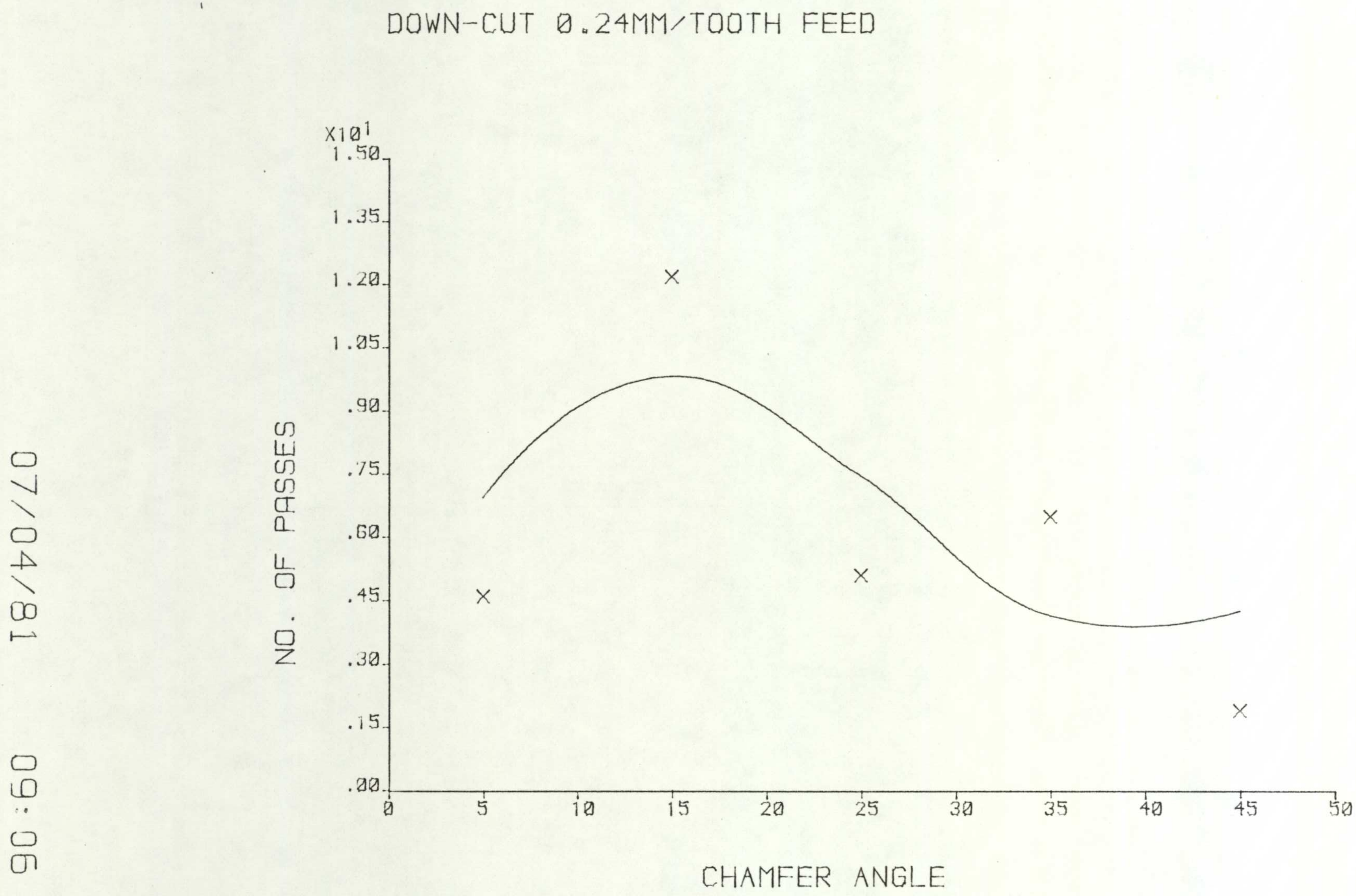


FIG 6.13 TOOL LIFE 0·24 FEED (DOWN-CUT)

10

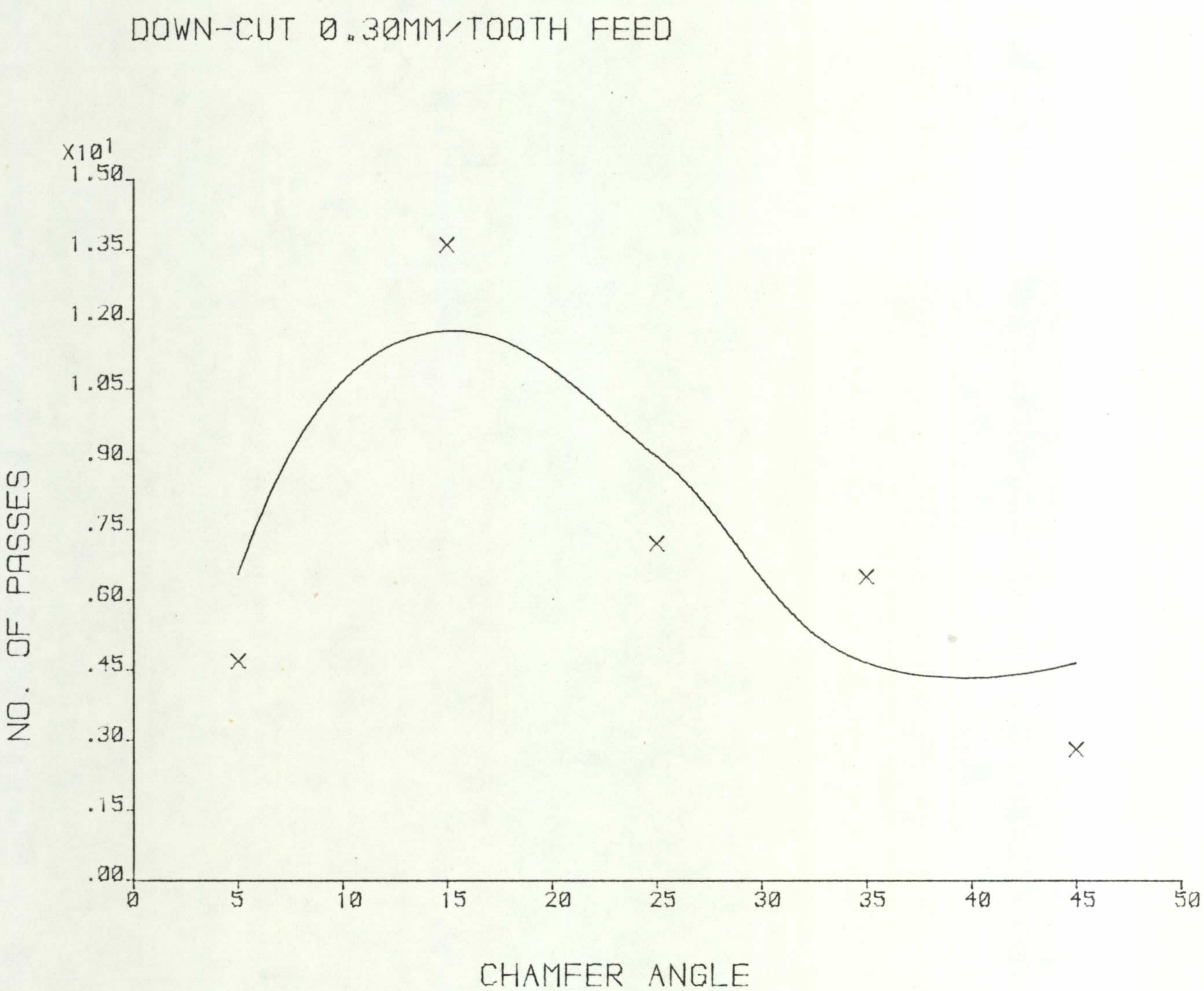


FIG 6.14 TOOL LIFE 0.30 FEED (DOWN-CUT)

07/04/81 09:06

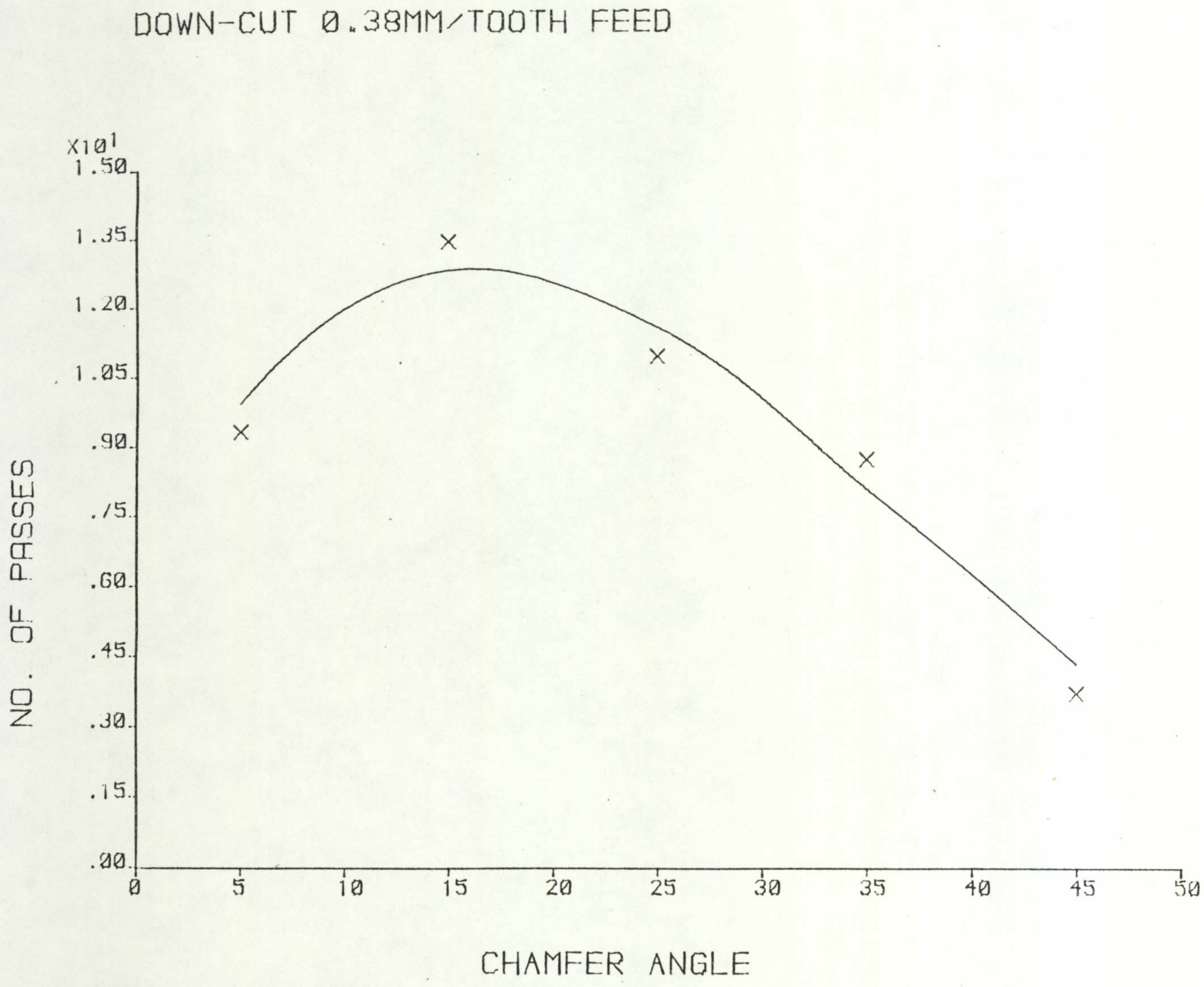


FIG 6.15 TOOL LIFE 0.38 FEED (DOWN-CUT)

07/04/81 09:07

11

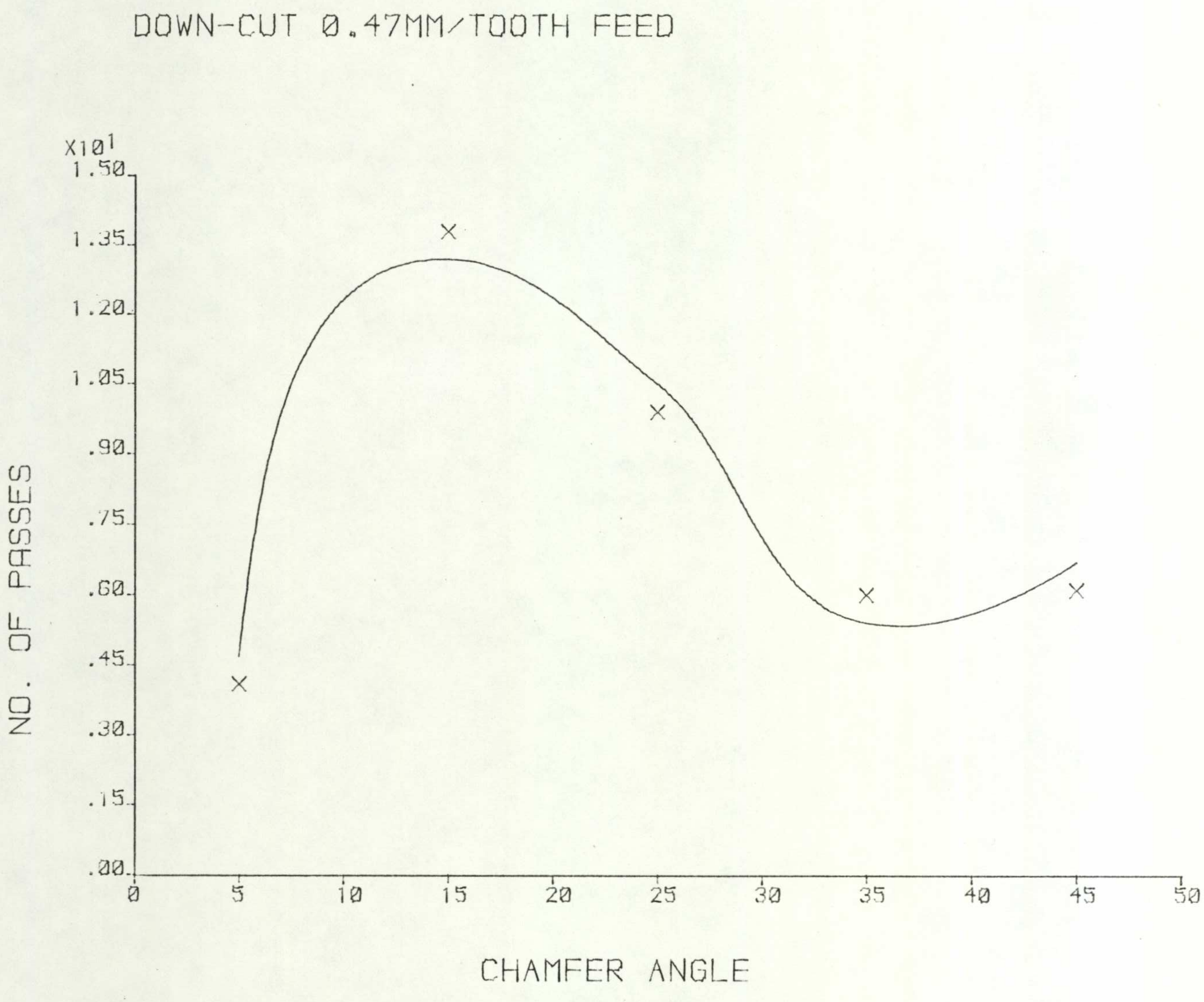


FIG 6.16 TOOL LIFE 0·47 FEED (DOWN-CUT)

07/04/81 09:07

12

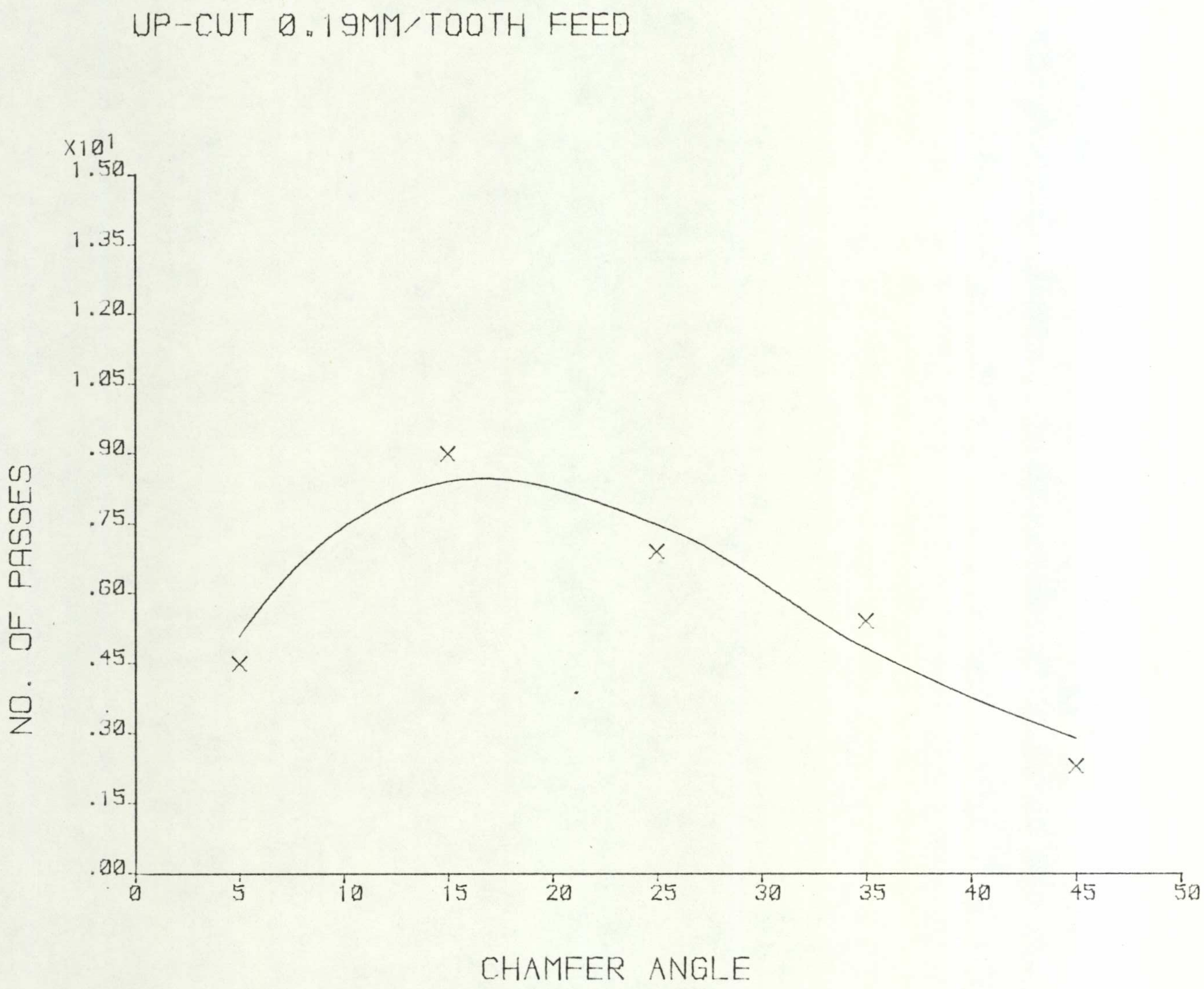


FIG 6.17 TOOL LIFE 0·19 FEED (UP-CUT)

07/04/81 09:08

14

15

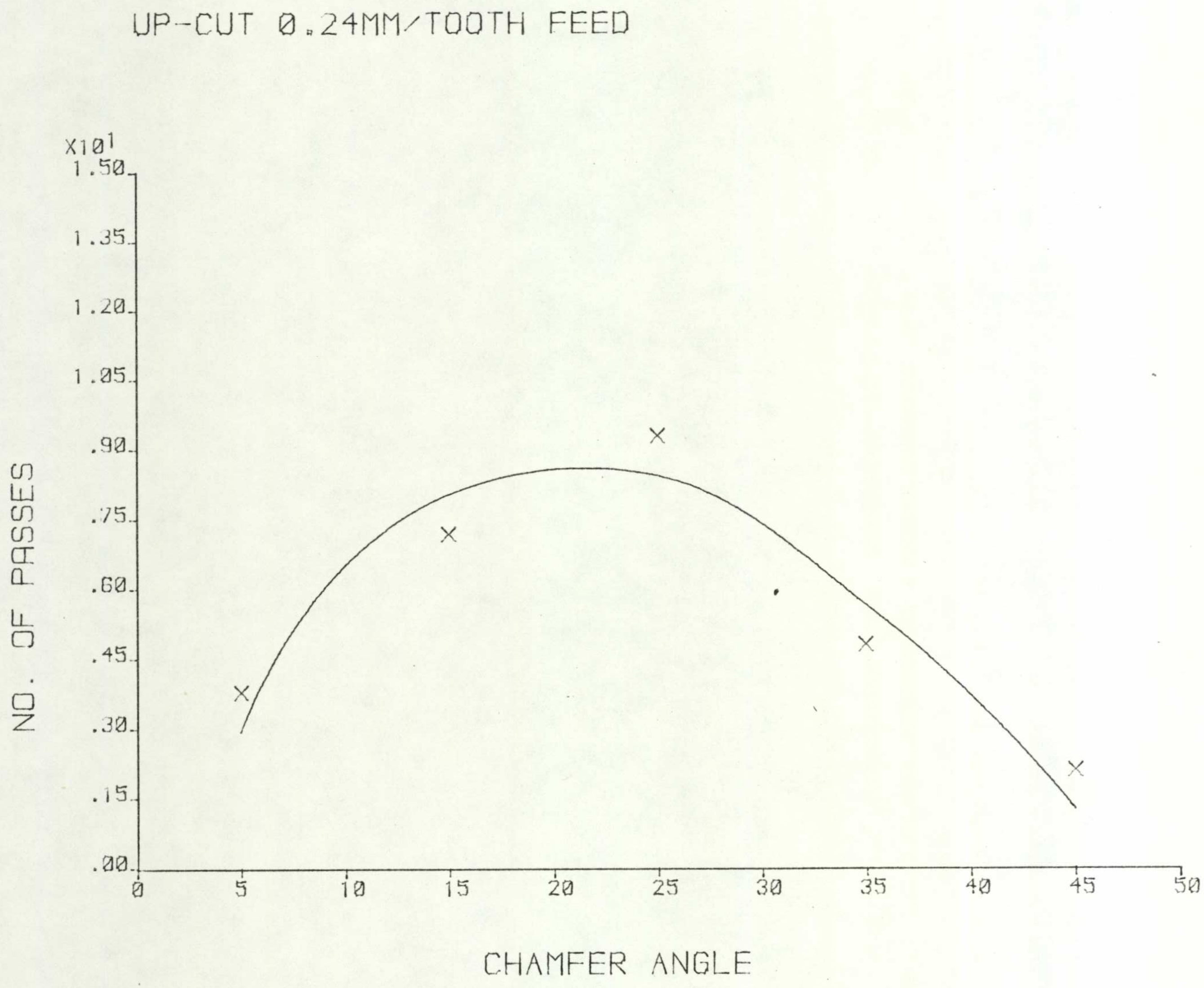


FIG 6.18 TOOL LIFE 0·24 FEED (UP-CUT)

07/04/81 09:09

UP-CUT 0.30MM/TOOTH FEED

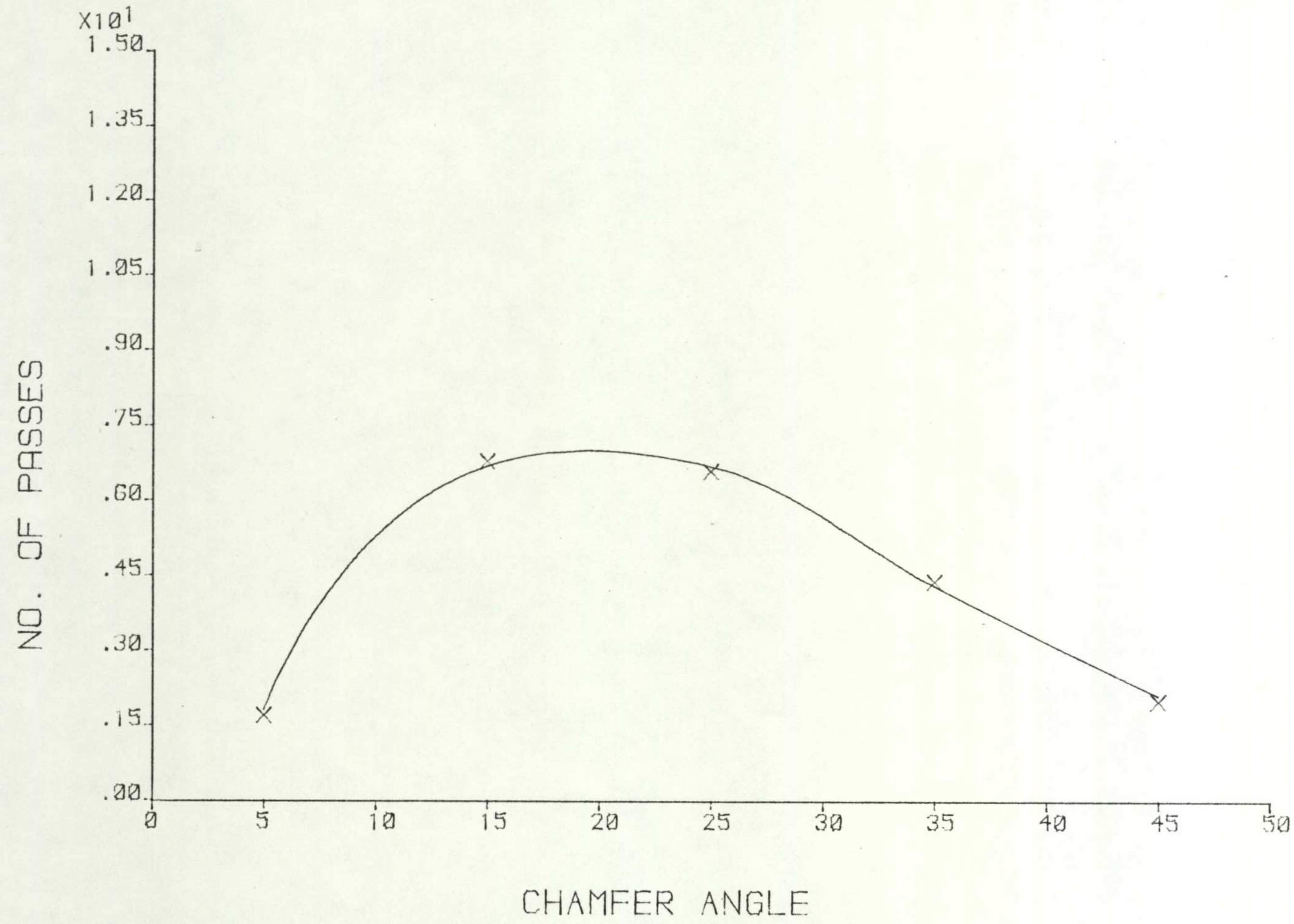


FIG 6.19 TOOL LIFE 0.30 FEED (UP-CUT)

07/04/81 09:09

16

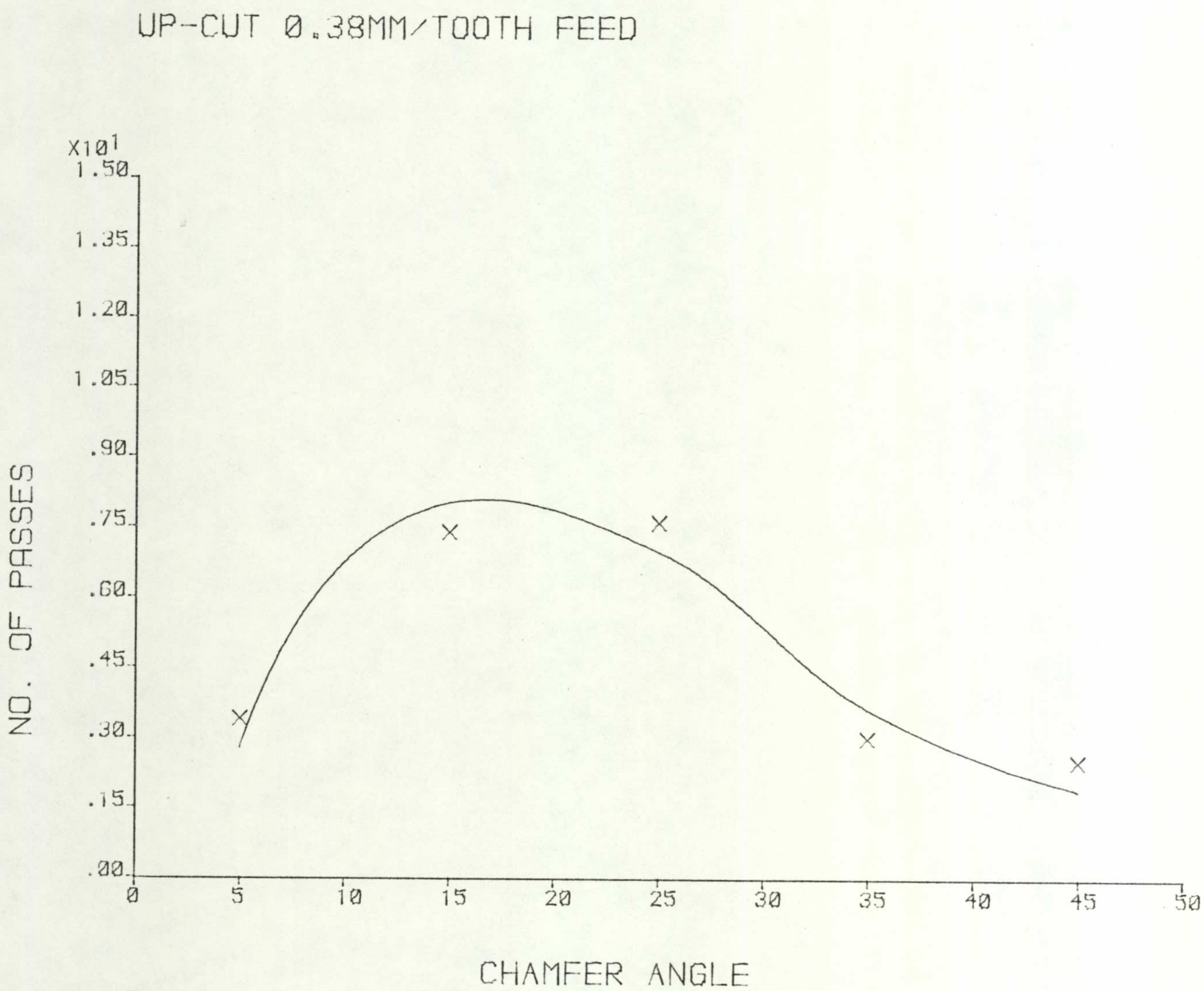


FIG 6.20 TOOL LIFE 0·38 FEED (UP-CUT)

17

07/04/81 09:09

UP-CUT 0.47MM/TOOTH FEED

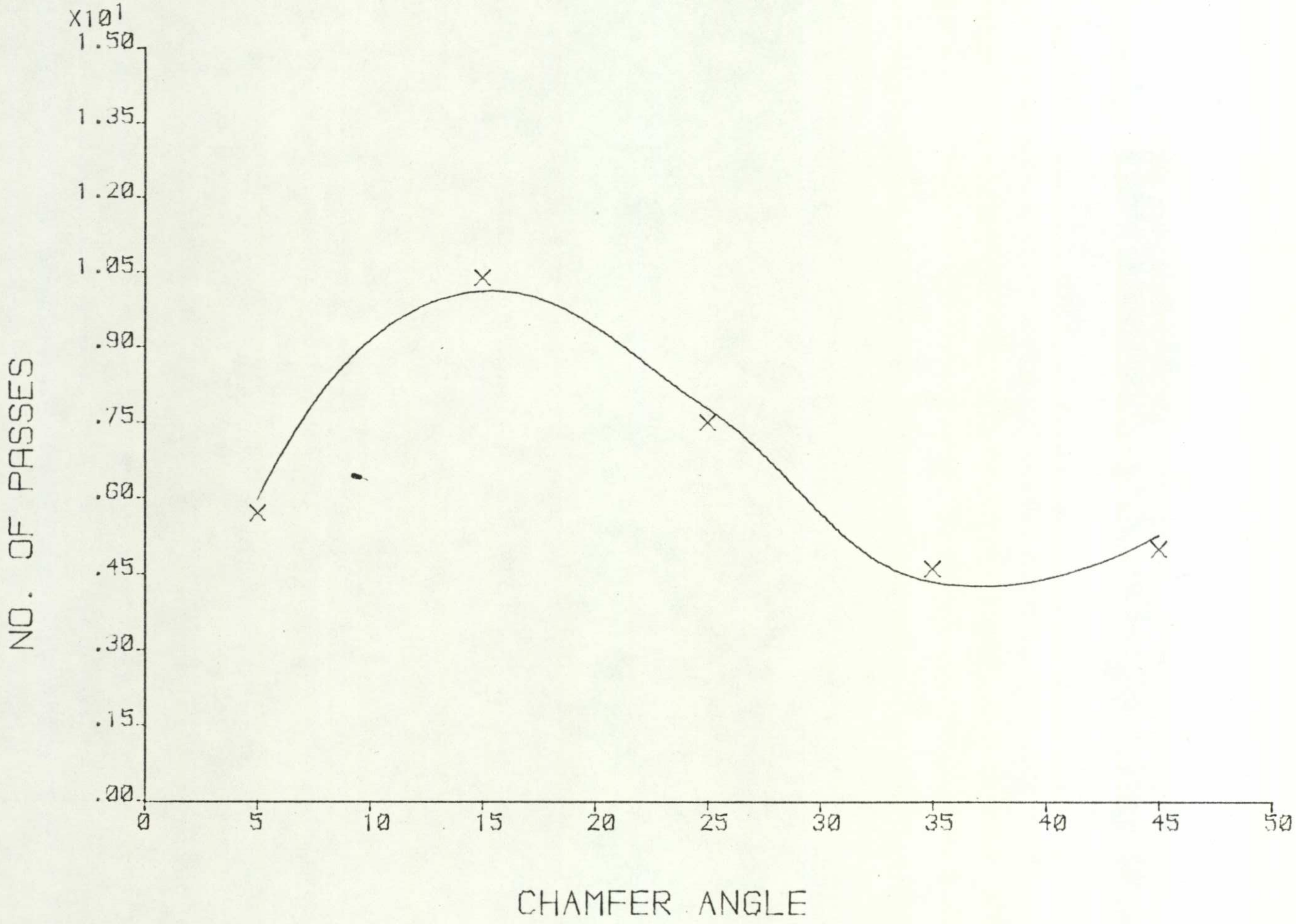


FIG 6.21 TOOL LIFE 0·47 FEED (UP-CUT)

07/04/81 09:09

18

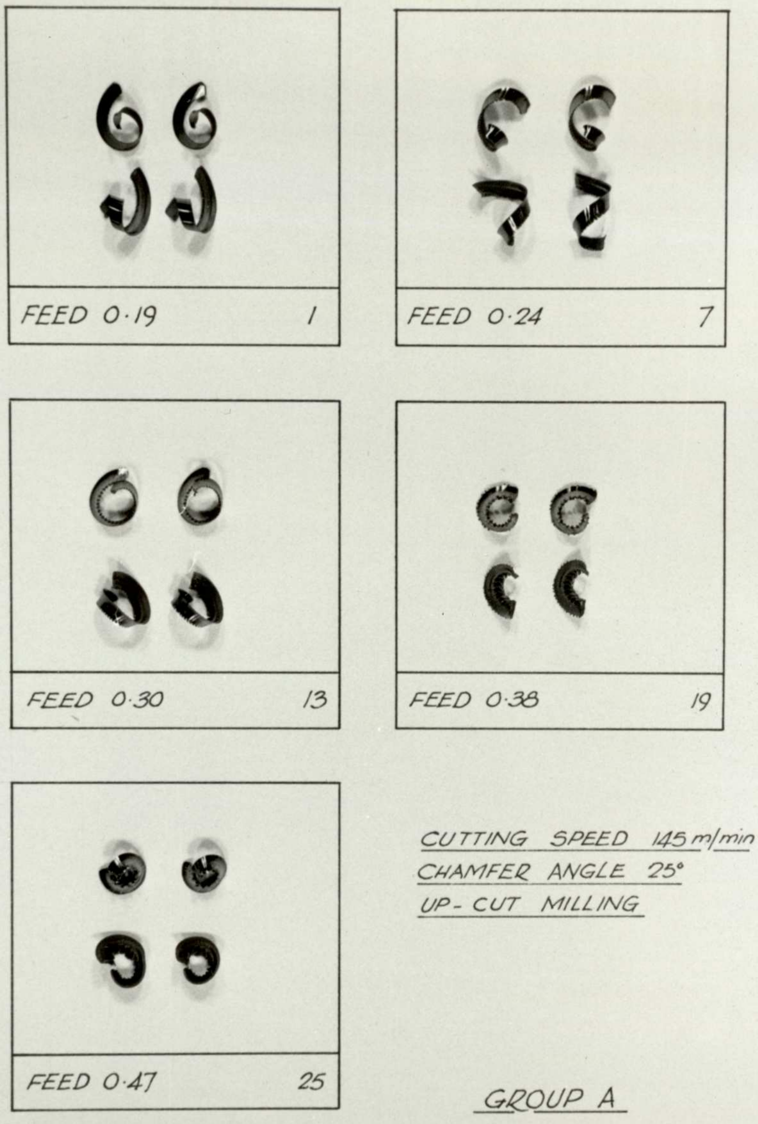


FIG 6.22 SWARF FROM 25° CHAMFER INSERTS

SCALE 2/3

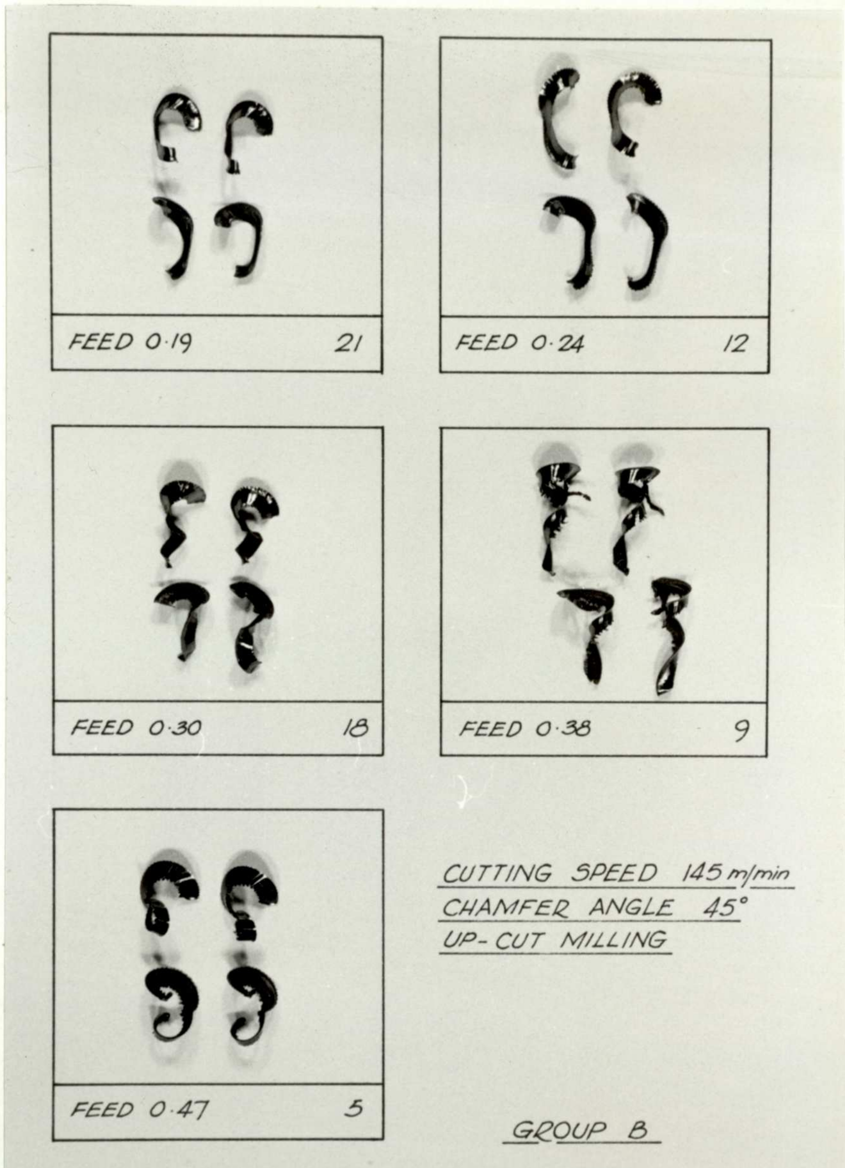


FIG 6.23 SWARF FROM 45° CHAMFERED INSERTS

SCALE 2/3

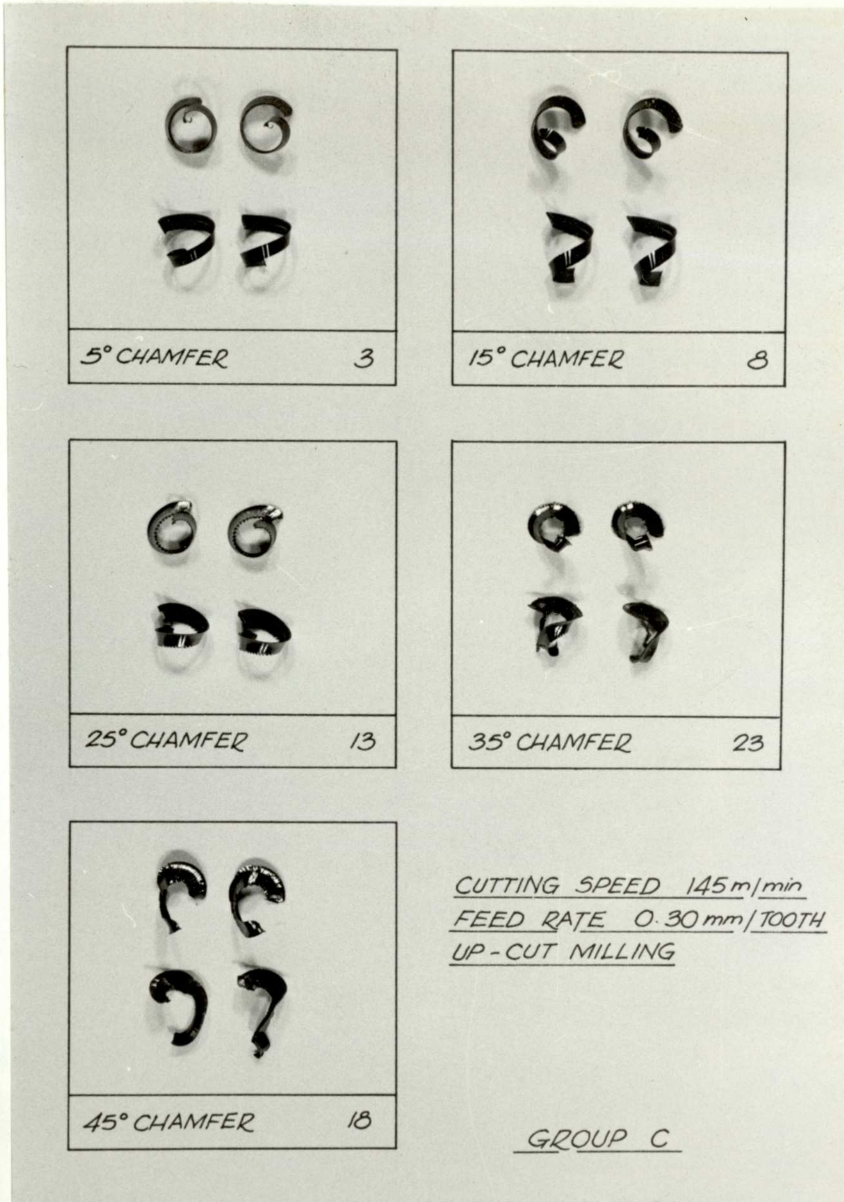


FIG 6.24 SWARF FROM VARIOUS CHAMFERS

SCALE 2/3

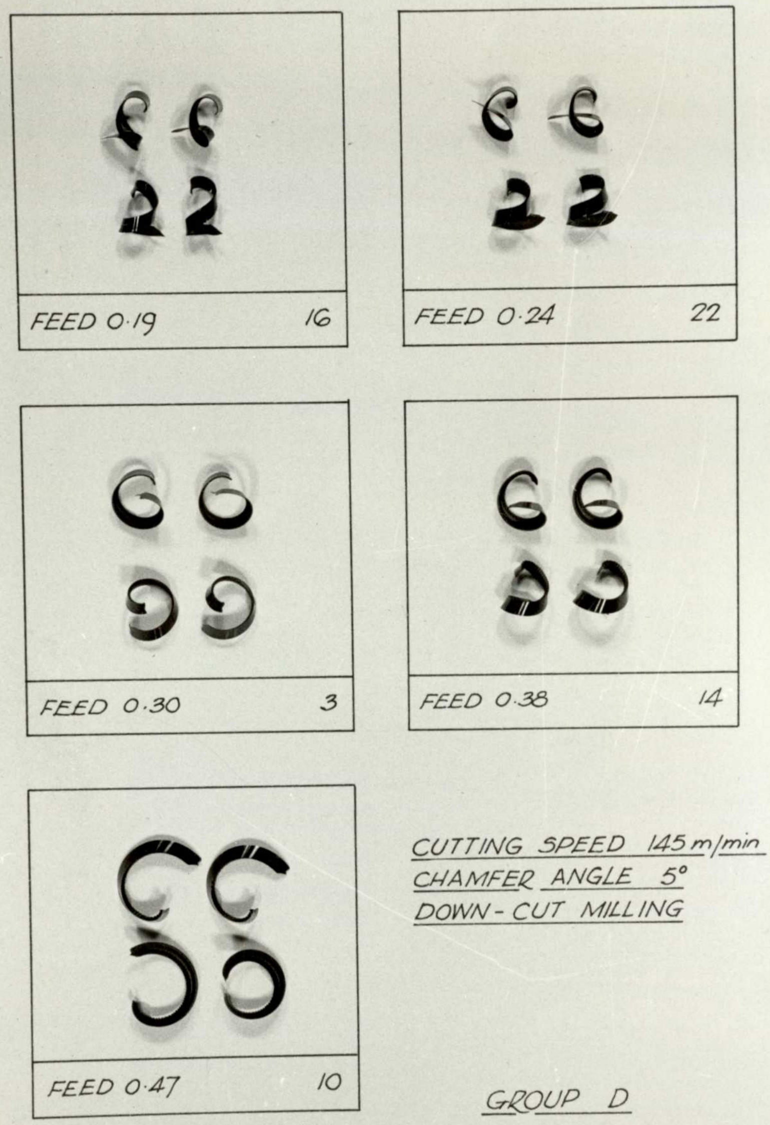


FIG 6.25 SWARF FROM 5° CHAMFERED INSERTS

SCALE 2/3

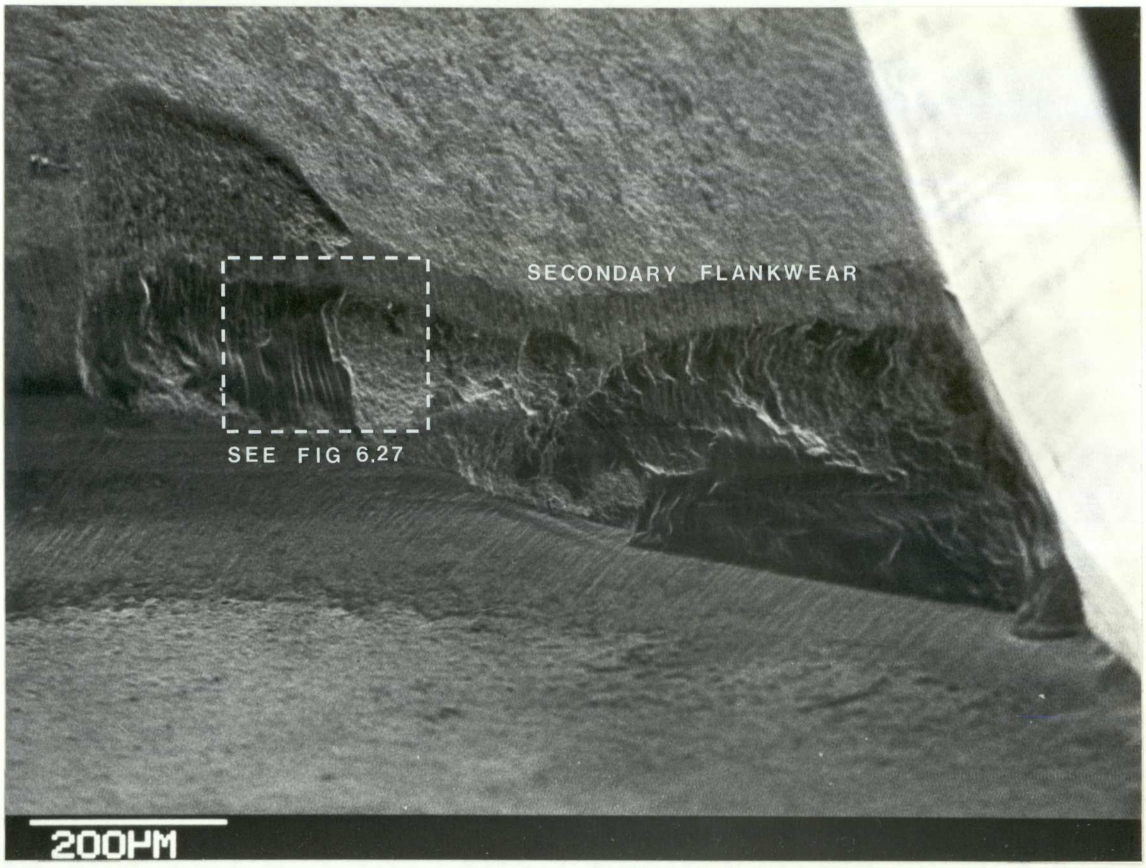


FIG 6.26 BROKEN CUTTING EDGE SHOWING SECONDARY FLANKWEAR

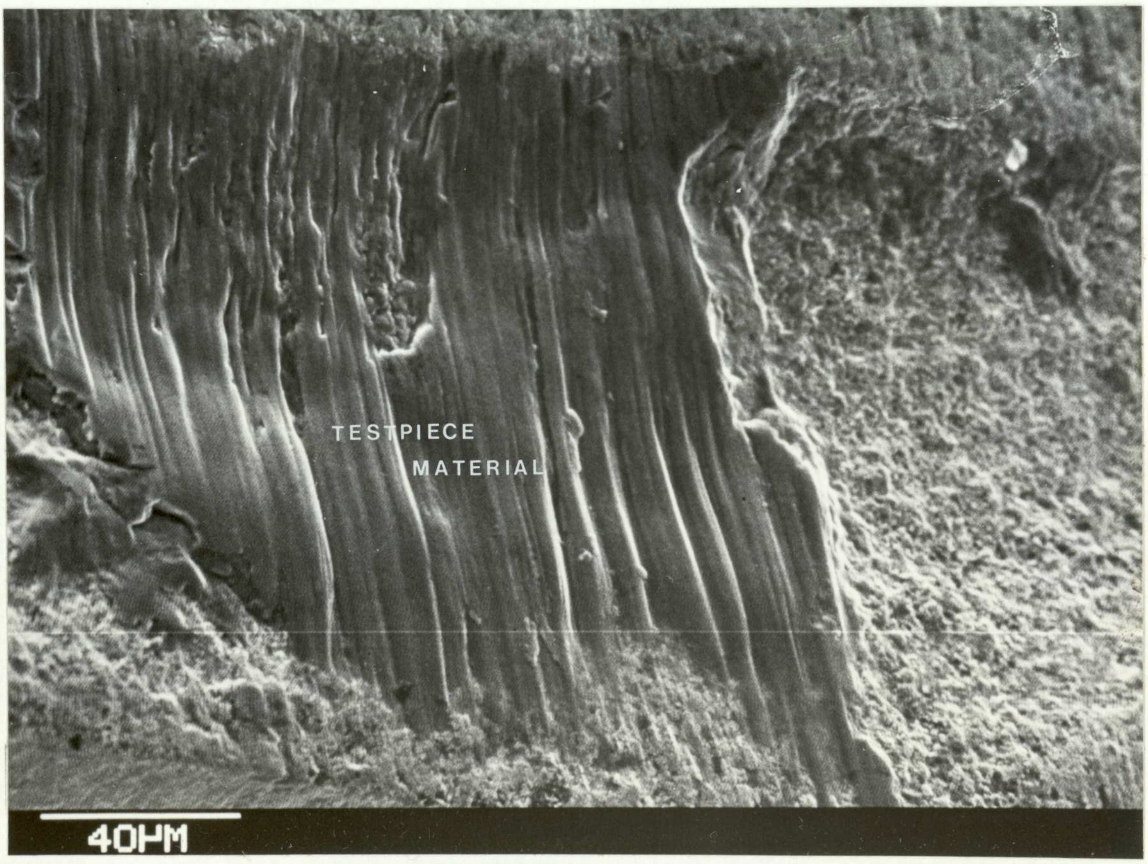


FIG 6.27 TESPIECE MATERIAL IN DAMAGED AREA OF INSERT FIG 6.26

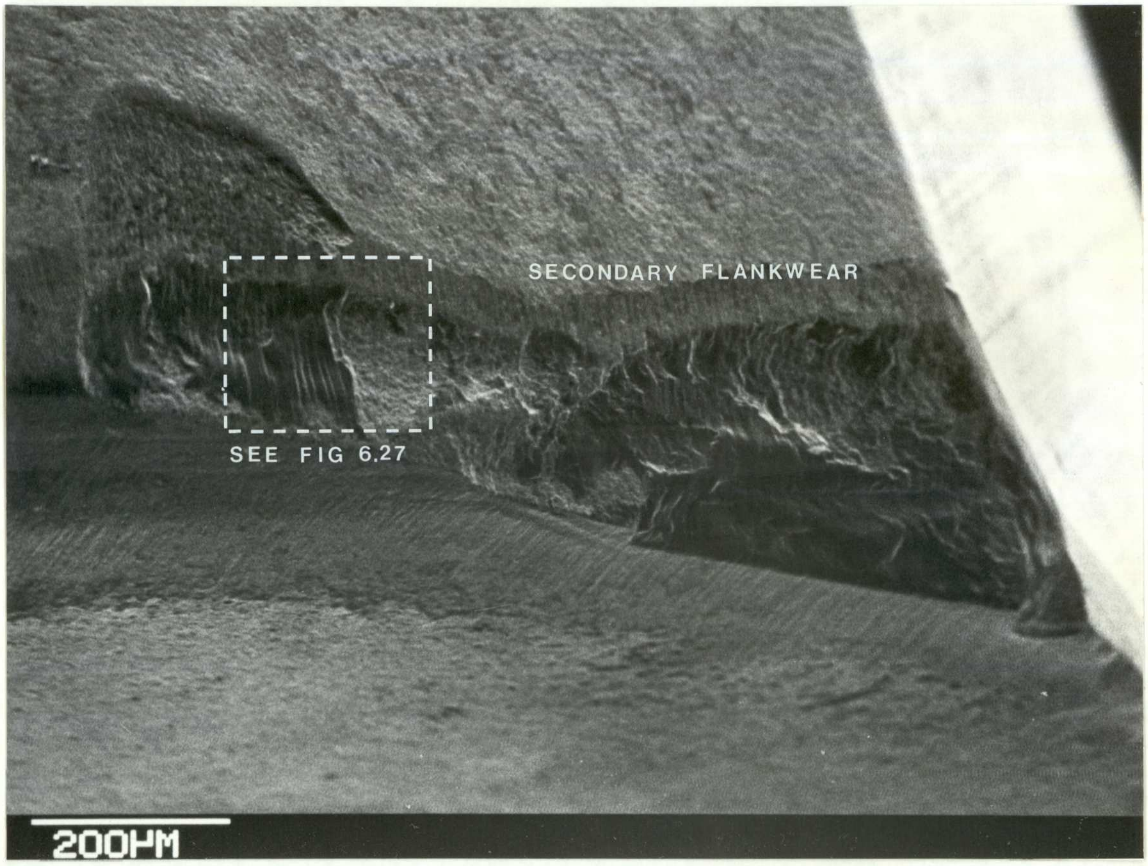


FIG 6.26 BROKEN CUTTING EDGE SHOWING SECONDARY FLANKWEAR

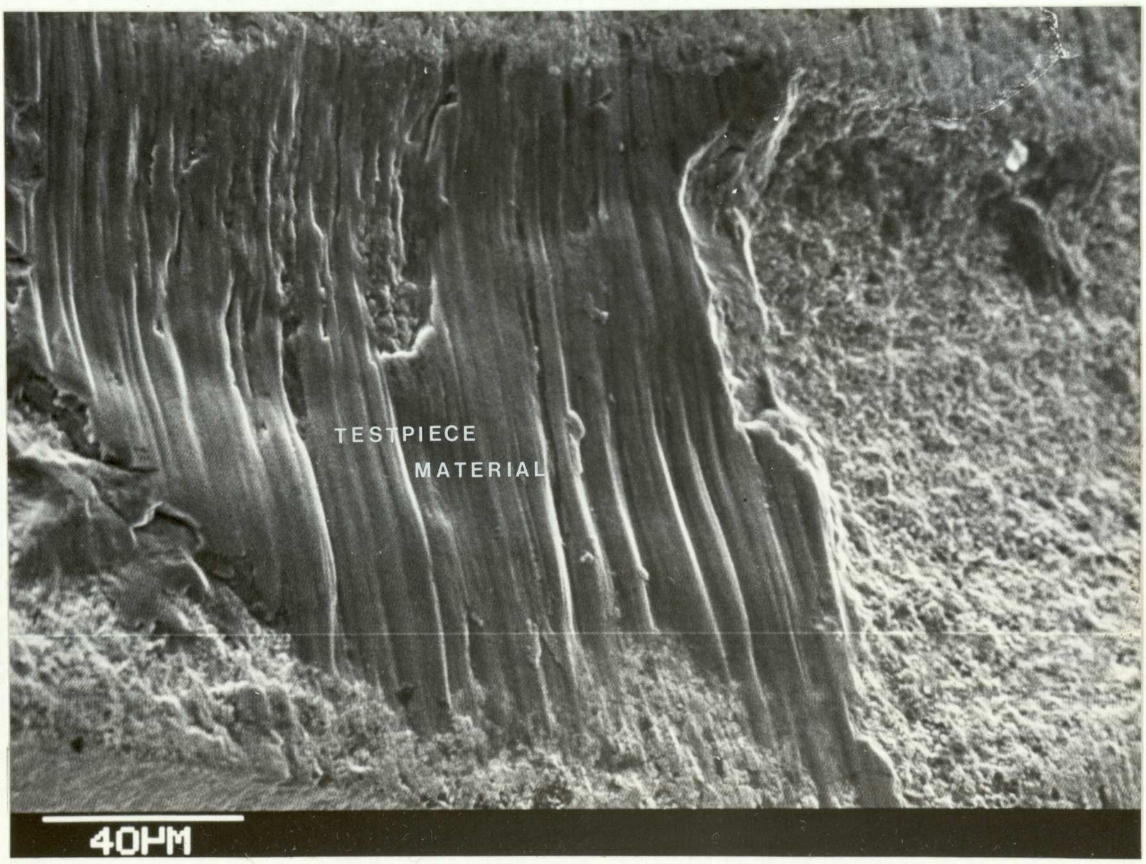


FIG 6.27 TESPIECE MATERIAL IN DAMAGED AREA OF INSERT FIG 6.26

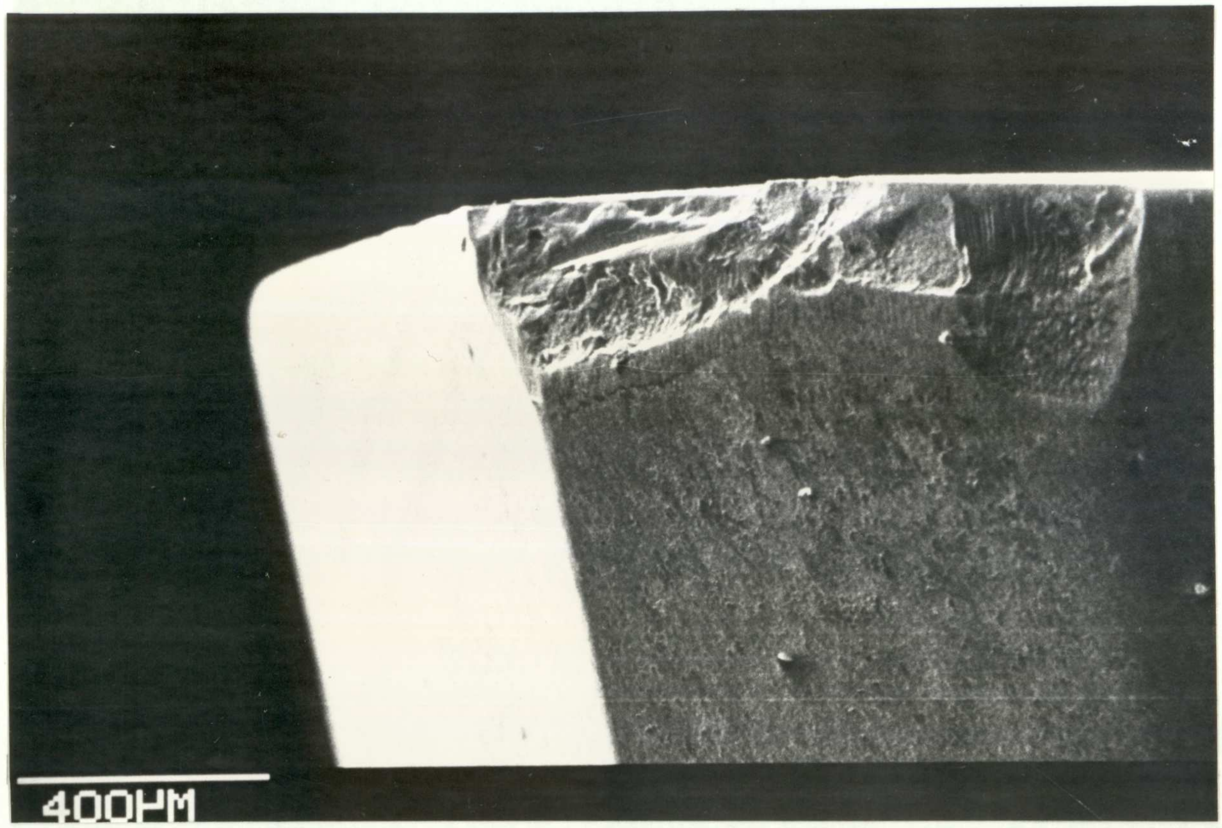


FIG 6.28 POSITIVE RAKE INSERT AFTER A FEW SECONDS UP-CUT MILLING

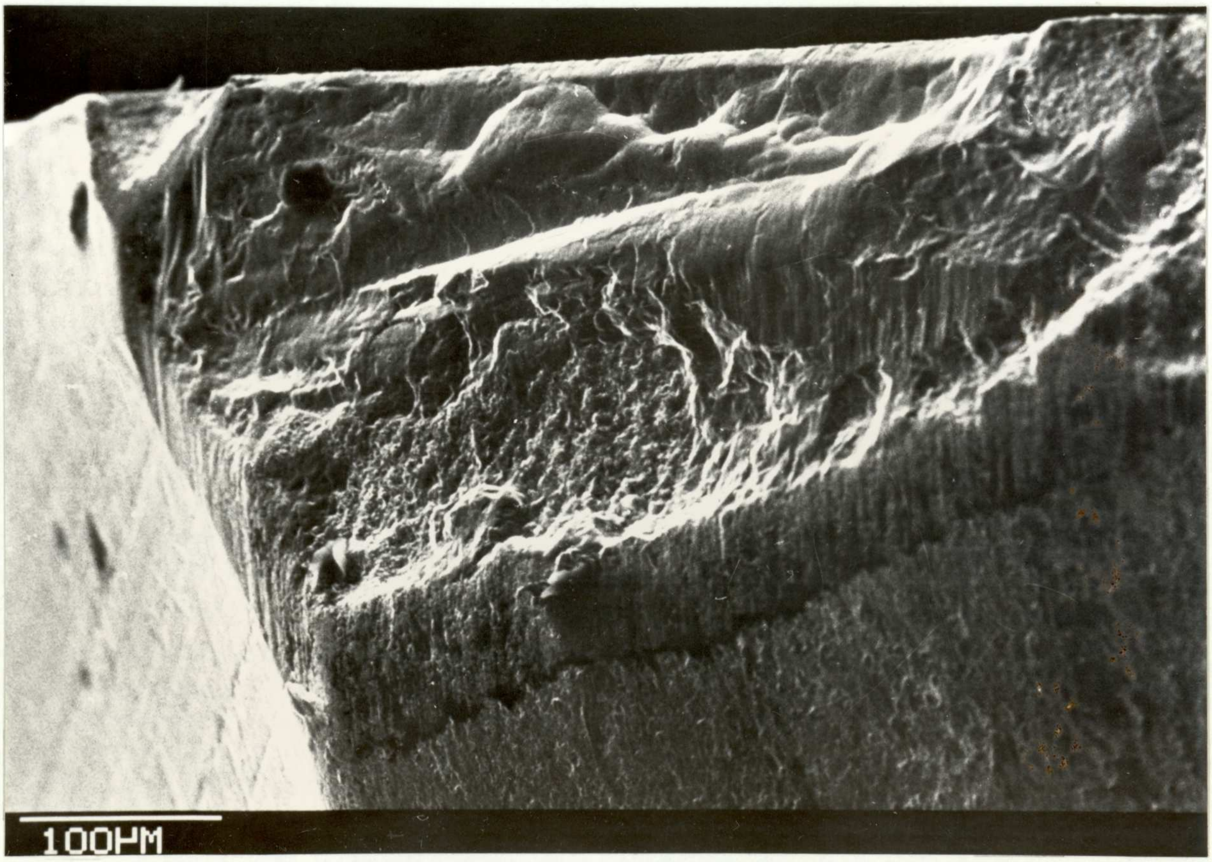


FIG 6.29 ENLARGEMENT OF ABOVE INSERT

FIG 6.30 CRACK IN FLANKWEAR

FIG 6.31 THERMAL CRACK

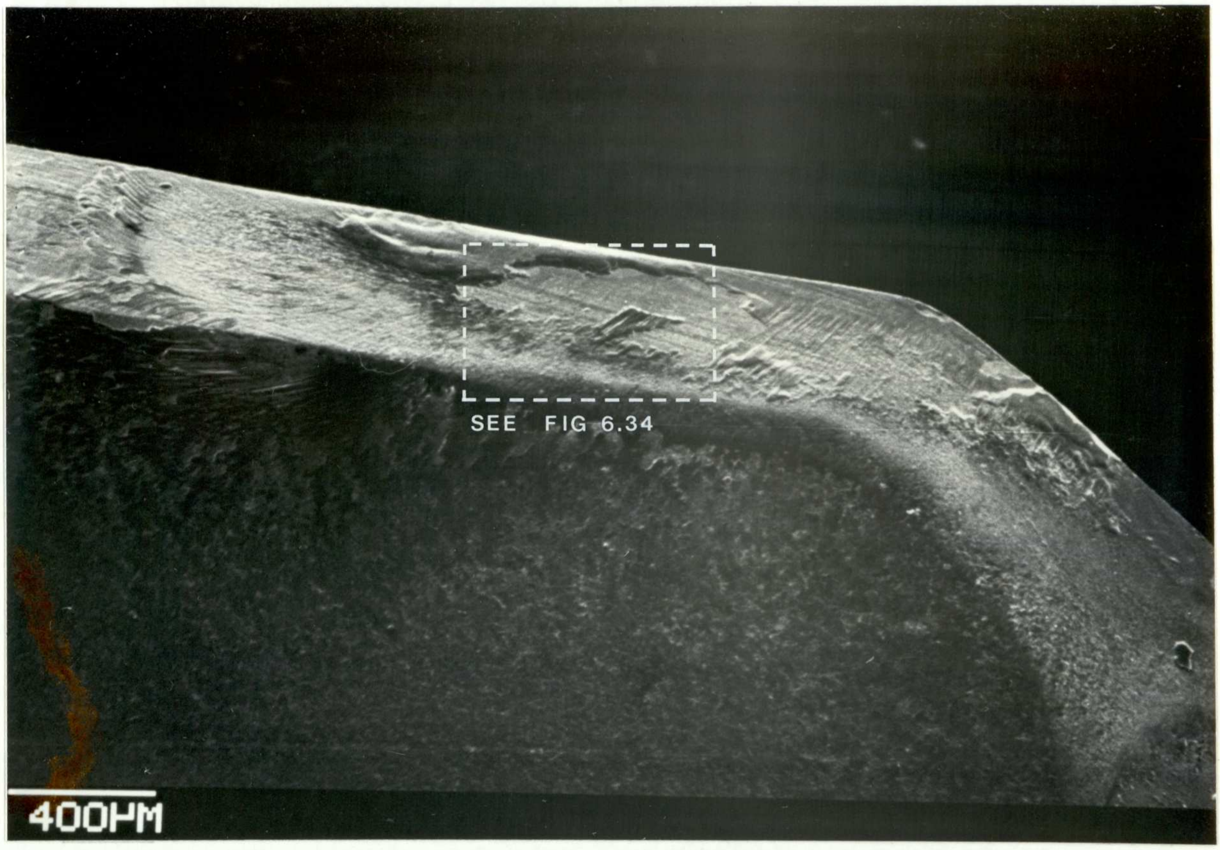


FIG 6.32 CHAMFER ON INSERT No 15 AFTER SERVICE

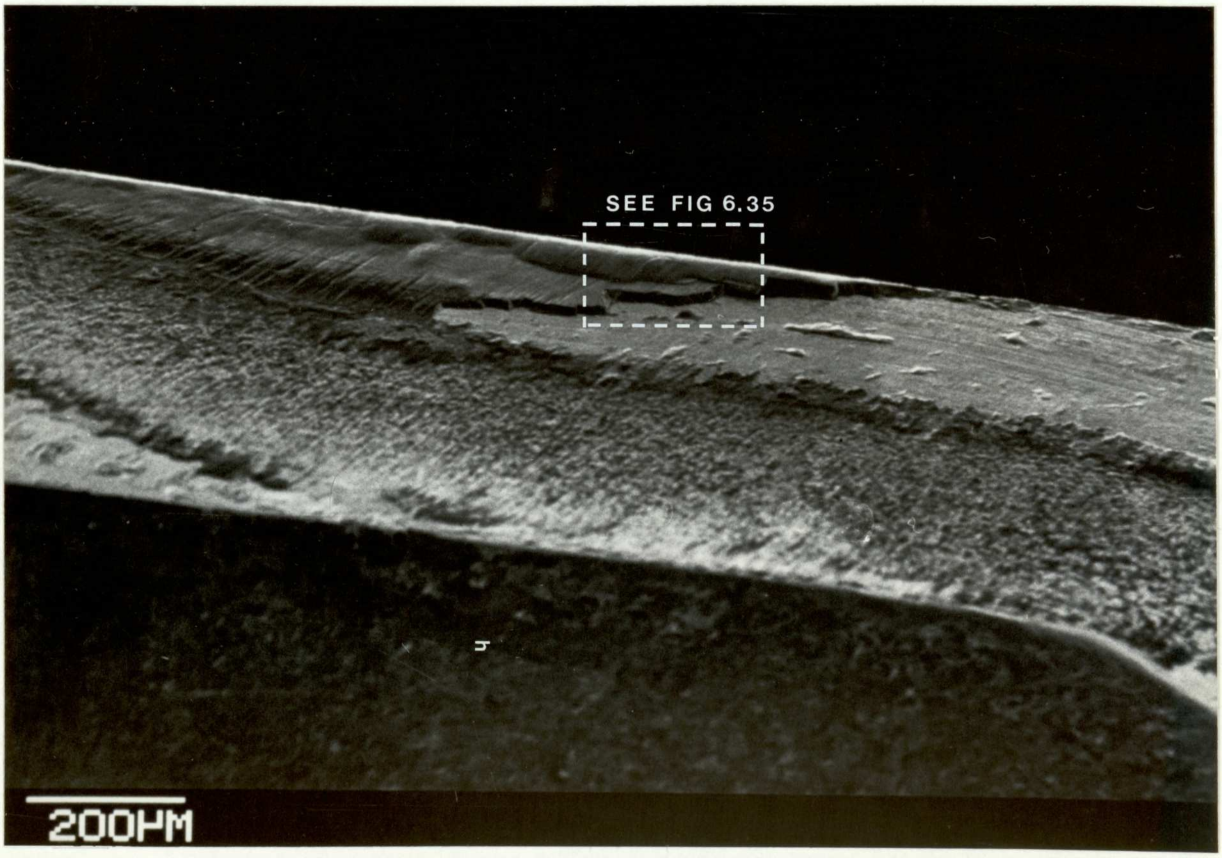


FIG 6.33 CHAMFER ON INSERT No 18 AFTER SERVICE

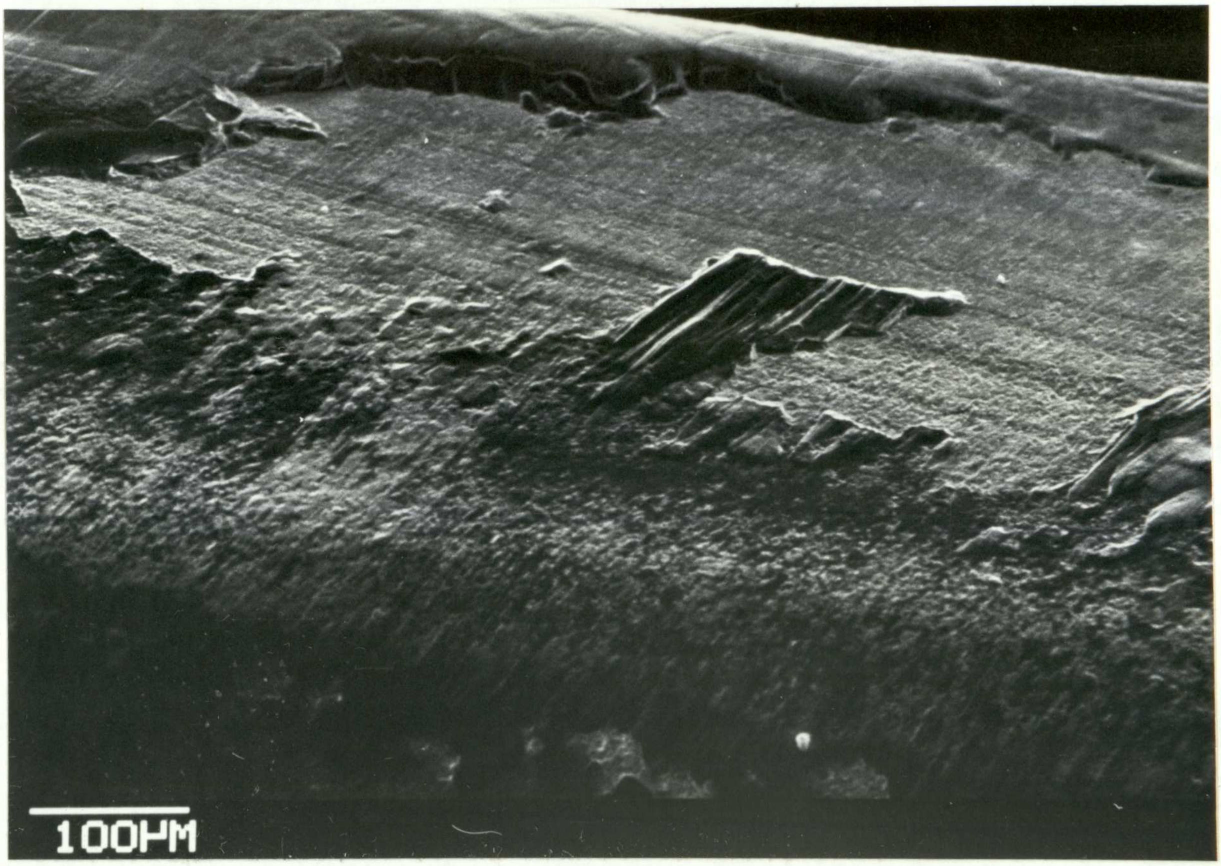


FIG 6. 34 ENLARGEMENT OF INSERT 15

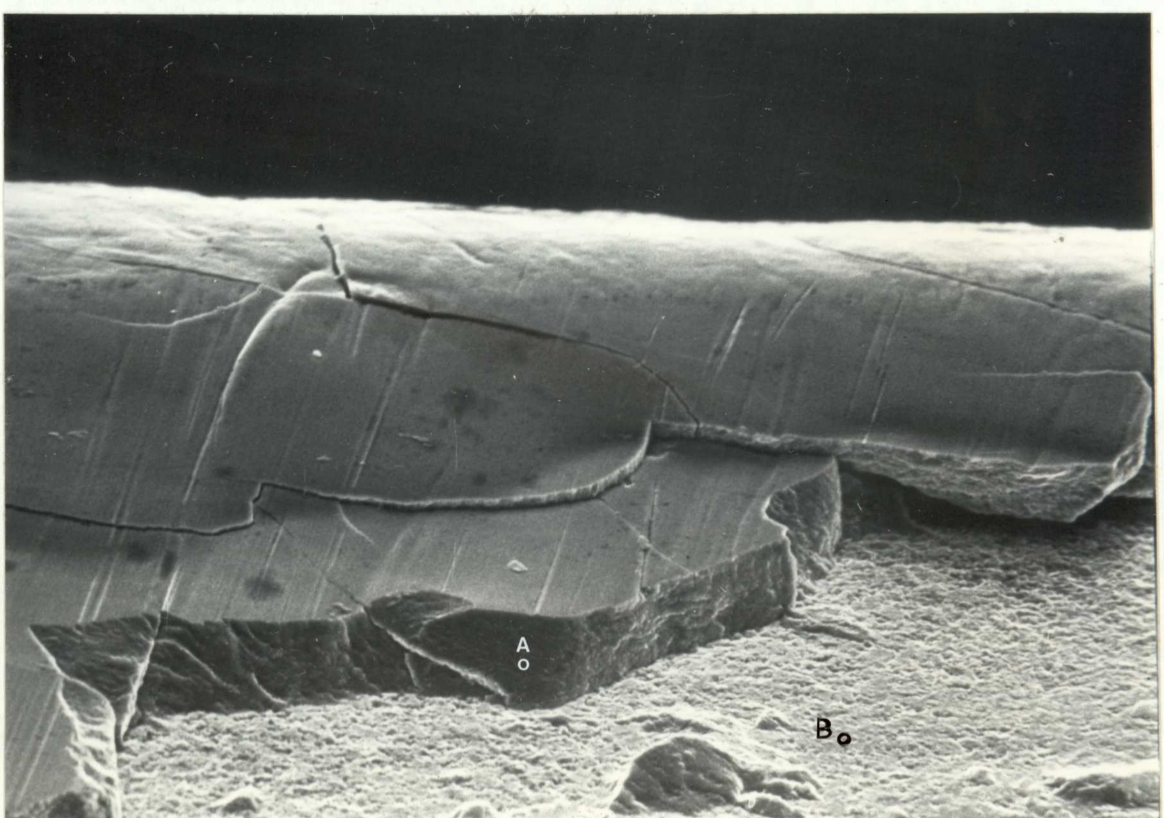


FIG 6.35 ENLARGEMENT OF INSERT No 18

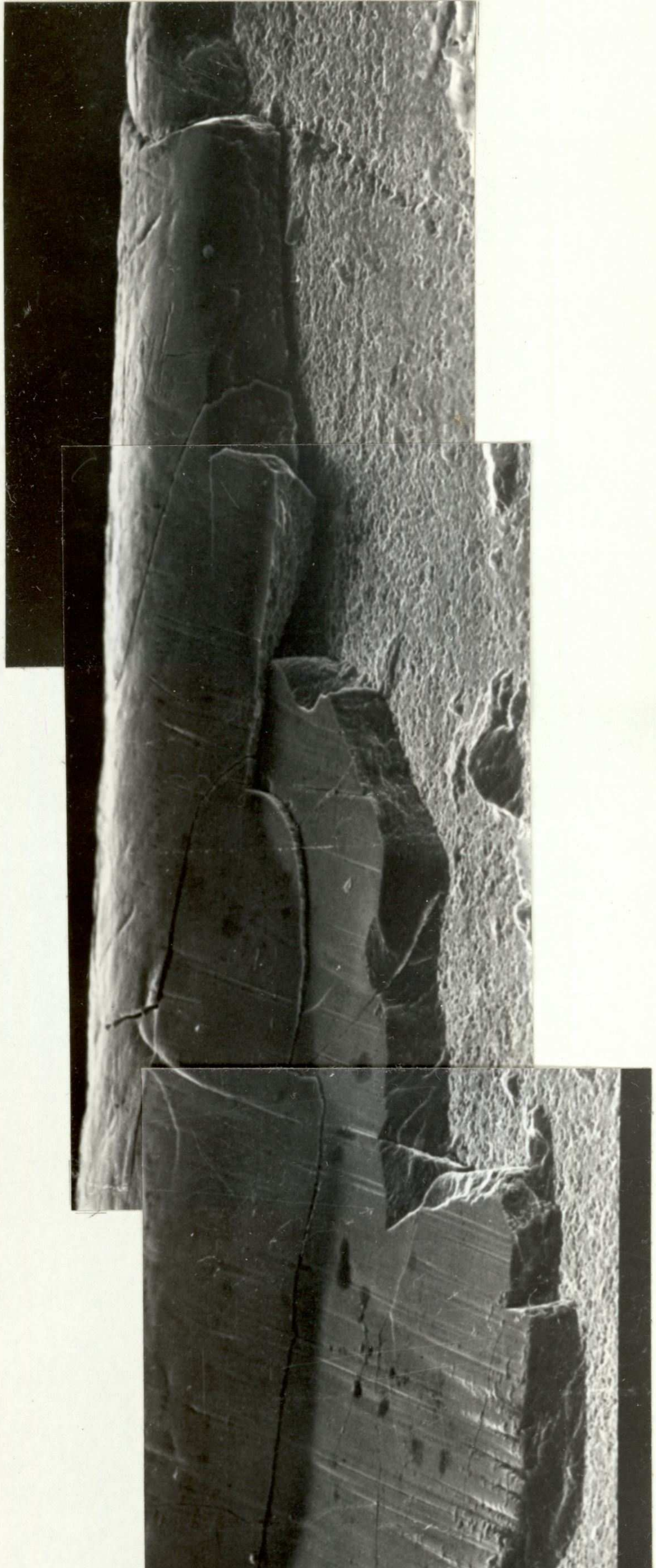


FIG 6.36 COMPOSITE PHOTOGRAPH OF INSERT No 18

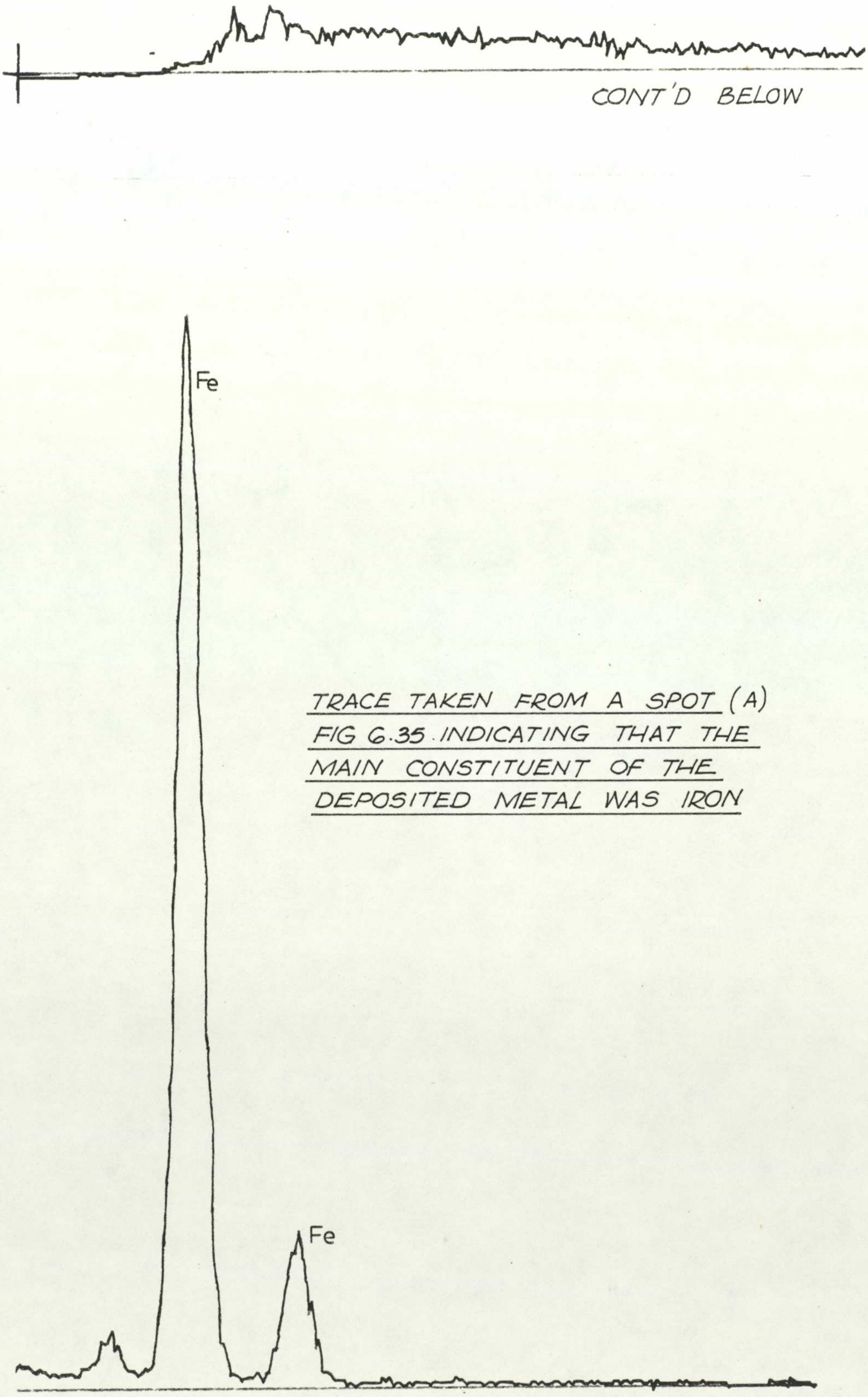


FIG 6.37 TRACE OBTAINED FROM SPOT (SHOWN IN FIG 6.35)

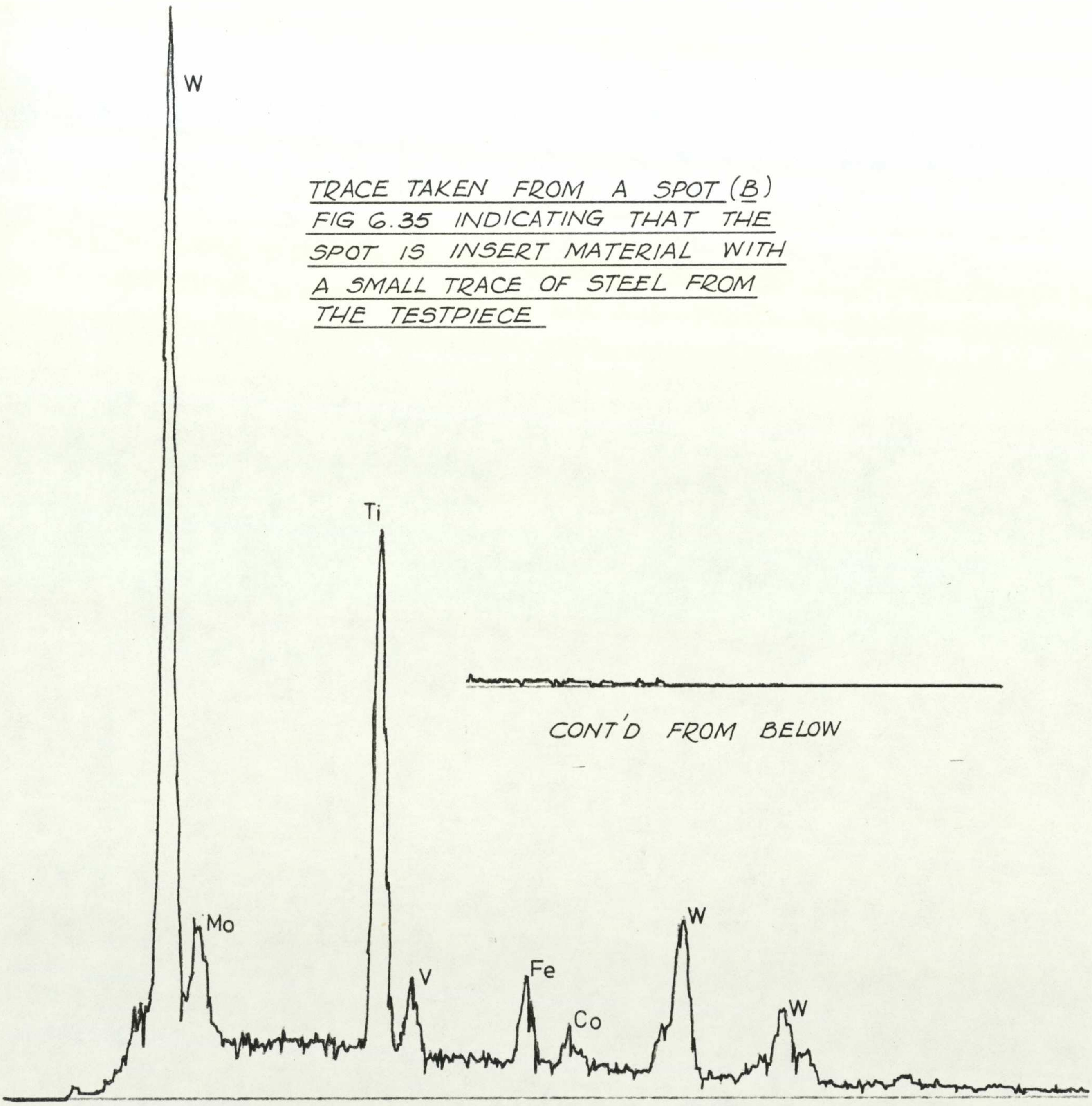


FIG. 6.38 TRACE OBTAINED FROM SPOT (SHOWN IN FIG 6.35)

CHAPTER 7

CUTTING FORCES

CHAPTER 7: CUTTING FORCES

A series of tests were carried out to determine the magnitude and direction of the cutting forces produced during face milling. The effects on the forces, by the variables involved in the tool life tests (feedrate, chamfer angle and entry conditions), were investigated, together with the effects produced by flank wear.

These tests were of particular importance because of some of the principles established during the earlier life tests, namely -

(i) the life of a positive rake insert can be increased by grinding a chamfer on its cutting edge.

(ii) within the range of feedrates used for a particular cutting speed the life of a cutting tool increased as the feedrate increased.

It was therefore necessary to investigate whether the suggested modifications could be a conceivable proposition or if the changes in the forces would be too high for practical consideration.

7.1 THE SET-UP

All of the force tests were carried out at The Polytechnic, Wolverhampton in the Department of Production Engineering. The machine tool used was a Parkson horizontal milling machine having a 5.5 kW motor, the table traverse was power driven in three axes independently from the spindle drive, making the feedrate infinitely variable. The same positive rake face-mill was used for the force tests as used in previous life tests.

The milling machine did not have a flywheel fitted to the main spindle, therefore it was not necessary to raise the testpiece above the table to enable the cutter to make contact with it, however it was considered a better support for the testpiece to be bolted onto a bolster overhanging the rear of the machine table, this raised the testpiece approximately 75 mm above the table.

The dynamometer used to measure the cutting forces was a Kistler piezoelectric universal 3-force dynamometer, the output from which was recorded on an ultra-violet recorder. The cutting forces were resolved into three component forces, mutually perpendicular to one another, as shown in fig 7.1. Each force may be considered as positive or negative, depending on the direction of the force. A useful feature of the dynamometer was that any cut taken within 25 mm of its top surface produced a correct reading, i.e. there was no requirement to make any compensation due to the changing thickness of the sample as it was machined away.

The dynamometer is normally used in the horizontal plane and a fixture had to be made to hold it vertically. at such a height that a sample of the steel being machined could be bolted onto the face of the dynamometer at the same height as the testpiece on the table. This allowed the cutter to be held horizontally in the machine spindle, as in previous tests, and enabled a cut to be taken along the testpiece, if required, and the cutter could continue onto the sample on the dynamometer maintaining exactly the same cutting mode. The fixture was made from a solid piece of grey cast iron and is shown in figs 7.2 and 7.3.

The samples used for the force tests were machined to the dimensions shown in fig 7.4, from the testpieces used for the tool life tests.

The feedrate was checked by engaging the table traverse and measuring the distance moved by the table during a specific period of time.

7.2 Test 1 - The effects of chamfer angle on cutting forces

Positive rake inserts similar to those used for the cutting tests described in Chapter 6 were employed for this test. Six inserts were used, one being left unchamfered and the others had their cutting edges ground to angles of 5°, 15°, 25°, 35° and 45° for a width of 1 mm (see Section 4.2).

The sample on the dynamometer was set at such a height relative to the cutter that the cutting mode was down-cut milling.

Each insert was used in turn to take a cut of 3 mm depth from a sample of EN 8 fastened to the dynamometer. The cutting speed was 125 m/min and the feedrate was 0.2 mm/rev of the cutter (i.e. 0.2 mm/tooth).

A copy of the trace obtained from the U.V. recorder is shown in fig 7.5 together with a table of the forces and the results are shown graphically in fig 7.6.

7.2.1 Conclusions

The largest force produced during each cut was that in the X axis. The component force in the positive Y axis remained constant for all the chamfer angles.

Upto about 25° chamfer angle did not significantly increase the cutting forces but for angles greater than this there is a considerable increase in the forces, in all but the negative Y axis. The greatest change took place in the positive Y axis where the forces increased from 350N at 25° upto 1500N at 45°, this latter value almost became as large as the force in the X axis.

If positive rake inserts chamfered upto 25° were used for face milling there would be no great increase in cutting forces.

7.3 Test 2 - The effects of entry conditions on cutting forces

Positive rake unchamfered inserts were used throughout this test. The cutting speed was 125 m/min and the feedrate was set at 0.3 mm/rev. The depth of cut was maintained at 3 mm.

The height of the table was varied for each cut to produce a range of entry angles, from zero (down-cut milling as used for many of the tool life tests), through 90^{o} (up-cut) to -30^{o} (down-cut milling across half the width of the sample).

The trace obtained from the forces is shown in fig 7.7 and a table of the forces and a pictorial representation of the cutting mode and entry angles is shown in fig 7.8.

7.3.1. Conclusions

When machining the full width of the sample (tests A to E, fig 7.8), the forces in the X axis and the Z axis remained constant whatever cutting mode was used. With the exception of test A the sum of the positive Y and negative Y forces was constant. This could account for the down-cut milling mode giving longer tool life because the collective positive Y and negative Y forces are less than for any other cutting mode and the individual Y component forces are exceeded in either the positive or negative direction, by all of the others. Down-cut milling requires less power to achieve the same results as the other entry modes.

If the whole width of a component is to be machined and it is within the capabilities of the machine tool to achieve it in one pass, there is no advantage gained in taking narrower cuts (tests F and G). In this condition the inserts are more prone to thermal cracks due to a longer quench period during the free rotation of the insert, causing a greater fluctuation in cutting temperatures.

7.4 Test 3 - The effects of feedrate on cutting forces

Two sets of results were obtained, one set using plain unchamfered positive rake inserts and a second set from positive rake inserts chamfered at 15° for a width of 0.6 mm.

All inserts were used for down-cut milling at 120 m/min using a depth of cut of 3 mm. Successive cuts were taken using feedrates varying from 0.5 mm/rev to 0.45 mm/rev in increments of 0.05 mm.

A copy of the traces obtained from the unchamfered inserts, together with a table of the measured forces, is shown in fig 7.9 and the graph of forces plotted against feedrate is shown in fig 7.10.

A copy of the U.V. record for the chamfered inserts and the associated forces is shown in fig 7.11, the resultant graph is given in fig 7.12.

7.4.1 Conclusions

Within the range of feedrates used the X axis forces for both sets of inserts were directly proportional to the feedrate. The other forces increased with increased feedrate but the rate of increase reduced as the feedrate increased. It appeared that the positive Y force and the Z axis force had reached a maximum value.

The pattern for both sets of inserts was very similar except that the chamfered inserts produced slightly higher forces than the unchamfered set.

When face milling the feedrate should be the highest possible within the constraints of, the strength of the component, the power of the machine tool, the ability of the insert to withstand the cutting forces and the required finish on the component.

7.5 Test 4 - The effects of flankwear on the cutting forces

A testpiece of EN 8 was mounted on the milling machine table, aligned with a sample secured onto the dynamometer. Using a standard positive rake insert, a 3 mm deep cut was taken across the dynamometer sample at 125 m/min, using down-cut milling and a feedrate of 0.3 mm/rev. A record of the initial forces before any flankwear had taken place was made.

The same insert was used to take a 3 mm cut from the full size testpiece, following on to take a cut from the sample on the dynamometer. The flankwear was measured and a record of the cutting forces taken, so that the two could be related. The procedure was repeated until the flankwear on the insert was in excess of 200µm.

A copy of the U.V. recording of the forces is shown in fig 7.13 and the results are shown graphically in fig 7.14.

7.5.1. Conclusions

Upto about 100µm flankwear it appeared that the forces were directly proportional to the amount of flankwear but as the wear increased the rate of increase in the forces reduced. At about 200μm the forces had reached their maximum values except for the positive Y value which was still increasing approximately linearly.

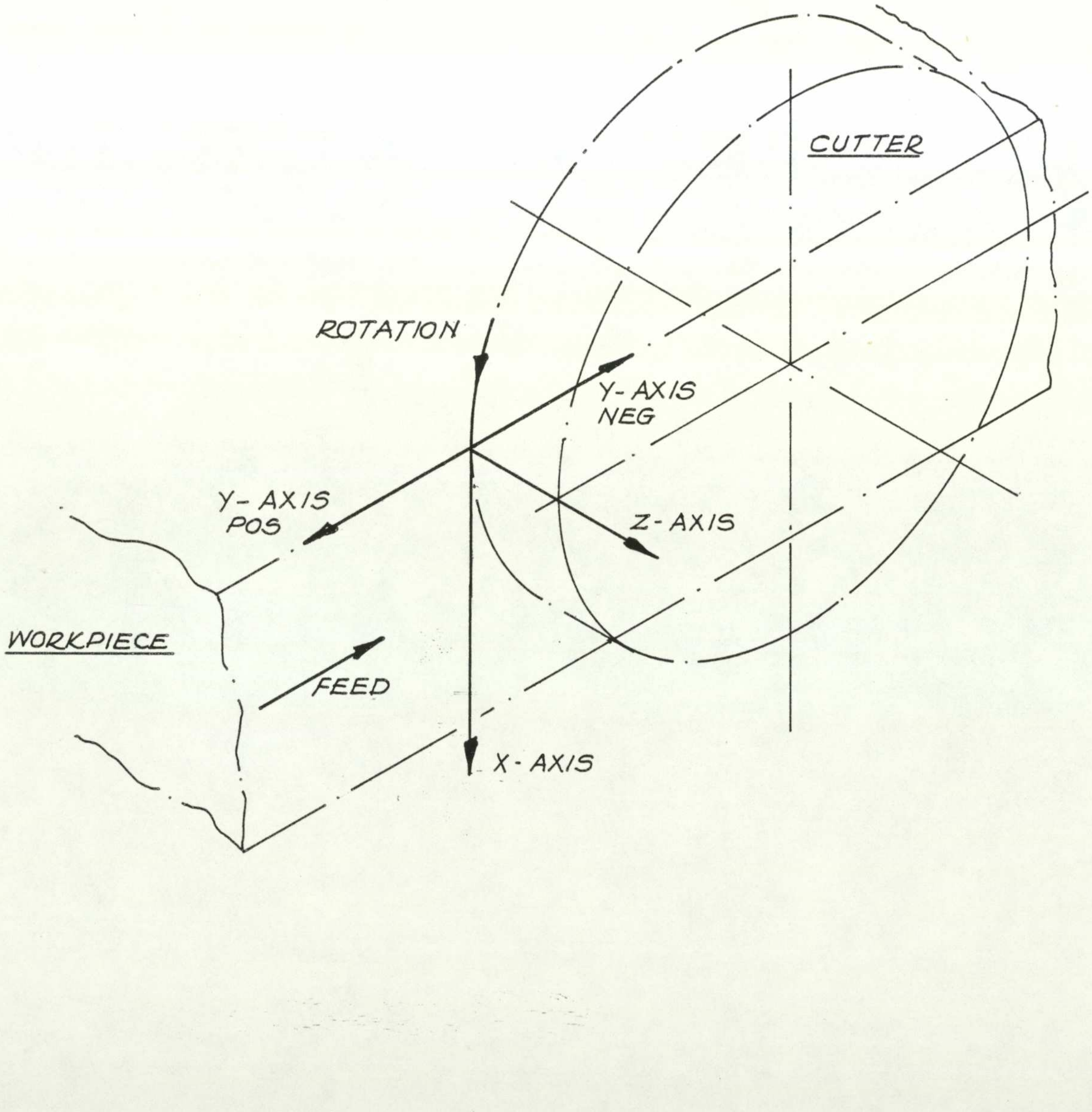


FIG 7.1 COMPONENT FORCES IN FACEMILLING

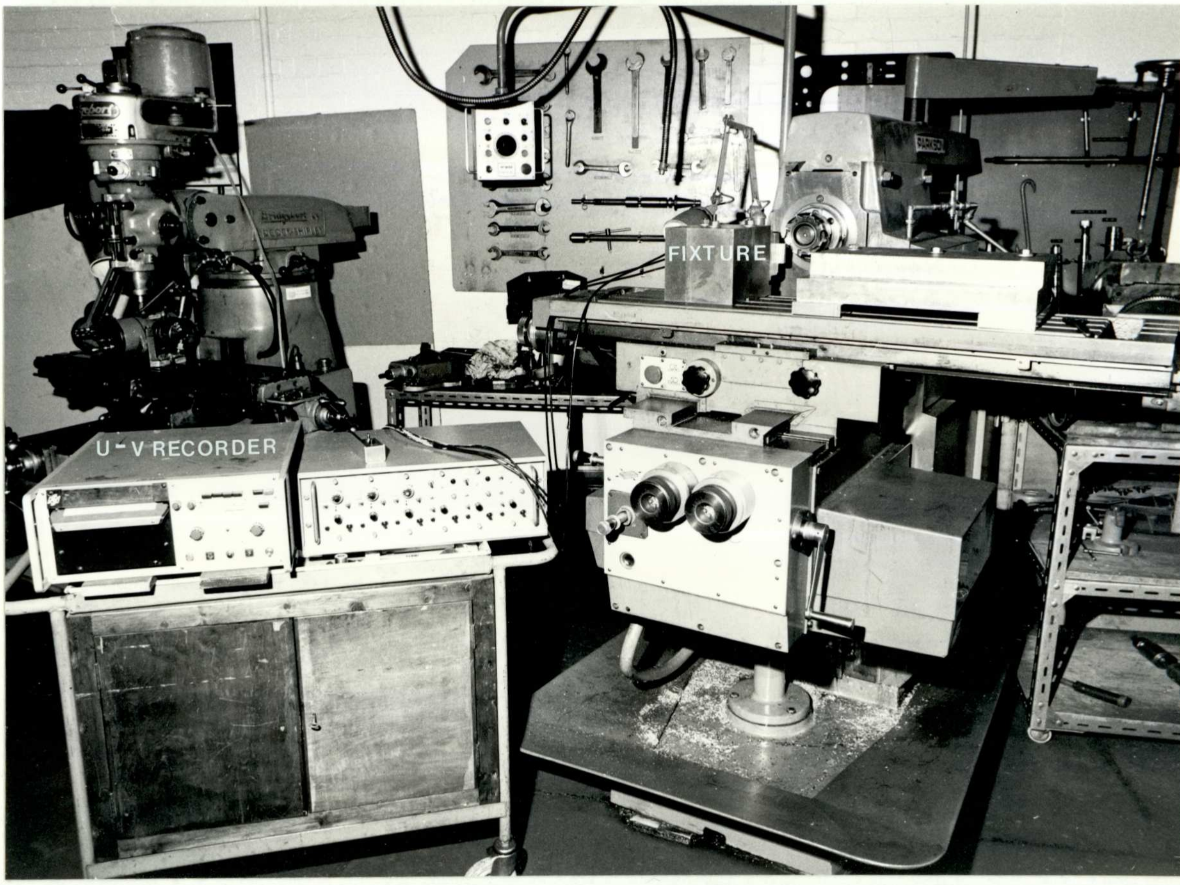


FIG 7.2 SET UP FOR FORCE TESTS

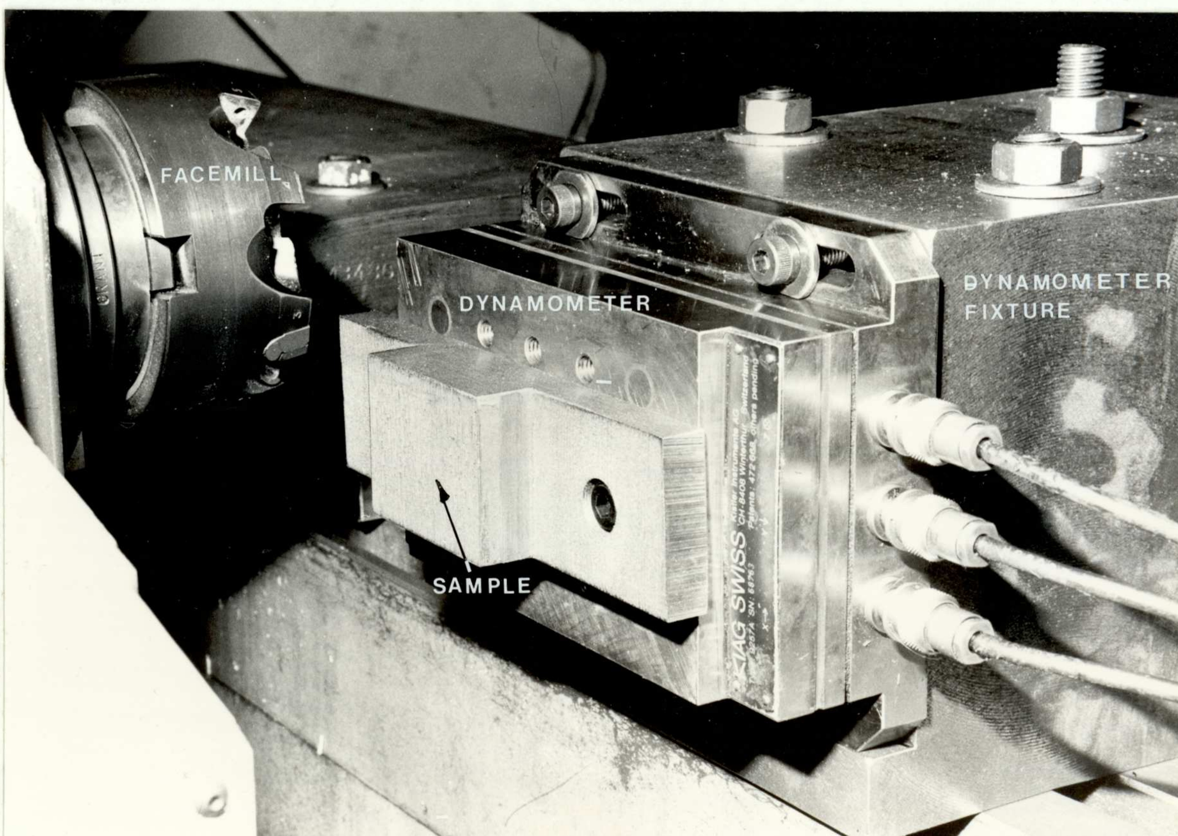


FIG 7.3 VIEW FROM REAR OF MACHINE

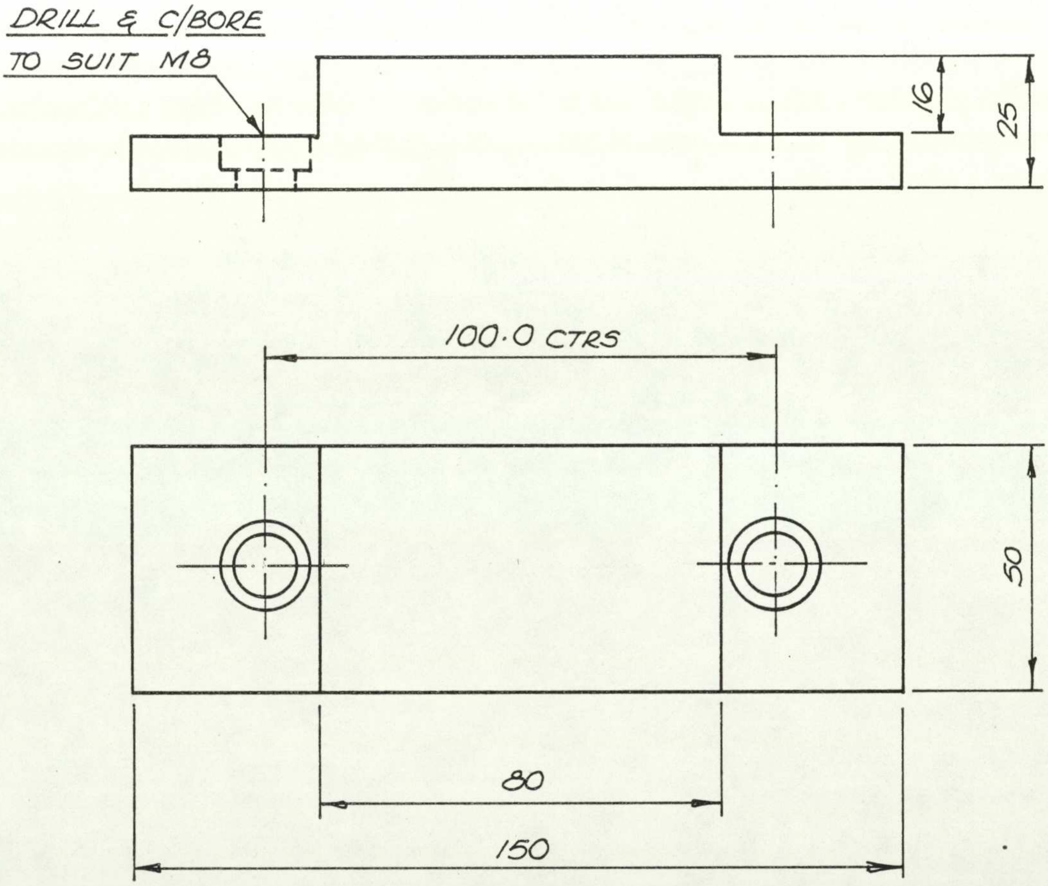
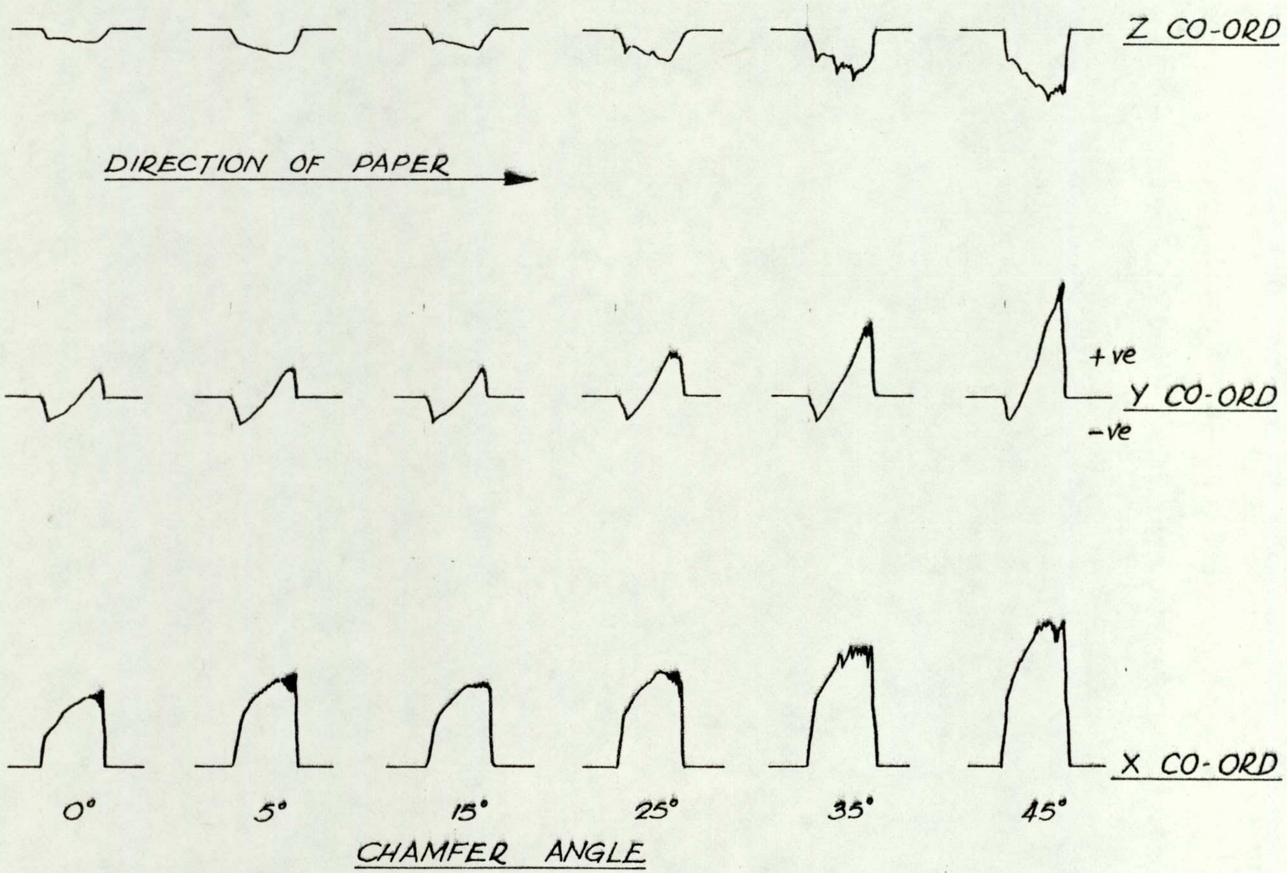


FIG 7.4 FORCE TESTS SAMPLE
(TO FIT KISTLER 3-FORCE DYNAMOMETER)



ANGLE	X	Y +ve	Y -ve	Z
0	900	300	300	160
5	1070	360	320	300
15	1050	350	340	280
25	1230	350	300	390
35	1500	1000	320	550
45	1800	1500	300	830

CUTTING FORCES (N)

FIG 7.5 COPY OF U-V RECORD - EFFECT OF CHAMFER ANGLE ON FORCES

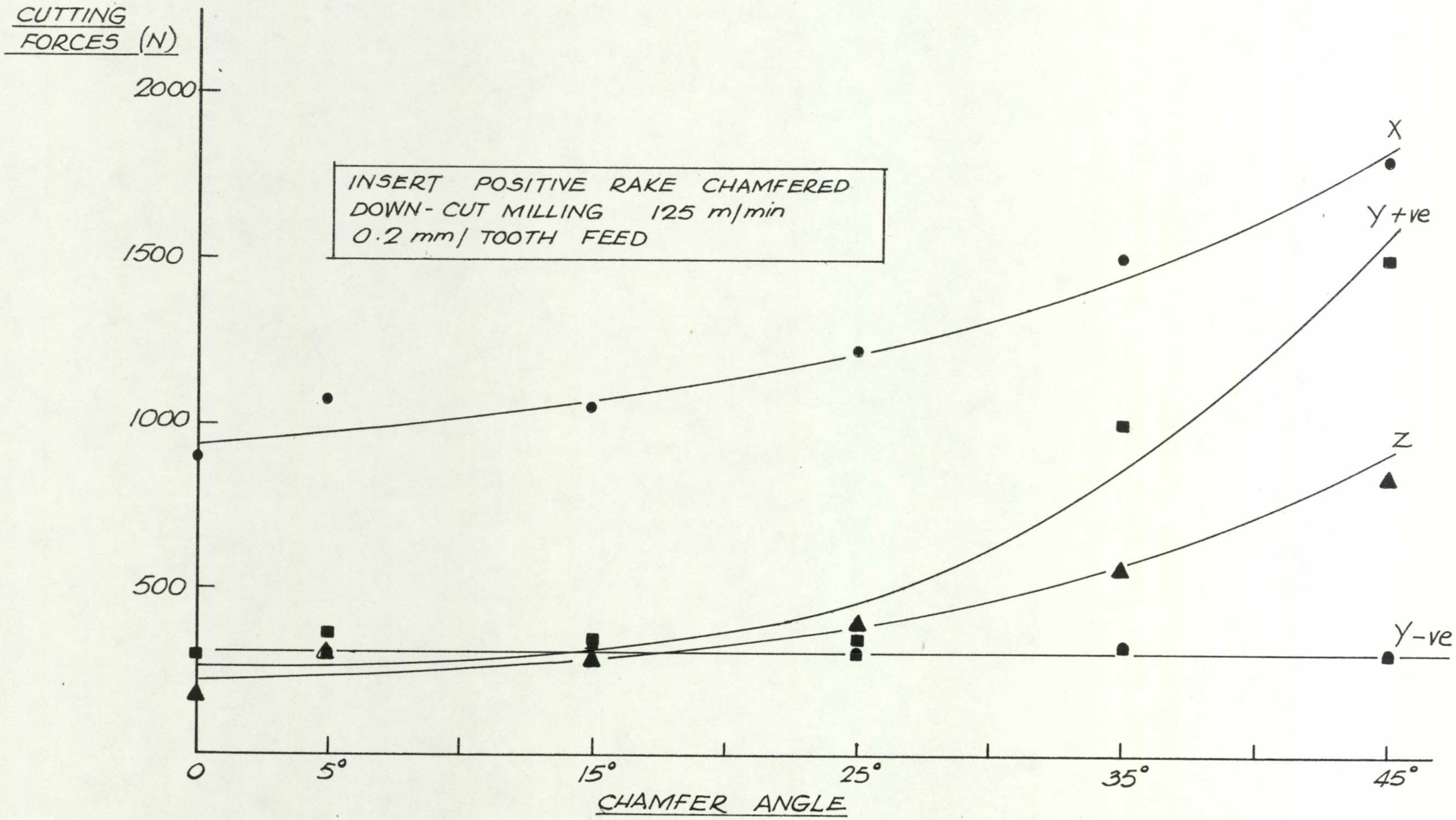
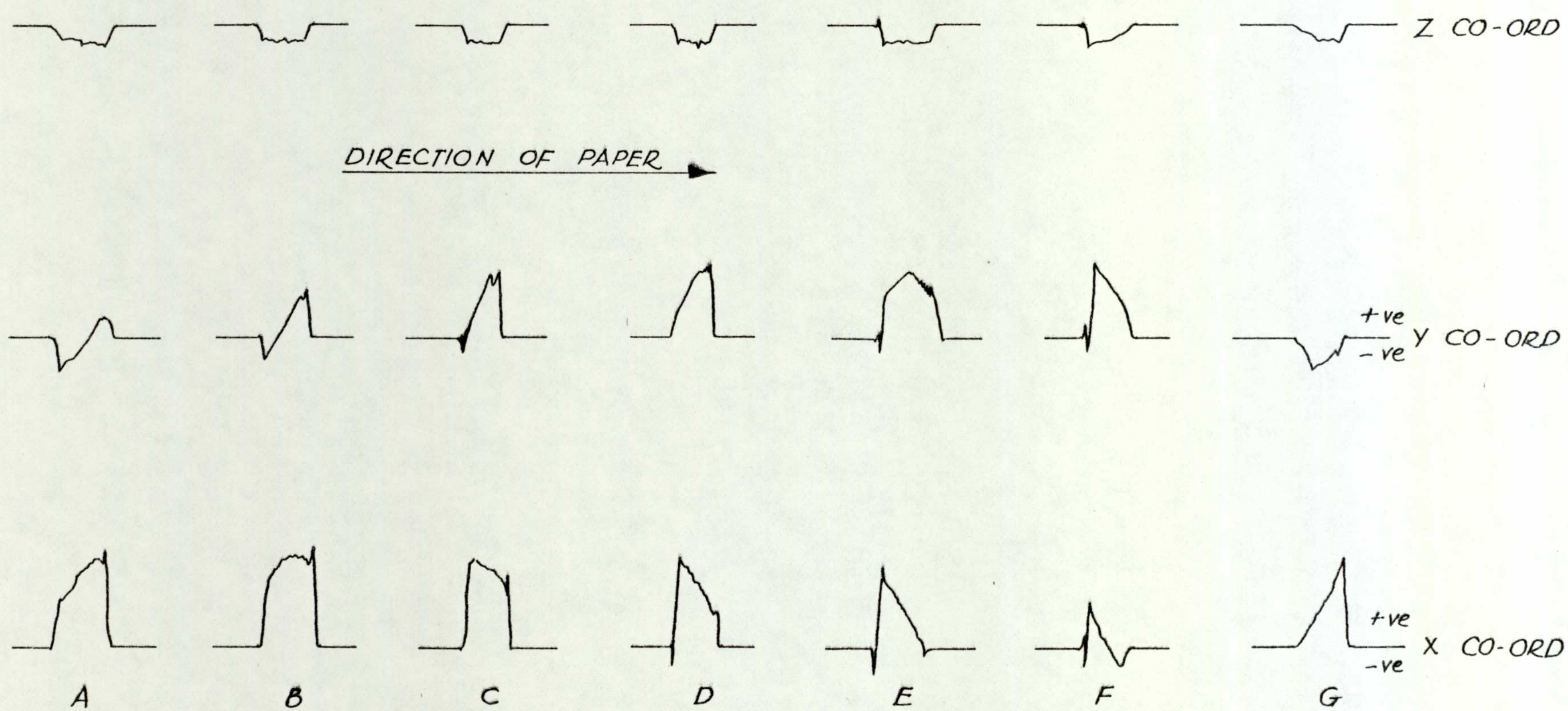
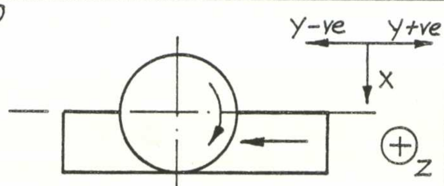
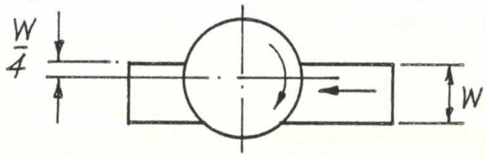
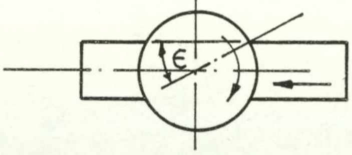
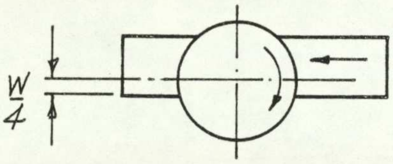
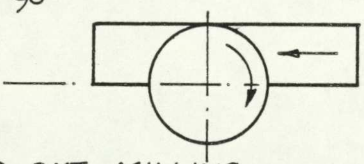
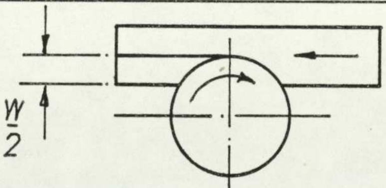
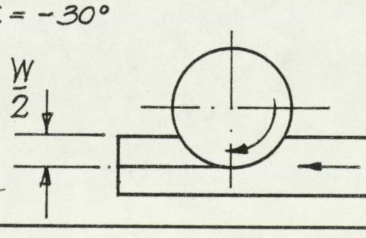


FIG 7.6 CUTTING FORCES DUE TO CHAMFER ANGLE



ENTRY CONDITION SEE FIG 7.8

FIG 7.7 COPY OF U-V RECORD - EFFECTS OF ENTRY CONDITION ON FORCES

CUTTING MODE	X AXIS	POS Y	NEG Y	Z
ε = 0  DOWN-CUT MILLING A	1300	280	460	280
ε = 14°  B	1250	600	330	250
ε = 30°  C	1280	770	120	280
ε = 48°  D	1260	900	0	260
ε = 90°  UP-CUT MILLING E	1200	910	0	280
 ε = 90° F	190 -ve 650 +ve	1000	0	270
ε = -30°  G	1150	0	450	200

EFFECT OF ENTRY ANGLE ON CUTTING FORCES

FIG 7.8

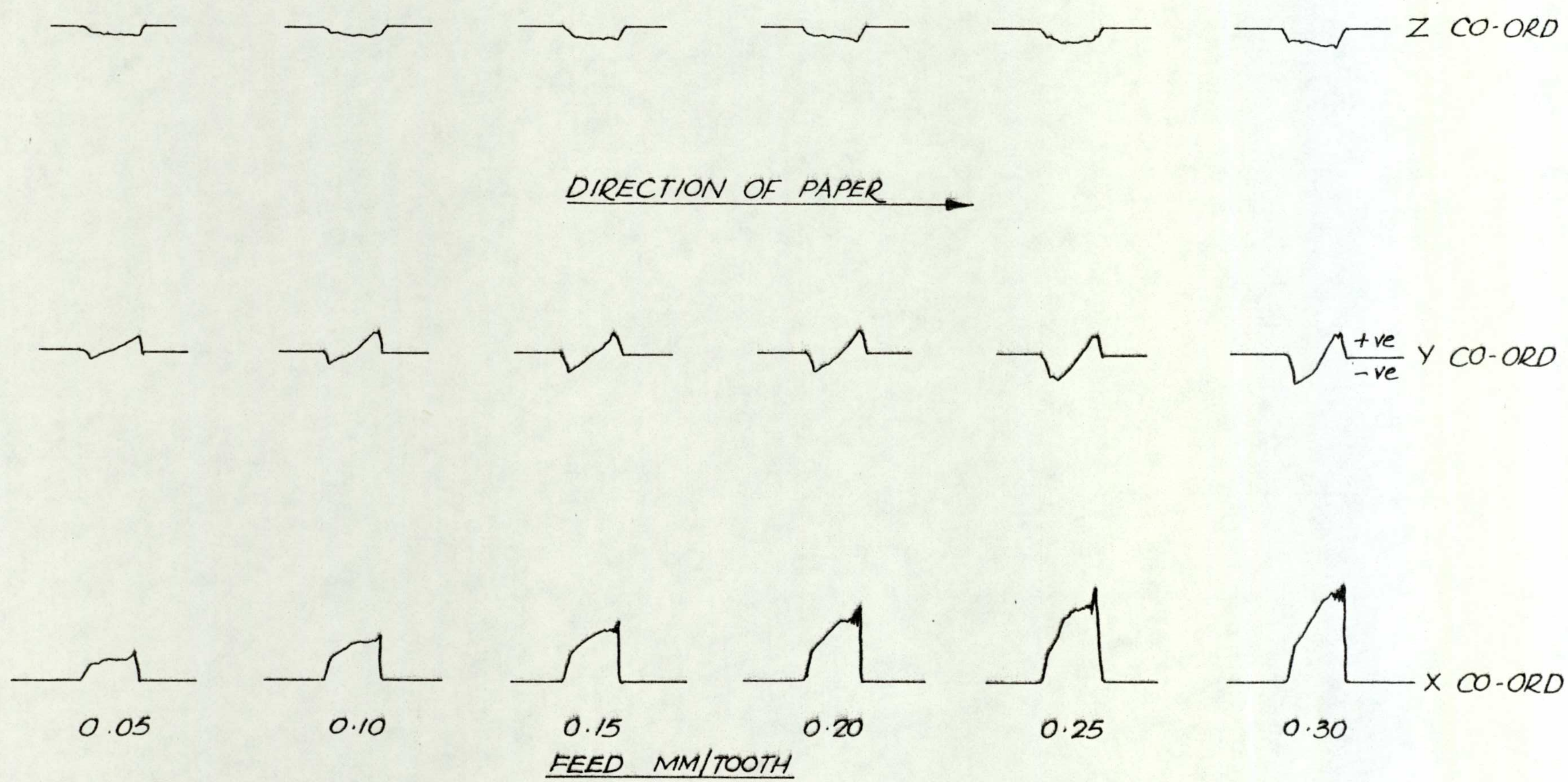
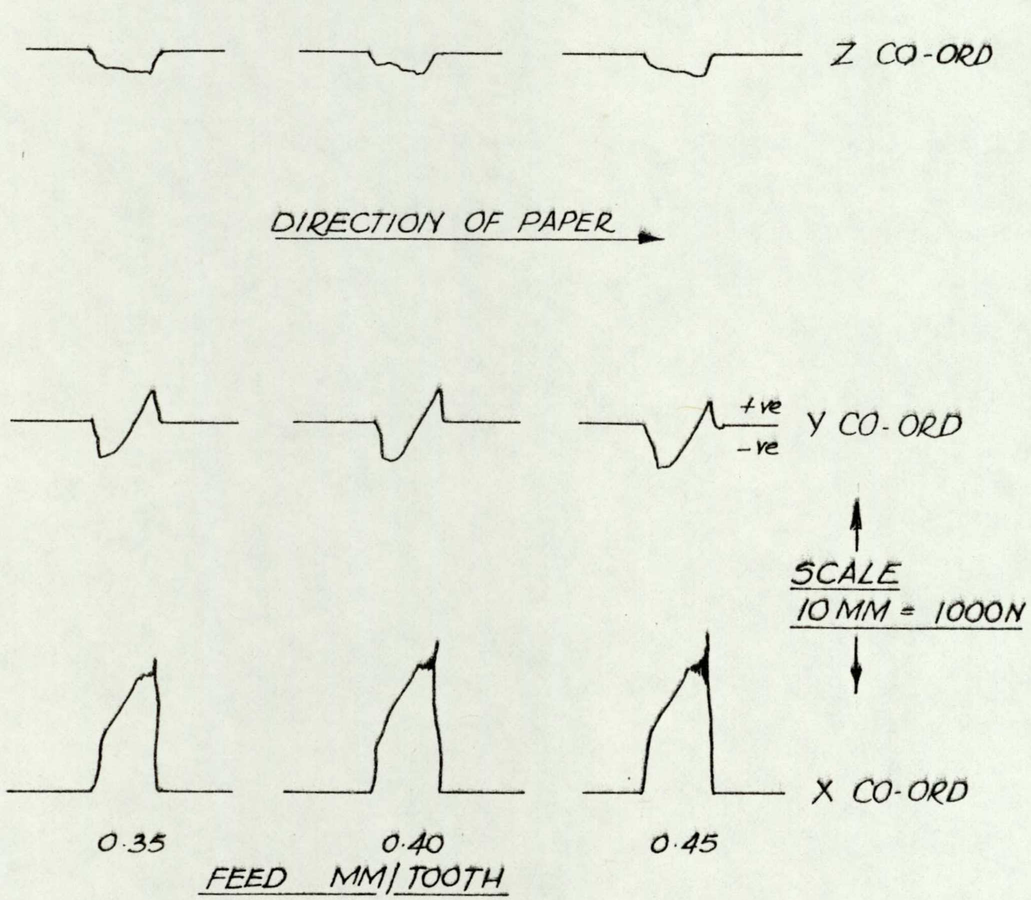


FIG 7.9 COPY OF U-V RECORD (PART) - EFFECT OF FEED ON FORCES

(CONTINUED ON NEXT PAGE)



CUTTING FORCES N				
FEED	X	Y +ve	Y -ve	Z
0.05	350	180	110	100
0.10	550	270	200	130
0.15	750	290	260	200
0.20	920	290	340	200
0.25	1120	310	400	200
0.30	1300	310	470	220
0.35	1480	350	480	240
0.40	1750	360	530	260
0.45	1680	310	580	260

INSERT USED
POSITIVE RAKE UNCHAMFERED

FIG 7.9 CONTINUED EFFECT OF FEED ON FORCES

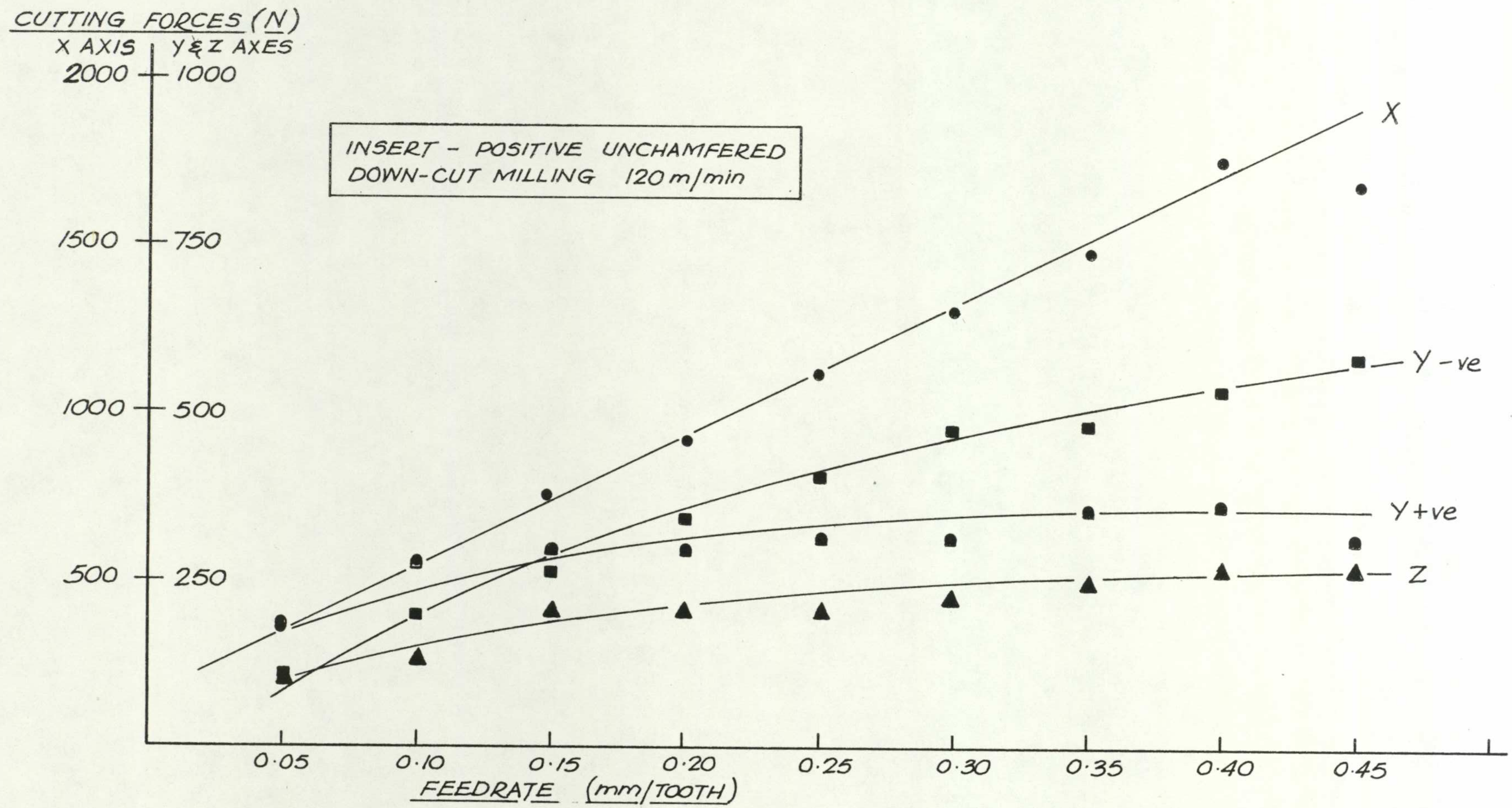


FIG 7.10 CUTTING FORCES DUE TO CHANGE IN FEED

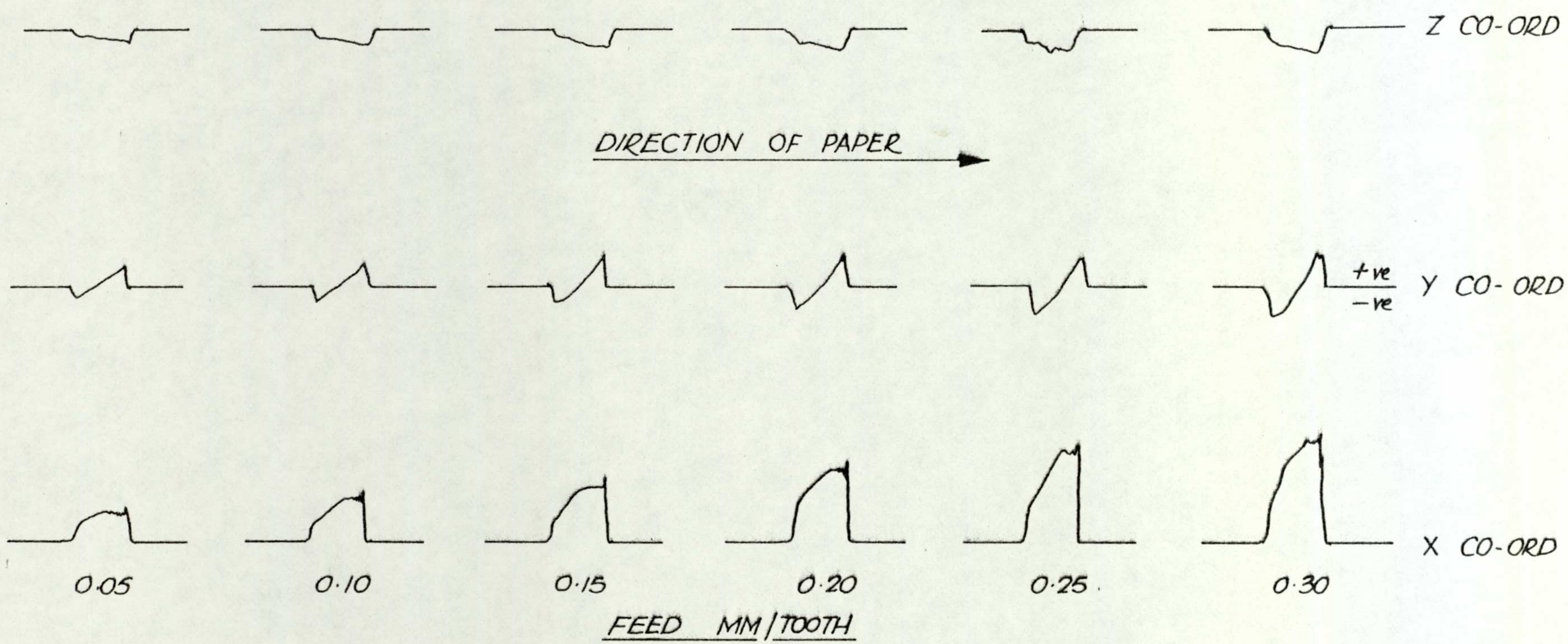
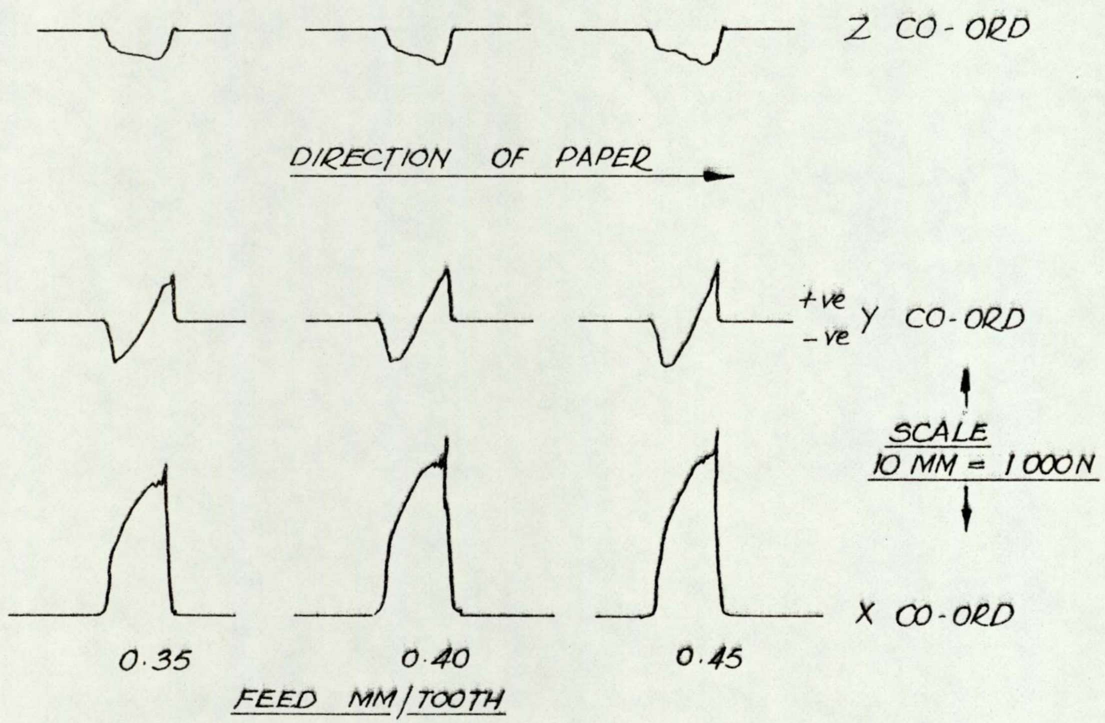


FIG 7.11 COPY OF U-V RECORD (PART) - EFFECT OF FEED ON FORCES USING A CHAMFERED INSERT
(CONTINUED ON NEXT PAGE)



CUTTING FORCES N				
FEED	X	Y +ve	Y -ve	Z
0.05	400	230	120	140
0.10	600	300	190	180
0.15	800	350	210	220
0.20	1020	400	300	280
0.25	1250	400	400	320
0.30	1500	460	450	380
0.35	1650	500	480	400
0.40	1840	590	580	440
0.45	1950	530	620	430

INSERT USED
POSITIVE RAKE CHAMFERED 15°

FIG 7.11 CONTINUED EFFECT OF FEED ON FORCES

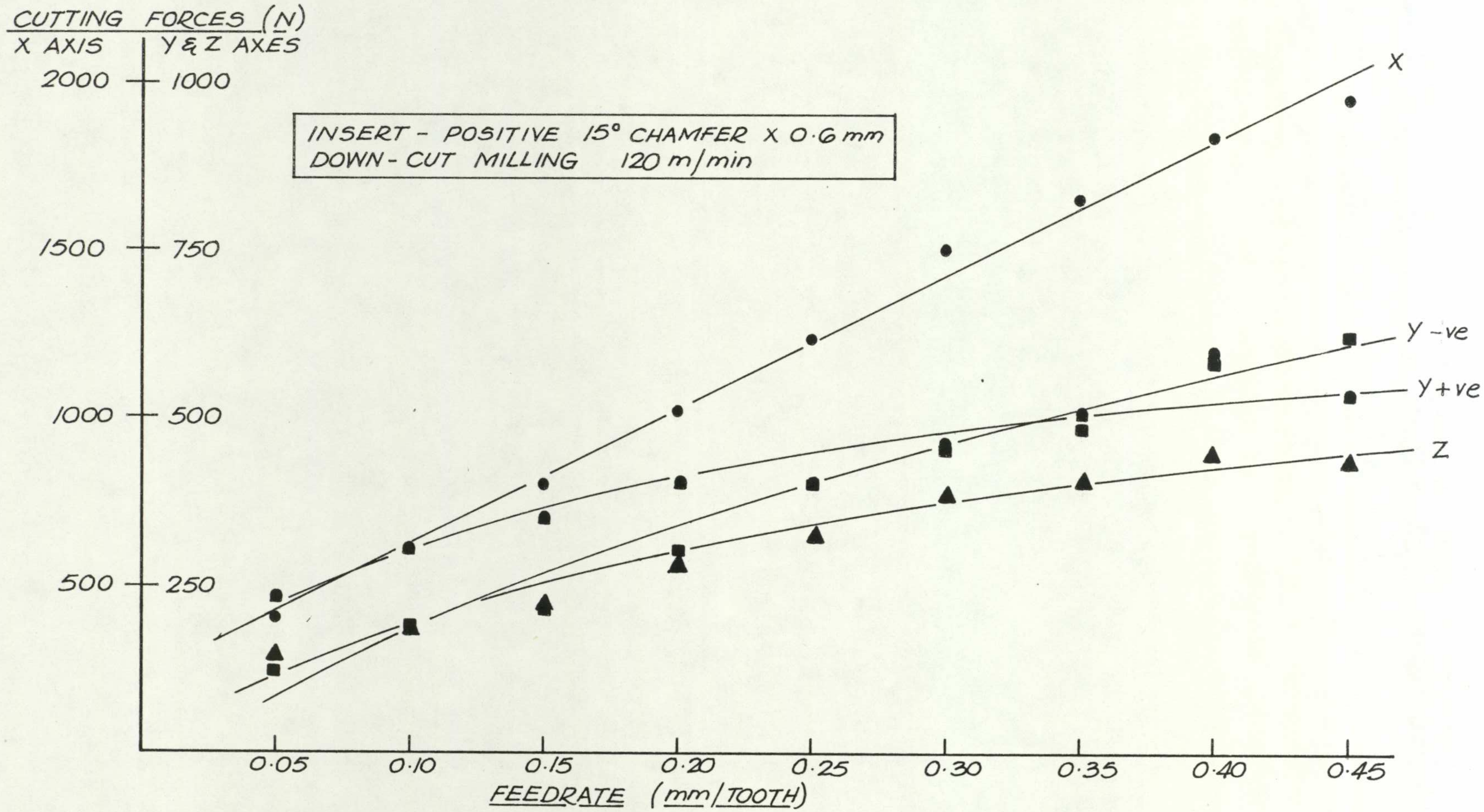


FIG 7.12 CUTTING FORCES DUE TO CHANGES IN FEED

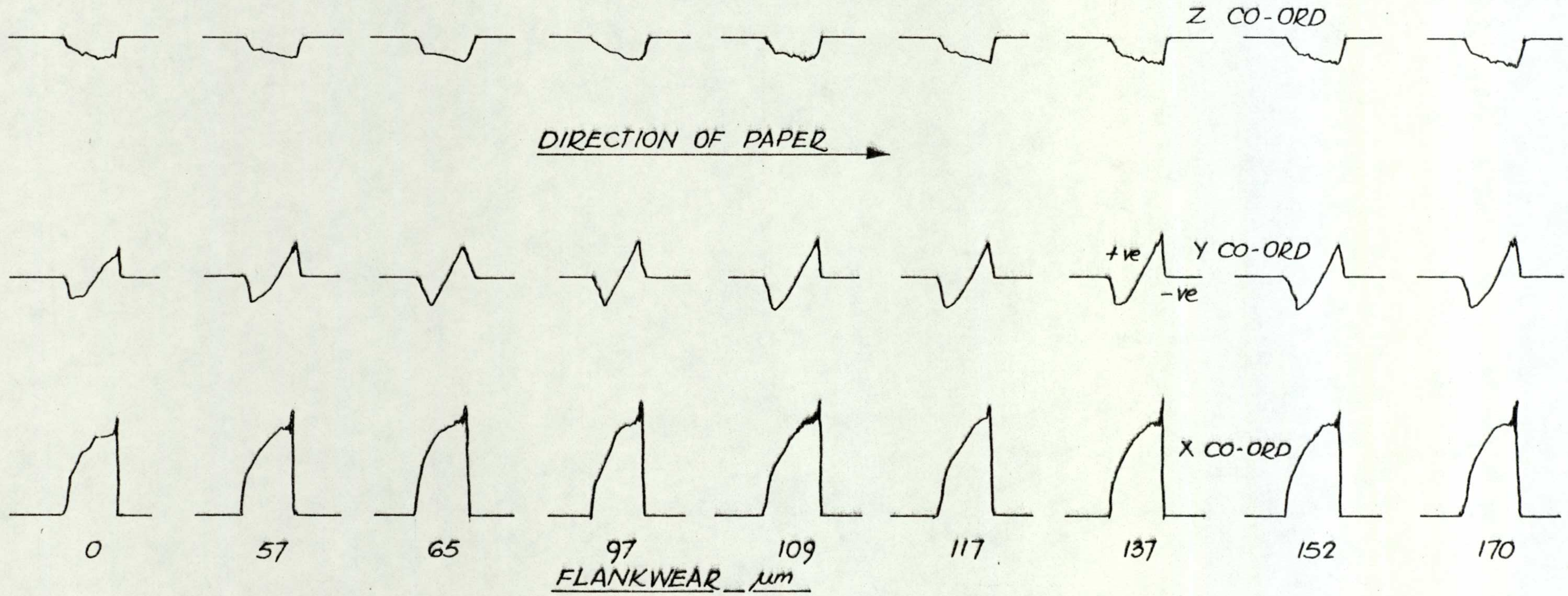


FIG 7.13 COPY OF U-V RECORD (PART) EFFECTS OF FLANKWEAR ON FORCES

(CONTINUED ON NEXT PAGE)

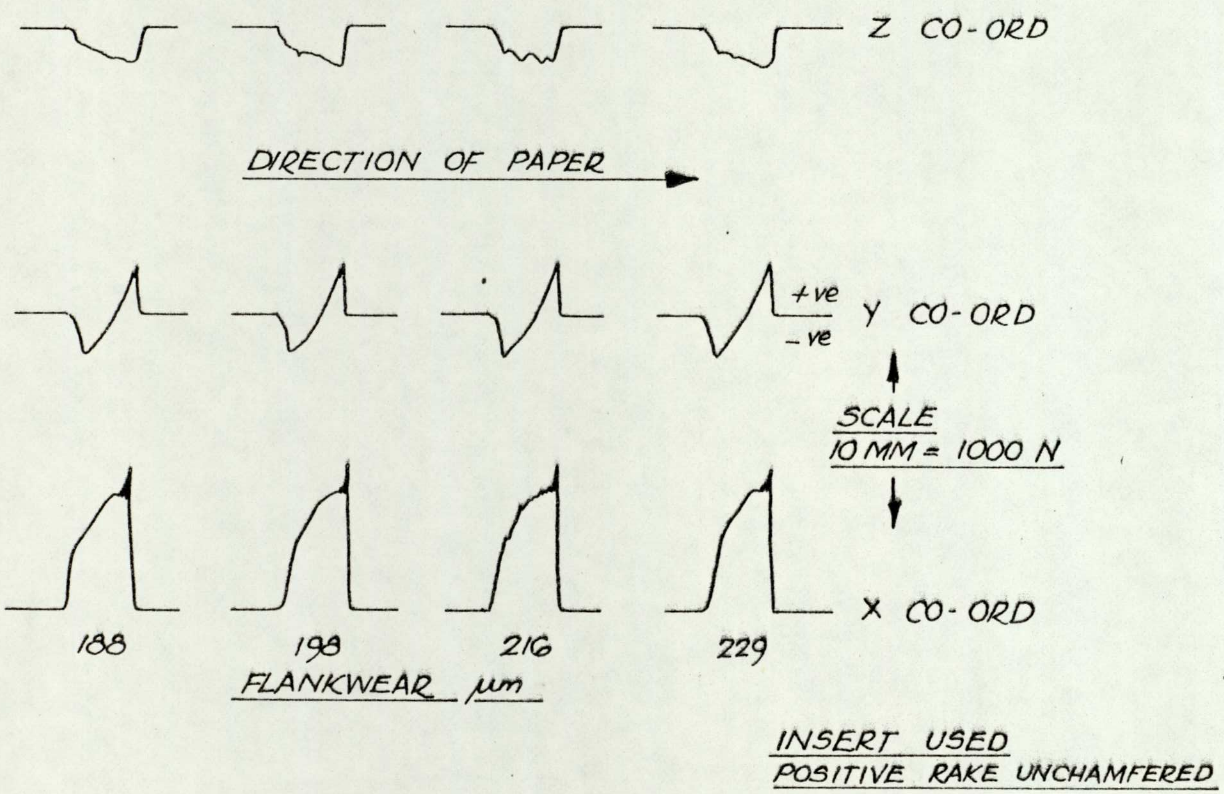


FIG 7.13 (CONTINUED) EFFECTS OF FLANKWEAR ON FORCES

CUTTING FORCES N				
WEAR	X	Y +ve	Y -ve	Z
0	1250	350	370	280
57	1350	370	410	300
65	1360	400	450	330
97	1400	430	480	370
109	1450	490	500	350
117	1460	410	480	380
137	1470	490	480	400
152	1480	490	500	420
170	1440	480	480	410
188	1500	500	500	400
198	1510	530	500	440
216	1500	550	500	410
229	1550	500	500	420

VALUES OBTAINED BY SCALING THE ACTUAL U-V TRACE

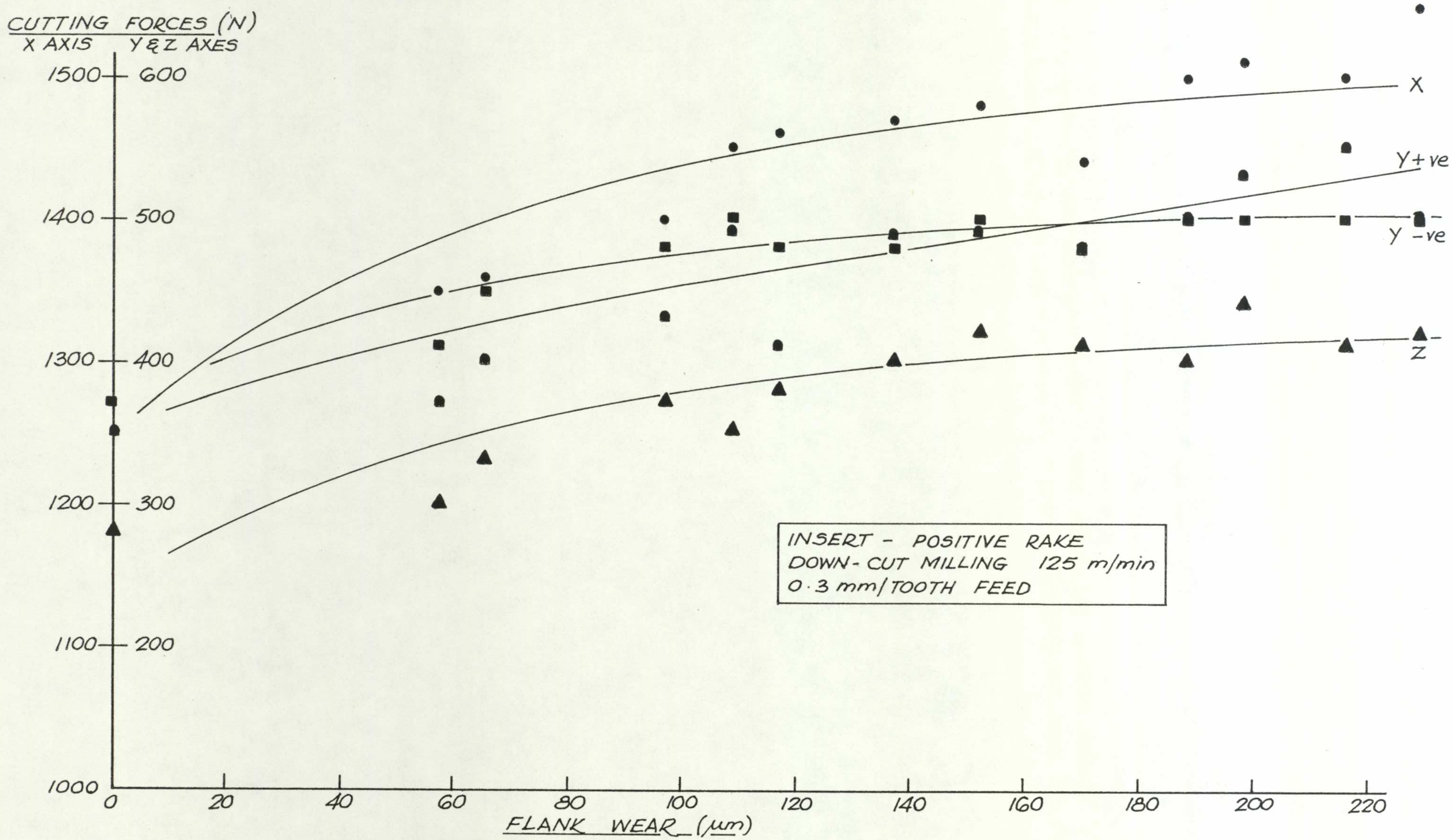


FIG 7.14 CUTTING FORCES DUE TO FLANK WEAR

CHAPTER 8

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

CHAPTER 8:

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

8.1 CONCLUSIONS AND DISCUSSIONS

The following remarks are applicable to P25 grade tungsten carbide indexable inserts, when used for face-milling EN 8 steel in its normalised condition.

Metal cutting tests are renowned for producing erratic results due to the complexity of the process and the inconsistencies of the cutting tools and work-piece materials. For this research, testpieces were made from steel produced from a single ingot, so reducing many of the variables in the material being machined. Modern manufacturing processes have minimised the differences between inserts but the process of facemilling remains one of the most complex metal cutting processes. Against this background it was satisfying to obtain consistent results which confirmed that the techniques adopted were suitable for a study of this type.

The rate of flankwear taking place on inserts was found to be linear, within seconds of starting to cut. This fact gave confidence in using a relatively small flankwear as the criterion for tool life. The flankwear was also easily and accurately measured optically.

Standard negative rake inserts were used for machining in the down-cut and up-cut modes but positive rake inserts failed within seconds when attempting to use them for up-cut milling. This repeated failure was partly due to the initial contact between the insert and the testpiece. The contact (considered to be the worst type) was on the corner of the insert, that is, an 'S' point contact but this form of contact also occurred when down-cut milling and a longer tool life was obtained in this mode. Analysis of the cutting forces indicated that the resultant force was greater when up-cut milling than when down-cut milling. To overcome this increased force a stronger cutting edge was required and it was established that a chamfered cutting edge gave a longer tool life.

Virtually any chamfer angle improved the tool life of a positive rake insert, when up-cut milling, but it was found that a chamfer of 15° produced the best results on positive rake inserts for up-cut and down-cut milling. Little improvement was noted when chamfering negative rake inserts and it was not possible to conclude that a specific angle gave the optimum solution. Improvements were observed when machining with chamfered negative rake inserts but the improvement was not as great as that which occurred with the positive rake inserts.

When referring to tool life no relationship between chamfer width and feedrate existed. This view may be contrary to that expressed by most researchers who state a specific ratio between chamfer width and feedrate, even though there are conflicting views ranging from 9:1 to 1:2. A ratio could well exist when turning because in that case the undeformed chip thickness remains constant during the whole of the cutting, whereas when milling, the chip thickness is constantly changing. It would seem illogical to express the width of a chamfer in terms of a continually changing variable.

An analysis of the cutting forces produced during face milling showed that chamfering the inserts upto about 25° had little effect on the cutting forces. From this it can be concluded that if a milling machine had the power to mill a workpiece with a facemill containing standard inserts, it would be capable of milling with inserts having a double rake.

Although the surface finish obtained on the testpiece was not measured during the cutting tests the machined surface was given a visual inspection. The finish produced by any of the inserts was typical of high quality machining and would be acceptable for most industrial applications. Using large chamfer angles gave rise to speculation that the metal would be removed by a tearing action or that severe rubbing would take place. Examination of the swarf revealed that a satisfactory cutting action had taken place and no deterioration of the testpiece surface was observed.

It was established that for a given set of machining conditions such as cutting speed, depth of cut, type of insert and entry condition the life of the cutting tool was improved as the feedrate increased. Generally there is a reluctance to use machine tools upto their maximum power capacity but this is essential if the machining costs and tooling costs for a particular application are to be minimised.

8.2 SUGGESTIONS FOR FURTHER WORK

Further cutting tests should be performed on different types of steels having a range of hardness values, using inserts having the appropriate grade of carbide, in an attempt to try and establish a single chamfer angle suitable for a wide range of applications.

The effects of coating chamfered inserts should be investigated. This must be carried out in conjunction with the manufacturer of the inserts to be used, because it is possible to use a tougher and hence softer substrate if it is to be coated with a highly wear resistant surface. The geometry of the uncoated insert should be modified and then coated by the manufacturer. Examination of the coating after machining could be carried out using a scanning electron microscope rather than a standard optical one. The electron microscope would reveal the wear characteristics better and an analysis of the materials could be made, using the energy dispersive X-ray analyser, which could identify the substrate material in any crater formed in the tool or where the coating had been removed due to flankwear.

APPENDIX I

NEGATIVE RAKE

TABLE I.1

SPEED		370		370		460	
FEED		89		175		217	
OVERHANG		4	50	4	50	4	50
NUMBER OF PASSES	1	80	70	70	80	90	80
	2	95	90	80	85	100	100
	3	110	105	85	88	120	110
	4	115	120	95	90	125	125
	5	130	125	100	100	130	135
	6	140	135	110	105	140	145
	7	145	140	115	110	160	160
	8	150	145	120	115	165	170
	9	160	155	125	125	170	175
	10	165	165	130	135	180	190
	11	170	175	135	140	200	200
	12	180	180	140	142	210	210
	13	185	190	150	145	230	220
	14	195	200	160	155	240	240
	15	205	205	165	165	245	250
	16	215	210	170	170	250	
	17	225	220	175	180		
	18	235	230	180	185		
	19	245	240	185	190		
	20	255	250	190	195		
	21		255	200	200		
	22			205	205		
	23			215	210		
	24			220	220		
	25				225		
SLOPE		8·23	8·18	6·29	6·25	11·0	11·5
INTERCEPT		84·5	83·2	68·0	69·0	79	75
No OF PASSES FOR 200 µm		14·5	14·3	21·0	20·9	11·0	10·8

EFFECTS OF TESTPIECE OVERHANG (SHOWING WEAR IN µm)

DOWN-CUT

SECTION 4.1

NEGATIVE RAKE

TABLE I.2

SPEED		370		370			
FEED		89		175			
OVERHANG		4	50	4	50		
NUMBER OF PASSES	1	80	65	90	100		
	2	100	85	100	105		
	3	110	100	115	110		
	4	115	110	120	120		
	5	120	115	125	125		
	6	130	120	132	130		
	7	135	135	135	135		
	8	140	140	138	140		
	9	FAILED	145	145	FAILED		
	10		150	155			
	11		FAILED	FAILED			
	12						
SLOPE		7·9	8·9	6·5	5·9		
INTERCEPT		80·9	67·7	89·9	94·1		
No OF PASSES FOR 200 μm		15·2	14·9	17·0	18·0		

EFFECTS OF TESTPIECE OVERHANG

UP-CUT

SECTION 4.1

NEGATIVE RAKE

TABLE I.3

SPEED		370	370	370	370	370	460
FEED		89(0·24)	110(0·30)	139(0·38)	175(0·47)	217(0·57)	110 (0·24)
NUMBER OF PASSES	1	70	90	95	80	70	85
	2	90	105	100	85	75	95
	3	105	110	105	88	80	110
	4	120	120	115	90	85	120
	5	125	123	120	100	90	130
	6	135	125	125	105	100	140
	7	140	135	130	110	102	155
	8	145	145	140	115	105	165
	9	155	150	145	125	110	175
	10	165	160	155	135	115	185
	11	175	170	160	140	120	200
	12	180	175	170	142	122	215
	13	190	185	180	145	125	225
	14	200	200	185	155	127	230
	15	205	205	195	165	130	245
	16	210	208	200	170	135	260
	17	220	212	205	180	140	CONTD.
	18	230	215	215	185	145	170
	19	240	220	225	190	147	173
	20	250	225	230	195	150	175
	21	255	240	235	200	155	180
	22		245	245	205	160	185
	23		255	250	210	163	
	24			255	220	165	
	25				225	168	

FLANK WEAR DOWN-CUT MILLING SECTION 4.1

NEGATIVE RAKE

TABLE I.4

SPEED		460	460	460	580	580	580
FEED		139(0.30)	175(0.38)	217(0.47)	139(0.24)	175(0.30)	217(0.38)
NUMBER OF PASSES	1	95	85	95	80	80	90
	2	105	105	105	90	95	135
	3	115	120	120	110	100	165
	4	120	130	125	125	115	200
	5	130	140	145	140	135	240
	6	135	150	150	160	145	265
	7	145	160	165	175	160	
	8	150	170	185	190	180	
	9	160	180	190	210	195	
	10	175	190	200	225	200	
	11	178	205	215	240	220	
	12	190	215	225	255	240	
	13	195	225	235		250	
	14	203	230	250			
	15	206	240				
	16	215	255				
	17	225					
	18	235					
	19	240					
	20	250					

UNITS
SPEED REV/MIN
FEED mm/MIN & mm/TOOTH
FLANKWEAR μm

FLANK WEAR DOWN-CUT MILLING

SECTION 4.1

NEGATIVE RAKE

TABLE I.5

SPEED		370	370	370	370	370	460
FEED		89(0.24)	110(0.30)	139(0.38)	175(0.47)	217(0.57)	110(0.24)
NUMBER OF PASSES	1	65	75	85	100	115	80
	2	85	85	95	105	120	90
	3	100	95	100	110	125	100
	4	110	100	110	120	130	120
	5	115	105	115	125	132	130
	6	120	110	120	130	135	145
	7	135	120	132	135	145	275
	8	140	125	135	140	150	CONT SPARKS
	9	145	130	140	CONT SPARKS	155	
	10	150	135	150		160	
	11	CONT SPARKS	150	160		CHIPPED	
	12		200	165			
	13		FAILED	175			
	14			180			
	15			CONT SPARKS			
	16						

NEGATIVE RAKE TABLE I.6

	SPEED	460	460	460	580	580	580
	FEED	139(0·30)	175(0·38)	217(0·47)	139(0·24)	175(0·30)	217(0·38)
NUMBER OF PASSES	1	85	85	80	60	85	100
	2	100	105	100	80	95	115
	3	120	110	110	105	105	140
	4	125	120	125	130	125	150
	5	135	135	135	145	130	165
	6	145	140	145	270	140	190
	7	150	150	160		CHIPPED	200
	8	170	160	170			220
	9	180	175	175			245
	10	190	185	190			
	11	210	200	200			
	12	CONT SPARKS	CONT SPARKS	CHIPPED			

FLANK WEAR UP-CUT MILLING

POSITIVE RAKE TABLE I.7

	SPEED	460	460	460	460
	FEED	45(0·10)	89(0·19)	110(0·24)	217(0·47)
NUMBER OF PASSES	1	70	80	70	75
	2	110	120	100	100
	3	128	155	130	120
	4	140	175	145	150
	5	165	195	155	160
	6	190	210	175	180
	7	205		185	210
	8	220		205	

FLANK WEAR DOWN-CUT MILLING SECTION 4.1

APPENDIX II

TABLE II.1

FEED (MM/MIN)		89					175				
CHAMFER ANGLE/WIDTH		UNCHAM.	10/0·25	10/0·50	30/0·25	30/0·50	UNCHAM.	10/0·25	10/0·50	30/0·25	30/0·50
NUMBER OF PASSES	1	90	60	45	105	125	60	50	40	100	110
	2	110	75	75	140	165	85	65	55	120	180
	3	125	100	100	155	190	95	90	90	165	250
	4	135	125	120	195	240	115	100	100	210	
	5	155	150	130	230		125	120	115		
	6	180	160	150			140	130	115		
	7	195	180	160			150	145	135		
	8	215	205	175			170	150	150		
	9			190			180	175	165		
	10			195			195	185	185		
	11			205			205	200	195		
	12							215	200		
	13								215		
	14										
INTERCEPT		71	38	71	74	88	57	47	47	55	40
PASSES FOR 200μm		7·3	7·8	10·2	4·1	3·0	10·5	11·0	11·7	3·9	2·3

FLANKWEAR NEGATIVE RAKE UP-CUT MILLING 460 REV/MIN SECTION 4.2

TABLE II.2

FEED (MM/MIN)		89					175				
CHAMFER ANGLE/WIDTH		UNCHAM	10/0·25	10/0·50	30/0·25	30/0·50	UNCHAM	10/0·25	10/0·50	30/0·25	30/0·50
NUMBER OF PASSES	1	80	70	100	95	115	90	90	75	90	115
	2	125	90	140	145	160	105	100	100	130	155
	3	135	125	150	180	210	130	125	120	150	190
	4	155	150	170	210	255	140	140	135	165	230
	5	180	165	190	250		155	150	150	205	
	6	200	180	215			170	160	155	215	
	7	215	190.				185	175	165		
	8		215				195	185	180		
	9						210	195	190		
	10							215	205		
INTERCEPT		82	79	86	76	68	79	89	89	73	78
PASSES FOR 200μm		6·2	7·2	5·3	3·6	2·8	8·1	9·1	9·9	5·2	3·2

FLANKWEAR NEGATIVE RAKE DOWN-CUT MILLING 460 REV/MIN SECTION 4.2

TABLE II.3

FEED (MM/MIN)		89					175				
CHAMFER ANGLE / WIDTH		UNCHAM	10/0·25	10/0·50	30/0·25	30/0·50	UNCHAM	10/0·25	10/0·50	30/0·25	30/0·50
NUMBER OF PASSES	1	INSERT FAILED AFTER 1/3 PASS	135	90	115	105	INSERT FAILED IMMEDIATELY	115	90	95	105
	2		160	130	140	135		140	140	130	130
	3		200	155	160	155		170	160	150	170
	4		210	175	200	160		185	175	175	190
	5			FAILED	210	185		215	205	185	205
	6					195				200	
	7					215				225	
	8										
INTERCEPT			110	86	90	96		92	97	96	82
PASSES FOR 200μm			3·4	5·1	4·4	6·1		4·4	4·9	5·7	4·5

FLANK WEAR POSITIVE RAKE UP-CUT MILLING 460 REV/MIN SECTION 4.2

TABLE II.4

FEED (MM/MIN)	89					175				
CHAMFER ANGLE / WIDTH	UNCHAM	10/0·25	10/0·50	30/0·25	30/0·50	UNCHAM	10/0·25	10/0·50	30/0·25	30/0·50
1	85	100	85	85	85	80	85	75	65	95
2	100	130	120	105	125	85	115	100	85	120
3	120	140	150	115	135	105	135	125	105	130
4	140	170	170	140	150	115	140	140	115	150
5	150	175	185	160	190	FAILED	150	160	130	160
6	170	180	190	170	200		FAILED	165	155	180
7	185	185	205	210				175	175	200
8	215	205						180	195	230
9								195	210	
10								205		
11										
INTERCEPT	66	111	115	62	69	65	97	98	46	78
PASSES FOR 200 μm	7·6	7·6	6·5	7·0	5·8	10·8	9·4	9·5	8·5	6·8

FLANK WEAR POSITIVE RAKE DOWN-CUT MILLING 460 REV/MIN SECTION 4·2

APPENDIX III

FEED 89 MM/MIN

TABLE III.1

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45	0
NUMBER OF PASSES	1	88	66	88	100	100	64	120			100
	2	114	76	114	128	128	82	158			126
	3	140	102	132	152	152	102	172			140
	4	160	128	148	178	172	128	228			162
	5	168	152	166	178	190	152	266			178
	6	182	158	180	204	204	158	304			192
	7	190	178	190	216	228	178	356			216
	8	196	204	198	242	280	228	420			228
INTERCEPT		87	44	82	89	78	39	64			88
150 μm		4.2	5.4	4.4	3.2	3.1	5.1	2.0			3.7

0.25 CHAMFER 460 REV/MIN

FEED 89 MM/MIN

TABLE III.2

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45
NUMBER OF PASSES	1	88	82	95	114	114	114	76		
	2	114	114	114	134	128	158	152		
	3	128	146	128	152	158	204	204		
	4	152	152	152	158	172	216	330		
	5	166	178	166	172	190	266	470		
	6	178	190	190	190	216	292			
	7	178	204	190	204	242	356			
	8	204	210	216	216	242	382			
INTERCEPT		82	107	80	104	94	78	-43.4		
150 μm		4.4	3.3	4.2	3.3	2.8	1.9	2.0		

0.50 CHAMFER 460 REV/MIN

EFFECT OF CHAMFER ANGLE ON FLANKWEAR

NEGATIVE RAKE UP-CUT CHAPTER 5

FEED 89 MM/MIN TABLE III.3

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45	0
NUMBER OF PASSES	1	102	70	114	102	114	38	128			140
	2	120	88	134	130	128	88	184			152
	3	134	128	152	146	152	102	242			166
	4	166	152	178	165	178	128	280			184
	5	184	166	178	190	204	178	330			196
	6	190	190	204	210	234	216	380			208
	7	210	190	216	234	266	242	444			228
	8	216	216	228	248	292	260	558			234
INTERCEPT		88	57	100	84	78	11	63			125
150 μm		3·6	4·5	2·9	3·2	2·8	4·3	1·5			1·8

0·25 CHAMFER 460 REV/MIN

FEED 89 MM/MIN TABLE III.4

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45
NUMBER OF PASSES	1	102	102	88	114	102	128	88		
	2	128	140	128	166	128	204	128		
	3	140	166	140	184	146	228	204		
	4	166	190	152	210	190	280	266		
	5	190	190	166	234	204	304	280		
	6	204	216	178	280	216	420	356		
	7	216	228	190	304	266	470			
	8	228	254	216	330	304	546			
INTERCEPT		89	97	86	93	70	62	34		
150 μm		3·3	2·7	4·0	1·9	2·9	1·5	2·2		

0·50 CHAMFER 460 REV/MIN

EFFECT OF CHAMFER ANGLE ON FLANKWEAR

NEGATIVE RAKE DOWN-CUT CHAPTER 5

FEED 89 MM/MIN TABLE III.5

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45	0
NUMBER OF PASSES	1	102	88	102	64	58	76	64	64	64	FAILED
	2	140	114	114	88	88	108	114	102	102	
	3	152	140	140	108	108	128	128	128	140	
	4	166	152	158	134	128	140	166	146	166	
	5	178	166	178	146	140	166	178	178	228	
	6	204	178	178	166	158	190	204	204	280	
	7	216	196	190	172	166	216	240	228	304	
	8	228	204	204	184	178	228	280	254	368	
INTERCEPT		97	82	92	55	53	59	44	44	12	
150 µm		3.1	4.2	3.9	5.5	5.8	4.2	3.7	4.0	3.2	<1

0·25 CHAMFER 460 REV/MIN

FEED 89 MM/MIN TABLE III.6

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45
NUMBER OF PASSES	1	FAILED	70	58	50	50	58	76	76	88
	2		88	88	64	76	88	114	114	254
	3		114	114	108	88	108	140	140	304
	4		140	140	128	102	128	166	190	432
	5		158	146	140	114	152	190	228	
	6		166	166	152	120	166	210	266	
	7		184	178	166	128	172	242	304	
	8		190	190	178	152	190	266	406	
INTERCEPT			59	53	40	46	50	57	19	-1
150 µm		<1	5.1	5.3	5.9	8.1	5.4	3.5	3.0	1.4

0·50 CHAMFER 460 REV/MIN

EFFECT OF CHAMFER ANGLE ON FLANKWEAR

POSITIVE RAKE UP-CUT CHAPTER 5

FEED 89 MM/MIN TABLE III.7

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45	0
NUMBER OF PASSES	1	114	50	76	50	64	64	58	58	76	70
	2	152	102	88	88	88	88	88	82	114	102
	3	166	114	114	102	114	114	128	114	152	114
	4	178	140	134	114	128	134	140	128	182	128
	5	178	158	146	128	140	146	190	152	228	152
	6	184	172	158	152	152	158	204	178	280	172
	7	190	184	178	166	178	166	228	190	342	172
	8	204	216	190	178	204	190	248	204	394	184
INTERCEPT		141	63	61	55	50	57	37	43	18	65
150 μm		1·2	4·7	5·4	6·1	5·4	5·5	4·1	5·1	2·9	5·3

0·25 CHAMFER 460 REV/MIN

FEED 89 MM/MIN TABLE III.8

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45
NUMBER OF PASSES	1	70	64	50	50	64	50	64	70	64
	2	102	88	64	70	76	76	88	96	128
	3	114	96	82	96	102	102	120	128	166
	4	140	102	102	114	126	128	140	152	242
	5	140	114	114	140	152	152	152	166	318
	6	166	128	140	152	172	178	178	190	444
	7	178	140	152	166	184	196	190	222	482
	8	184	166	166	178	190	216	216	266	558
INTERCEPT		65	54	32	37	44	29	54	43	-28
150 μm		5·3	7·4	6·9	6·1	5·3	5·0	4·8	4·1	2·4

0·50 CHAMFER 460 REV/MIN

EFFECT OF CHAMFER ANGLE ON FLANKWEAR

POSITIVE RAKE DOWN-CUT CHAPTER 5

FEED 45 MM/MIN TABLE III.9

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45	0
NUMBER OF PASSES	1	152	76	96	76	76	82				102
	2	178	108	114	128	128	128				128
	3	196	158	152	172	166	158				166
	4	210	178	178	184	184	178				178
	5	242									190
	6	266									216
	7	292									222
	8	318									254
INTERCEPT		126	41	64	48	48	57				91
150 μm		1·0	3·1	3·0	2·8	2·8	2·9				2·9

0·25 CHAMFER 460 REV/MIN

FEED 45 MM/MIN TABLE III.10

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45
NUMBER OF PASSES	1	82	76	76	76	76	76			
	2	134	108	114	114	128	108			
	3	152	140	140	140	146	146			
	4		166	152	166	172	178			
	5		190	178	178	204	216			
	6		204	204	216	216	216			
	7		216	210	242	242	242			
	8		228	248	260	292	254			
INTERCEPT		53	81	63	58	60	64			
150 μm		2·8	3·5	3·8	3·6	3·3	3·4			

0·50 CHAMFER 460 REV/MIN

EFFECT OF CHAMFER ANGLE ON FLANKWEAR

POSITIVE RAKE UP-CUT

FEED 45 MM/MIN TABLE III. 11

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45	0
NUMBER OF PASSES	1	108	70	76	82	82	76				70
	2	134	114	102	108	114	128				108
	3	166	140	120	140	140	166				128
	4	190	172	140	166	166	190				140
	5		190	166	190	190					166
	6			190							190
	7										204
	8										222
INTERCEPT		80	48	54	55	58	45				59
150 μm		2.5	3.4	4.3	3.5	3.4	2.8				4.3

0·25 CHAMFER 460 REV/MIN

FEED 45 MM/MIN TABLE III. 12

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45
NUMBER OF PASSES	1	82	50	88	88	96	114			
	2	114	96	114	120	140	128			
	3	152	128	128	140	158	166			
	4	178	146	152	158	178	178			
	5		152	178	178					
	6		190	190						
	7		204	196						
	8		216	204						
INTERCEPT		50	46	79	71	77	89			
150 μm		3.1	4.6	4.1	3.6	2.8	2.7			

0·50 CHAMFER 460 REV/MIN

EFFECT OF CHAMFER ANGLE ON FLANKWEAR

POSITIVE RAKE DOWN-CUT CHAPTER 5

FEED 175 MM/MIN

TABLE III.13

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45	0
NUMBER OF PASSES	1	64	50	70	50	50	38				64
	2	96	88	88	76	64	64				FAILED
	3	114	102	108	88	76	82				
	4	134	114	128	102	102	102				
	5		140	140	128	114	114				
	6		146	166	134	128	140				
	7		172	178	140	140	152				
	8		190	190	152	152	172				
INTERCEPT		45	42	54	45	36	24				
150 μm		4·6	5·8	5·4	7·4	7·6	6·7				

0·25 CHAMFER 460 REV/MIN

FEED 175 MM/MIN

TABLE III.14

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45
NUMBER OF PASSES	1	76	64	38	38	44	50			
	2	88	96	64	50	64	76			
	3	108	102	76	76	76	88			
	4	120	128	102	88	96	114			
	5	140	140	114	102	102	140			
	6	152	158	120	114	128	152			
	7	166	166	140	128	140	178			
	8	204	178	152	140	152	204			
INTERCEPT		55	58	30	26	31	29			
150 μm		5·6	5·8	7·6	8·5	7·7	5·7			

0·50 CHAMFER 460 REV/MIN

EFFECT OF CHAMFER ANGLE ON FLANKWEAR

POSITIVE RAKE UP-CUT

CHAPTER 5

FEED MM/MIN TABLE III.15

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45	0
NUMBER OF PASSES	1	96	38	38	38	38	38	38			64
	2	128	58	64	76	50	64	58			96
	3	140	FAILED	82	88	64	70	76			120
	4	152		102	102	76	96	88			128
	5	178		108	128	88	102	102			140
	6	178		108	140	88	120	114			140
	7	190		134	152	102	140	120			152
	8	190		152	166	114	152	134			158
INTERCEPT		109		33	44	23	26	30			98
150 µm		3·6		8·0	6·8	9·4	7·8	8·9			6·9

0·25 CHAMFER 460 REV/MIN

FEED MM/MIN TABLE III.16

CHAMFER ANGLE		5	10	15	20	25	30	35	40	45
NUMBER OF PASSES	1	50	82	58	50	76	64	58		
	2	76	102	76	64	108	76	64		
	3	FAILED	114	76	76	120	96	102		
	4		134	96	82	140	114	128		
	5		140	102	102	140	128	146		
	6		152	114	108	166	140	172		
	7		158	128	114	172	152	190		
	8		178	140	128	190	166	216		
INTERCEPT			75	48	42	72	51	29		
150 µm			5·9	9·0	10·0	5·2	6·7	5·2		

0·50 CHAMFER 460 REV/MIN

EFFECT OF CHAMFER ANGLE ON FLANKWEAR

POSITIVE RAKE DOWN-CUT CHAPTER 5

APPENDIX IV

TABLE IV.1

	INSERT Nº																									No OF PASSES
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
FLANK WEAR μm	70	75	85	40	70	75	75	50	90	70	50	130	50	75	75	80	75	90	50	50	90	90	75	45	45	1
	95	95	125	65	85	95	105	75	135	105	65	195	80	95	105	110	100	150	70	70	135	125	100	60	65	2
	120	110	150	90	115	120	135	85	165	155	85	290	105	110	120	130	125	210	90	85	185	150	125	80	90	3
	150	120	180	110	135	145	170	105	215		105		130	125	145	155	140		105	95	230	185	140	90	105	4
	175	140	210	125	175	175	200	115			115		145	145	175	185	175		120	110		210	175	110	115	5
	200	150		150	195	190	225	130			130		175	160	195	210	195		130	125			190	120	140	6
	220	155		170	230	225		145			145		195	170	235		205		150	135			205	145	155	7
		165		185				150			165		215	185					165	150				155	165	8
		175		205				170			185			195					175	160				165	180	9
		180						175			200			205					190	165				170	195	10
		190						180			215								200	175				180	225	11
		195						190											210	185				190		12
		205						195												195				195		13
								200												200				205		14
								210												210						15
SLOPE	25·5	8·7	28·5	19·8	27·1	25·4	30·6	7·6	40·5	42·5	16·5	80·0	23·3	13·6	25·5	25·7	22·1	60·0	14·0	9·6	47·0	30·0	22·1	8·4	16·8	
INTERCEPT	45	93·6	66·5	32·1	35·0	45·7	44·7	96·1	50·0	25·0	33·7	45·0	32·1	73·3	47·9	55·0	55·7	30·0	47·9	67·7	42·5	62·0	55·7	87·5	33·6	
No OF PASSES FOR 200 μm	6·1	12·2	4·7	8·7	6·1	6·1	5·1	13·6	3·7	4·1	10·1	1·9	7·2	9·3	6·0	5·6	6·5	2·8	10·9	13·8	3·4	4·6	6·5	13·4	9·9	

DOWN-CUT MILLING RESULTS OF CUTTING TESTS CHAPTER 6

TABLE IV.2

	INSERT Nº																									Nº OF PASSES
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	
FLANK WEAR µm.	70	40	80	90	65	70	60	55	90	85	65	115	55	50	65	110	85	120	55	40	110	90	70	45	45	1
	95	75	(B)	130	90	110	85	80	150	115	100	185	95	85	100	140	110	195	70	60	175	140	105	70	75	2
	120	90		205	130	135	110	110	250	135	110	270	115	110	135	170	145	295	100	75	245	175	140	100	100	3
	145	105			150	160	125	130		165	135		140	(C)	175	185	175		115	100		200	185	130	125	4
	165	125			200	195	145	155		185	145		165		220	210	205		140	110		225	230	150	145	5
	180	140			240	215	150	180		205	155		185						165	130				175	170	6
	200	165					170	205			170		210						190	145				190	190	7
	220	(A)					180				185								210	160				210	205	8
							195				200									180						9
							210				215									195						10
																				205						11
SLOPE	20.4			57.5	35	27	14	24	80	24	14.3	77.5	23.1		38.5	24.5	30.5	87.5	22.7	16.7	67.5	26.3	40	21.6	22.9	
INTERCEPT	59			27	23	55	70	36	3.3	64	72	35	48		24	90	53	28	29	27	42	99	26	41	29	
No OF PASSES FOR 200 µm	6.9	7.2	1.7	3.0	5.0	5.4	9.3	6.8	2.5	5.7	9.0	2.1	6.6	3.4	4.6	4.5	4.8	2.0	7.6	10.4	2.3	3.8	4.4	7.4	7.5	

(A) CHIPPED AT 7.2 PASSES   (B) BROKE AT 1.7   (C) CHIPPED AT 3.4

UP-CUT MILLING   RESULTS OF CUTTING TESTS   CHAPTER 6

		FEEDRATE				
		0·19	0·24	0·30	0·38	0·47	TOTAL $Y_{i..}$
CHAMFER WIDTH	0·2	C : 6·1	B : 12·2	A : 4·7	D : 8·7	E : 6·1	37·8
	0·4	D : 6·1	C : 5·1	B : 13·6	E : 3·7	A : 4·1	32·6
	0·6	B : 10·1	E : 1·9	C : 7·2	A : 9·3	D : 6·0	34·5
	0·8	A : 5·6	D : 6·5	E : 2·8	C : 10·9	B : 13·8	39·6
	1·0	E : 3·4	A : 4·6	D : 6·5	B : 13·4	C : 9·9	37·8
TOTAL $Y_{.j.}$		31·3	30·3	34·8	46·0	39·9	182·3

CHAM ANGLE	A	B	C	D	E	
	28·3	63·1	39·2	33·8	17·9	182·3

TOTAL SUM OF SQUARES $= 1622 \cdot 91$

MEAN SS $\dfrac{182.3^2}{25} = 1329 \cdot 33$

SS BETWEEN ROWS $\dfrac{6678.85}{5} - 1329.33 = 6 \cdot 44$

SS BETWEEN COLUMNS $\dfrac{6816.83}{5} - 1329.33 = 34 \cdot 04$

SS BETWEEN LETTERS $\dfrac{7781.99}{5} - 1329.33 = 227 \cdot 07$

ERROR SS $26 \cdot 03$

A.O.V

SOURCE OF VARIANCE	d.f.	S.S.	m.s.	F
TOTAL	25	1622·91		
MEAN	1	1329·33		
DUE TO CHAMF. WIDTH	4	6·44	1·61	0·74
DUE TO FEED	4	34·04	8·51	3·92
DUE TO CHAMF. ANGLE	4	227·07	56·77	26·16
ERROR	12	26·03	2·17	

$F_{0.001}(4,12) = 9.61$ $F_{0.05}(4,12) = 3.26$

A.O.V DOWN-CUT MILLING RESULTS FROM TABLE IV.1

			FEEDRATE			TOTAL
	0·19	0·24	0·30	0·38	0·47	$Y_{i..}$
CHAMFER WIDTH 0·2	C : 6·9	B : 7·2	A : 1·7	D : 3·0	E : 5·0	23·8
0·4	D : 5·4	C : 9·3	B : 6·8	E : 2·5	A : 5·7	29·7
0·6	B : 9·0	E : 2·1	C : 6·6	A : 3·4	D : 4·6	25·7
0·8	A : 4·5	D : 4·8	E : 2·0	C : 7·6	B : 10·4	29·3
1·0	E : 2·3	A : 3·8	D : 4·4	B : 7·4	C : 7·5	25·4
TOTAL $Y_{.j.}$	28·1	27·2	21·5	23·9	33·2	133·9

CHAM ANGLE	A	B	C	D	E	
	19·1	40·8	37·9	22·2	13·9	133·9

TOTAL SUM OF SQUARES			861·97
MEAN SS	$\frac{133\cdot9^2}{25}$		717·17
SS BETWEEN ROWS	$\frac{3612\cdot67}{5} - 717\cdot17$	=	5·36
SS BETWEEN COLUMNS	$\frac{3665\cdot15}{5} - 717\cdot17$	=	15·86
SS BETWEEN LETTERS	$\frac{4151\cdot91}{5} - 717\cdot17$	=	113·21
ERROR SS			10·37

A.O.V

SOURCE OF VARIANCE	d.f	S.S.	m.s.	F
TOTAL	25	861·97		
MEAN	1	717·17		
DUE TO CHAMF. WIDTH	4	5·36	1·34	1·55
DUE TO FEED	4	15·86	3·97	4·62
DUE TO CHAMF. ANGLE	4	113·21	28·30	32·91
ERROR	12	10·37	0·86	

$F_{0.001}(4,12) = 9.61$ $F_{0.05}(4,12) = 3.26$

A.O.V. UP-CUT MILLING RESULTS FROM TABLE IV.2

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