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Citation: Worthington, B. (1975). Chip formation and metal cutting performance when using non-plane rake face tools. (Unpublished Doctoral thesis, The City University)

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THE CITY UNIVERSITY

DEPARTMENT OF MECHANICAL ENGINEERING

CHIP FORMATION AND METAL CUTTING PERFORMANCE
WHEN USING NON-PLANE RAKE FACE TOOLS

By

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~~A~~ thesis submitted to THE CITY UNIVERSITY for the degree of

Doctor of Philosophy

April 1975

ERRATA

- P. 10 section 2.4 0 to 2,000 to read 13 to 2,000.
- P. 20 para. 2 line 4 inclination angle to read cutting edge angle.
- P. 65 $R_t = s^2/8r_\epsilon \mu \text{ mm}$ to read $R_t = s^2/8r_\epsilon \text{ mm}$.
- P. 76 para. 3 Fig. 5.16 to read Fig. 5.1a.
- P. 79 para. 2 Fig. 5.15 a and b to read Fig. 5.14 a and b.
- P. 82 para. 4 line 3 section 4.8 to read section 4.10.
- P. 85 para. 2 line 4 tool inclination angle to read cutting edge angle.
- P. 87 end of last line X-Y to read Y-Z.
- P. 91 para. 3 cutting edge inclination angle to read cutting edge angle.
- P. 109 section (f) 1. $\cos v_s$ to read $\cos v_r$
section (e) line 6 W of $\approx 10 L$ to read W of $\approx 10 b_{Yr}$
- Fig.G.1 Read v_s , Z, $\gamma_{\max}$, to read v_r , Z_o $\gamma_{\max}$
last box $s_{\max} = h/\cos v_s$ to read $s_{\max} = h/\cos v_r$
- Fig.2.12 dimension $d_t = \int_0^{ts} v_{dt}$ to read $d_t = \int_0^{ts} v_{dt}$
- Fig. 5.2 CUTTING EDGE INCLINATION λ_s to read CUTTING EDGE ANGLE v_r
- Fig. 5.13 $0^\circ - -30^\circ - -60^\circ$ to read $-7^\circ - -23^\circ - -53^\circ$
- Fig. 5.14 add $\gamma_1 = -16^\circ$
- Fig. 5.15 CUTTING EDGE INCLINATION 45° to read CUTTING EDGE ANGLE 45°
- Fig. 6.4 dimension B_{Yo} to read b_{Yr}
- Fig. 6.14 Land length column insert 0.15, 0.15, 0.15 where omitted
and row $\square$ to include 0.27 mm feed.

SUMMARY

Previously published work on the mechanics of chip breaking, the performance of chip forming devices and cutting with controlled contact length cutting tools is critically appraised and the need for a greater understanding of the chip control process is established.

Machining with tools having chip forming grooves on the tool face is often characterised by the existence of a special built-up-edge at values of undeformed chip thickness greater than a particular value. The variation in the configuration of this special built-up-edge with different land configurations is examined, it is thought for the first time.

The stability of the special built-up-edge with change in cutting speed is investigated by examination of the machined surface, and the effect on surface roughness and subsurface deformation of cutting with negative lands is determined. The results indicate that for given cutting conditions at values of primary rake angle less than a particular value, sidespread of the workpiece is pronounced. This results in excessive cutting force, surface roughness and subsurface damage. However, it is shown that at more positive primary rake angles than the critical value, the surface profile produced during oblique machining may be smoothed.

A model of the chip formation when using controlled contact length tools is proposed involving a pattern of tangential velocity discontinuities. Using this model, reasonably good correlation is obtained between the theoretical and the experimental relationship between shear angle and undeformed chip thickness at low cutting speeds.

Modification of the model to account for observed changes in the configuration of the special built-up-edge at high temperatures, enables the effect on cutting performance to be predicted.

A mechanism of chip formation when using chip forming grooves at high cutting speeds is proposed. For this case, a procedure for

determining a relationship, not previously established, between the tool configuration and chip curl radius is outlined. Also a method of determining the tool configuration for chip breaking in a specified feed range is proposed.

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ACKNOWLEDGEMENTS

The work described in this thesis was carried out in the Manufacturing Processes Laboratory, Department of Mechanical Engineering, The City University. The author would like to thank the University for providing the necessary facilities, and in particular [REDACTED], Head of Department.

The author would also like to express his gratitude to [REDACTED] [REDACTED] for critically reading the draft thesis and providing many helpful suggestions, and also for his encouragement and guidance during the course of the work. Thanks are also due to [REDACTED] [REDACTED] [REDACTED] whose industry has often created much needed time, and to other colleagues in the Department who have from time to time provided counsel.

Throughout the experimental work [REDACTED], the senior laboratory technician, has consistently arranged to provide technical help and set up experimental equipment, often despite difficult conditions.

The author is also indebted to the technical staff and in particular [REDACTED] [REDACTED] [REDACTED] for preparation of tools and workpieces, [REDACTED] [REDACTED] [REDACTED] for manufacturing the quick-stop device and two component dynamometer, and [REDACTED] [REDACTED] for the production of drawings.

Finally thanks must go to my wife for her constant support and to [REDACTED] [REDACTED] [REDACTED] for typing the thesis.

NOTATION

a	depth of cut
a^1	apparent depth of cut
a_s	Stabler's constant
b_{YR}	Restricted contact length - land length
c	a constant to indicate the degree of chip breaking
$c_1 \}$ $c_2 \}$	constants in Okushima's equation
c_h	chip thickness ratio
h	undeformed chip thickness
h_c	chip thickness
h_e	effective chip thickness
h_g	depth of chip groove
h_m	mean chip thickness
h_s	undeformed chip thickness at which chip is formed straight
k	yield shear strength
l_s	length of the sticking friction zone
p	yield pressure
r_b	cutting edge roundness
r_c	tool corner radius
s	feed/rev
s_{min}	minimum feed/rev for effective chip breaking
v_d	Displacement ratio
w	width of chip breaker step
$\dot{w}$	Rate of change of external work done
C	a constant relating land length to $(h-h_s)(R_o-R_{min})$
E	Young's modules of Elasticity
F	resultant cutting force
F_f	feed force

F_p	thrust force
F_{shi}	Shear force on shear plane
F_{shin}	normal force on shear plane
F_γ	Friction force on tool face
$F_{\gamma n}$	Normal force on tool face
H	height of chip breaker step
K	$(h-h_s)(R_o-R_{min})$
K_h	a constant relating feed to chip thickness
K_m	a constant used in the determination of contact length
KB_o	Natural contact length
K_1	$(E-\sigma)(4\sigma c_h)$
K_2	$(0.2E-\sigma)(2.4\sigma c_h)$
P	Ploughing Force
P_1	Value of Z_o for 0° PRA
Q	$b_{\gamma r}(\gamma_1 Z + P_1)$
R	Chip curl radius at fracture
R_1	Chip curl radius before elastic recovery
R_a	C.L.A. value - mean average height
R_g	Radius of groove
R_n	Radius of neutral layer of chip
R_o	Chip curl radius after leaving tool, that is after elastic recovery
R_t	Peak to valley height
R_{tm}	Mean peak to valley height
R_L	Limiting expanded chip curl radius
R_T	Chip flow circle radius
R_{min}	Minimum value of chip curl radius for a particular groove configuration
W	Width of chip forming groove
W_v	Volumetric coefficient
Z	Slope of $Z_o - \gamma_1$ relationship

Z_o	Ratio of the undeformed chip thickness to cause the sticking length to equal the land length/land length
β	mean friction angle
β_u	built-up-edge angle
γ_1	Primary rake angle - rake angle of land
γ_2	Secondary rake angle
γ_n	rake angle in the normal plane
γ_u	Chip stream angle - rake angle of b.u.e.
γ_{umax}	Maximum value of chip stream angle
γ_o	orthogonal rake angle
ϵ	engineering strain
ϵ_f	strain at fracture
η	the angle of deflection of the chip from the main normal plane
θ	inclination of obstruction
λ_s	cutting edge inclination
ν_c	angle of chip flow measured in plane of tool face
ν_{ae}	the additional angular deflection due to the cutting edge inclination angle
ν_r	cutting edge angle
ψ	angle between shear plane and rake face
ϕ	shear angle
ρ_o	the angle measured in the normal plane between the direction of departure of the chip and the normal to the longer cutting edge when the rake angle is not zero
σ	stress
ω	angle between resultant cutting force and shear plane
μ	mean coefficient of friction

CHAPTER 1

INTRODUCTION

1.1. COST OF MACHINE TOOLS

With rising manufacturing costs and the continued trend towards highly sophisticated machine tools, the real average cost of machine tools continues to increase despite tremendous improvements in manufacturing efficiency. This is demonstrated in Fig.1.1. which shows the average cost of numerically controlled machine tools manufactured in the United Kingdom during the period 1966-71, (1). The heavy sloping line shows the mechanical engineering price index enabling the real difference to be ascertained. This and the increase in labour costs have served to increase running costs of machine tools, so that greater emphasis is placed on improving in all respects the performance of the machine tool. The benefits of this are many, not the least being the increase in production rate.

1.2. MACHINE TOOL PERFORMANCE

The ultimate performance of any machine tool is determined by the situation at the chip-tool interface, that is the performance of the cutting tool and the selection of cutting conditions. These should be selected so that the machine tool is cutting at, or near to, optimum conditions; that is for the particular performance criterion being considered, such as minimum cost or maximum metal removal rate.

The increasing use of automatic and numerically controlled machine tools has reduced the non cutting part of the manufacturing cycle, therefore if the potential of the machine tool is to be fully exploited greater emphasis is placed on maximising the performance of the cutting tool.

1.3. THE EFFECT OF THE CUTTING TOOL ON MACHINE TOOL PERFORMANCE

In a conventional metal cutting operation shear occurs in both the primary and secondary deformation zones causing the thickness of the chip produced to be greater than the undeformed chip thickness, as is shown in Fig.1.2.

The rake angle, the inclination of the tool face from a normal to the workpiece-tool relative motion, has considerable influence on both the efficiency of the cutting action and the strength of the cutting edge. The value assigned to the rake angle in conventional cutting is usually a compromise taking into account both strength and efficiency considerations and will vary with different workpiece-tool combinations. The efficiency may be assessed by examination of the chip thickness ratio, the undeformed chip thickness/chip thickness. An increase in this parameter, indicating greater efficiency, will usually occur with positive increase in rake angle and decrease in friction at the chip-tool interface.

A method of improving the efficiency of the cutting process is to use a double rake angle, or controlled contact length tool, shown in Fig.1.2. Under most cutting conditions this provides a cutting action approximating to that using a plane tool of rake angle equal to the secondary rake angle. If a negative primary land is used then additional strength is provided at the cutting edge. This is extremely advantageous with brittle tool materials and difficult to machine workpiece materials where cutting edge chipping is a problem, and may in some circumstances be beneficial when machining free cutting materials.

1.4. CHIP CONTROL

During the cutting operation the chip flows across the face of the tool in a direction governed principally by the tool geometry (2). The chip may be produced in the form of either a continuous chip or discontinuous segments as shown in Fig.1.3. this depending on the workpiece material and the cutting conditions. With the latter type of chip formation, which is usually characteristic of brittle workpiece materials, the chips are of manageable size and are easily handled, and can be directed towards a mechanised swarf disposal system. When machining ductile materials it is possible to arrange cutting conditions so that a discontinuous chip is produced but this usually results in uneconomic cutting speeds, and tool

angles that cause the cutting action to be inefficient. When cutting ductile materials with plane tools under more realistic conditions a continuous chip is produced.

Continuous chip formation whilst desirable for the actual machining operation has three main disadvantages when considering chip removal.

1. The chip may impinge on the newly cut workpiece surface and adversely affect the appearance of the surface, even though the change in surface finish is usually only minor.
2. The chip may flow along the face of the tool, that is have no curvature. This chip 'streaming' is perhaps the most troublesome type of chip formation and can be a hazard to the machine operator.
3. The chip often builds up into a large tangled mass which has a very low effective density compared with that of the parent material, and is usually difficult to remove from the machine either manually or automatically.

Several metal cutting operations, for example milling, by the nature of the process produce continuous chips which are relatively short and cause no handling problems. However, continuous chip formation in many operations, the commonest example being turning, can create a severe problem in chip control. As the biggest problem appears to be concerned with turning machines, the investigation will be concentrated in this area.

After leaving the face of the tool, the chip may adopt a spiral form and eventually break due to its own weight. However, more typically, the chip may 'stream'. This is perhaps the most troublesome type of chip formation, for as previously mentioned, the chip may become entangled with the workpiece or other parts of the machine. Ineffective chip control may cause machines which would normally operate unmanned, to require an operator in constant attendance. In some cases the machine may have to be stopped whilst swarf is cleared, with resulting loss of production.

Even if the swarf produced when the chip streams was easy to handle,

it has a low effective density - long unbroken swarf occupies up to five times the value of finely broken swarf (3).

The magnitude of the problem is illustrated by considering the rate at which swarf is produced on modern lathes using ceramic or cemented carbide cutting tools. When machining a low carbon steel the swarf will be produced at speeds up to 300 m/min that is 5 metres of chip per second, and at even higher rates with softer workpiece materials. The trend is towards ever increasing cutting speeds (4) making the problem more acute, as with increase in cutting speed there is a greater tendency for the chip to stream.

Mechanised systems for bulk chip (swarf) removal are now often an integral part of modern machine shops, and for these to be effective it is essential that the swarf produced is in the easiest form to handle, that is in the form of small broken segments.

As mentioned previously, the geometry of the chip and its path can be altered by changes in the cutting conditions. Consequently, some degree of chip control may be obtained purely by choosing suitable cutting conditions. However, this may necessitate the use of uneconomical cutting conditions or impractical tool geometries.

1.5. CHIP BREAKING TOOLS

Since Klopstock (5) in 1925 introduced a tool incorporating a 'chip breaking groove' which, it was claimed, both increased tool life and decreased power consumption, many chip control devices have been developed. The objective has been to produce swarf of the required type whilst maintaining or improving the cutting efficiency. Although some measure of success with regard to chip control has been achieved by oscillating feed devices which cause a periodic thin spot in the chip, it is felt that the devices having the most practical significance are those where modifications to the tool geometry have been made.

1.5.1. Obstruction and Groove Type Chip Formers

The two most common devices of this type are the obstruction type chip former and the groove type chip former and these are shown in Figs. 1.4A and 1.4B respectively. With both these types of chip control device, the chip is formed in an approximately circular arc and eventually impinges on some obstruction - usually the toolholder. With the free end of the chip anchored at the toolholder the chip expands and under suitable conditions breaks, approximately at a point on the circumference above the cutting edge, because of the increase in the bending stresses to which the chip is subjected. The breaking of the chip is therefore a secondary effect, the main purpose of the chip control device being to form the chip into a predetermined path. One condition sometimes encountered when using this method of chip control is that the chip curls to too small a radius. Under these circumstances the broken chips fly off randomly at very high speed and can be a hazard to the machine operator. Chips of this type are usually referred to as 'overbroken' chips. Alternatively, the chip curl radius may be too large and the chip on expanding will not break, in this case the chips are said to be 'underbroken'.

The use of indexable inserts, which are clamped in position in a holder instead of being brazed to the tool shank, is becoming increasingly more common in turning operations. As these tips are not normally reground they are commonly known as "throw away" tips. With this kind of tool, groove type chip formers have several advantages over obstruction type formers.

1.6. ADVANTAGES OF THE GROOVE TYPE CHIP FORMER

a) As mentioned previously the use of double rake angled tools may be extremely advantageous. On groove type formers the land on the tool can have a high negative rake angle which improves the strength of the tool and hence its performance, particularly with respect to cutting edge chipping.

- b) The tool and chip forming device are integral and the cost is less, as with obstruction type former the obstruction may need to be changed periodically - typically this may be once per ten inserts used.
- c) The chip breaking efficiency is determined by the groove design and does not rely upon the operator positioning the obstruction.
- d) The setting up time is shorter as there is no obstruction to adjust.
- e) Tool life may be increased compared with negative rake tools because
 - i) As will be shown, the tool cuts with effectively a positive rake due to a stable built-up-edge forming on the primary land.
 - ii) The contact area on the tool face is reduced as, if the tool is correctly designed there will be little contact with the groove, thus reducing rake face friction.
- f) Due to the effective rake angle being positive, cutting forces are reduced. This is particularly advantageous when machining slender workpieces and is also conducive to higher workpiece accuracy because of reduced workpiece-tool deflections. Power consumed in cutting is also reduced.

The main disadvantage is that the range of feeds over which a particular tool will effectively operate is smaller than that of an obstruction type former, as there is no adjustment. Also, if the groove type chip former is incorrectly designed or cutting conditions inappropriately selected, it is possible that cutting forces may be higher, tool life reduced and the surface finish of the workpiece may be rougher.

1.7. THE NATURE OF THE PROBLEM

Although a considerable amount of research has been performed with obstruction type chip formers, there is little published work on the performance of groove type chip formers. However it is realised that the cutting and chip breaking efficiency of a groove type chip former is influenced considerably by the configuration of the face of the tool and the cutting conditions.

An explanation of the mechanism of chip forming when using a chip forming groove at low cutting speeds has been previously proposed (6). This indicates the existence of a special built-up-edge at values of undeformed chip thickness greater than a particular value. The variation in the configuration of this special built-up-edge with different land configurations is examined, it is thought for the first time.

The effect of changes in rake face configuration on chip curvature, cutting forces, surface integrity and tool wear are investigated, and an explanation is given which is supported by experimental evidence as to how the groove type chip former operates. The effect of changes in cutting tool configuration on chip breaking efficiency according to this explanation, are determined.

A method of designing the former is proposed and an algorithm is constructed in order that tool selection may be facilitated in a computer numerical control or direct numerical control system.

The principal intentions of this thesis may now be summarised as:

1. To contribute to the area of knowledge concerning the mechanism of chip formation when using a tool with a chip forming groove at high cutting speeds.
2. To present the results of the effect of changes in tool configuration and cutting conditions on the variation in the shape and stability of the special built-up-edge which may form when cutting with double rake angle tools. Also, to indicate the effect on surface integrity and tool life of using these tools.
3. The relationship between tool configuration, cutting conditions and chip curl radius when using tools having chip forming grooves is also presented, and an explanation of the causes of such a relationship is proposed.

CHAPTER 2

DESCRIPTION OF EQUIPMENT AND EXPERIMENTAL TECHNIQUES

2.1. INTRODUCTION

In this chapter the workpiece materials and more common experimental equipment is described. Techniques or equipment of a more specialised nature are described in the relevant chapters.

2.2. WORKPIECE MATERIALS

In order to check the composition of the workpiece materials a chemical analysis was performed, the results of which are presented in Fig.2.1. For the tests performed on the shaping machine a 4 in. square bright bar of En 1A was sliced into 4 in. x 4 in. sections and ground to a width of 3 mm. Metallurgical examination was performed by viewing the polished but unetched specimens and also after etching in 2% Nital, in both cases at a magnification of up to 250 times. The etched microstructure in Fig.2.2. shows that the steel was probably normalised.

As some difference in performance seemed evident when cutting the extremity of the bar, sections were taken at various distances from the edge. These, shown in Fig.2.3. revealed segregation of the manganese sulphide inclusions and as a result of this the first centimetre of the bar was removed.

It was not possible to obtain an identical steel in tubular form and so a straight mild steel to BSS CDSI of composition shown in Fig.2.1. was obtained as 5 in. diameter tube $\frac{1}{4}$ " thick. The etched microstructure is shown in Fig.2.4a. In order to obtain uniform thickness it was turned and bored to a thickness of 4.0 mm. It was thought that cutting this diameter of workpiece closely approximated to orthogonal machining, Fig.3.1.

For the oblique surface finish tests a 4 in. diameter bar to BSS En 8 and a 6 in. diameter bar of En 1B were used, the chemical compositions are shown in Fig.2.1.

The etched microstructure revealed that the En 8 had been overheated in manufacture; Fig.2.4b. shows the exceptionally large grain size. Fig.2.5a. shows the microstructure of the En 1B bar to the same magnification.

For the initial tool life test a 4 in. diameter bar of En 16S was used. The chemical composition and etched microstructure are shown in Fig.2.1. and Fig.2.5. respectively.

Previous work by the author and other workers indicates that variation in steel type has little effect on the breaking characteristics of the chips. Low carbon steels are the most commonly used workpiece materials for machined components, and free cutting low carbon steels are generally machined at higher cutting speeds, with resulting problems of chip control. Therefore, for all the tests other than the tool life tests, a low carbon steel was the workpiece material although it was not felt necessary to maintain great consistency. A more difficult to machine workpiece material was used for the tool life tests in order to promote more rapid tool wear.

2.3. CUTTING TOOLS

The high speed steel tools were 18% W., 4% Cr., 1% Va composition and were in all cases 3/8 in. square. The rake and flank faces were ground with an aluminium oxide 100 grit wheel using a specially made fixture and a universal vice, on a surface grinding machine. The cemented carbide inserts were 12 mm square by 3 mm thick plain P30 grade throw away tips. The primary rake face was produced by lapping using a special fixture to hold the tip. Grooves were spark eroded in both types of tool using a cylindrical "Elconite" electrode which was rotated for the finishing cut to provide greater form accuracy.

The relevant dimensions of the tools were checked using a Nikon tool makers' microscope and a Mark 3 "Talysurf" equipped with a side

acting gauge. The groove configurations were designed so that the "inlet angle", that is the angle between the tangent to the groove at the intersection of the groove and the primary land, and the normal to the direction of workpiece-tool relative motion was in all cases 45° , unless specifically stated otherwise.

In the surface finish test accuracy of the tool corner radius was important. This was again measured using the tool makers' microscope, as was the wear land on the tool flank in the tool life tests.

2.4. MACHINE TOOLS

The lathe used for all the turning tests was a Lodge and Shipley 18 in. swing sliding, surfacing, and screwcutting lathe 54 in. between centres. The lathe was fitted with a 20 HP variable speed main motor driving an all geared headstock. The combination of the variable speed motor and the headstock gearing provided an infinitely variable speed range from 13 to 2000 rev/min. Feed control was by a feed gear box providing 60 discrete feeds from 0.00075 to 0.0469 in/rev the feed drive to the saddle being by rack and pinion. The workpiece was invariably held in a four jaw chuck and, when machining the end of a tube whose length exceeded 100 mm, was additionally supported by a fixed three point steady. When machining solid bar the additional support was provided by a live centre at the tailstock. Five inch diameter tube was used to simulate orthogonal cutting.

The surface speed of the workpiece was checked with a 'Smiths' surface speed tachometer fitted with a roller which provided readings in m/min. The readings were taken from the uncut workpiece surface after the cut was engaged, to compensate for any reduction in speed caused by the cutting force.

When the dynamometer was not used the cemented carbide inserts were held in a T-Max P. 25 x 25 mm shank toolholder which presented the plane

tools at a $+7^{\circ}$ rake angle, and a cutting edge angle of 75° .

The shaping machine used was a 'Hydetscho' hydraulic ram 500 mm maximum stroke machine with infinitely variable ram speed from 0 to 30 m/min. The depth of cut, which is the undeformed chip thickness in orthogonal machining, was set by means of the tool slide and assessed by measuring the height of the workpiece above the ground top of the vice, before and after each cut using the fixture shown in Fig.2.6. Two readings were taken for each cut and the mean of the two readings used. Although readings were obtained to 0.005 mm the accuracy was likely to be much less than this due to the roughness of the workpiece surface, particularly at the lower cutting speeds. The accuracy was thought to be more typically to within ± 0.01 mm at the lower values of undeformed chip thickness, that is $\pm 5\%$, and at higher values less than this. The cutting speed was obtained using an electronic counter activated by two limit switches 200 mm apart.

2.5. DYNAMOMETERS

2.5.1. Design Criteria

Rapier (7) summarised a number of reports outlining guidelines for dynamometer design. These and other additional considerations are outlined below.

1. The tool deflection should be small so that the cutting geometry is not significantly affected by the cutting force, a maximum recommended tool deflection being 0.05 mm.
2. The displacement ratio, v_d , displacement measured by transducer to the tool displacement, should be as large as possible, as in order to obtain maximum output from the instrumentation the gauge displacement should be large and as mentioned in 1 the tool displacement should be small. A value of v_d approaching unity is usually considered an efficient design.
3. The natural frequency of the dynamometer should be well in excess of any exciting frequency likely to be encountered when cutting. Most

successful dynamometers have a natural frequency in excess of 3,000Hz.

4. The dynamometer and instrument system should have linear response to an accuracy of $\pm 2\%$ of the indicated value. Also the interaction of a force exerted in one principal direction on the forces in the other principal directions should be as small as possible (8). The dynamometer body should if possible be manufactured from a solid block of material because of hysteresis effects usually encountered with clamps, bolts, rivets and hinges.

2.5.2. The Two Component Dynamometer

A two component metal cutting lathe dynamometer based on the design described by Boothroyd (9) was used for all the orthogonal machining tests and is shown mounted on the shaper in Fig.2.6. The dynamometer was developed, constructed and strain gauged as an undergraduate final year project (10). The construction and principle of operation is shown in Fig.2.7. where it can be seen that the tool is supported by four struts. The thickness of the struts was increased from the original design value to increase stiffness and the height modified to suit the lathe. Strain gauges on the struts are connected in two strain bridges. It is assumed that the sum of the strains in the horizontal struts would result from the horizontal force only, whilst the bridge formed from the gauges mounted on the vertical struts would give no output. Similarly the vertical bridge should measure only the strain induced by the vertical force; there should therefore be no interaction. The dynamometer body was machined from a solid block of En 32 steel.

The original toolholder was designed to accept $3/8$ in.sq. tools but an additional toolholder was designed and manufactured to accept 12 mm.sq. by 3 mm. thick inserts. It is of interest to note that according to the principles outlined above an alteration in the position of the cutting edge should not affect the output from the bridges.

2.5.3. Instrumentation

The strain gauge bridges are connected to an 'S.E. Laboratories' carrier amplifier system, a block diagram of which is shown in Fig.2.8. The oscillator supplies a 5v, 3kHz carrier which energises the bridge and the modulated signal is fed from each bridge to amplifiers which are fitted with stepped attenuators. The output is then demodulated and filtered with a low pass filter and fed to a mirror galvanometer which reflects a beam of ultra violet light in a U.V. recorder. Variation in the signal causes a deflection of the galvanometer and therefore of the beam of light which is recorded on the light sensitive paper. The paper can be fed through the recorder at speeds up to 2 m/s.

2.5.4. Calibration

A special fixture had been manufactured enabling the dynamometer to be loaded in both directions, albeit not simultaneously, on the Avery universal testing machine. The calibration procedure has been reported (10) but briefly it consisted of loading the dynamometer in each axis up to a maximum load of 5kN in discrete steps of 0.25kN whilst a trace of the galvanometer spot deflection was obtained at each load increment.

However, there were some inadequacies in the method and the following amendments were made. The test machine certificate of verification claimed that the accuracy complied to BS1610.1964 from 2.4 - 12.5 kN; however this is unsatisfactory as the accuracy for loads below 2.4kN is unspecified. Therefore the machine was calibrated for loads up to 5kN using a proving ring. It was also considered difficult and inconvenient to maintain the cutting edge of the tool in a fixed position relative to the dynamometer during its use. It was therefore decided to calibrate the dynamometer with the cutting tool in a number of different positions. The calibration curves at the instrument settings which were used throughout the tests are shown in Fig.2.9. and Fig.2.10. shows the effect of changing the position of the cutting edge.

The interaction between the force components was found to be less than 1% and it was therefore considered unnecessary to derive calibration equations. A small amount of hysteresis was originally recorded but this was found to be in the testing machine.

The tool deflection throughout each test was recorded with a dial gauge; the horizontal and vertical deflections at a load of 2kN were 0.045 and 0.038 mm respectively. The alignment of the platen traverse was checked and found to be within .05 mm in 50 mm of movement; this ensured that the force was accurately applied in the correct direction.

2.5.5. The 'Kistler' Measuring Platform

A three component measuring platform and instrumentation system manufactured by 'Kistler Instrumente' was used with a toolholder clamped to the top of the platform. This was in turn bolted to the cross-slide of the lathe. The arrangement is shown as used with the Lodge and Shipley lathe in Fig.2.11.

The system is described in (15) but the principle of operation is briefly as follows:

Piezoelectric force transducers are used in the measuring platform. The output voltage from these is amplified by a charge amplifier which incorporates twelve scale ranges from 10 - 500,000 pC. The output voltage is converted to a current by the galvo amplifier which is adjusted to the sensitivity of the galvanometer used in the U.V. recorder. The resulting spot deflection can therefore be calibrated by adjusting the current constant of the galvo amplifier. A block diagram of the arrangement is shown in Fig.2.11.

The manufacturers claim that interaction between the force components is negligible, but this is determined when the platform was loaded centrally. The linearity and interaction were therefore checked by applying loads to the tool point using a calibration procedure similar

to that described in section 2.5.4. The calibration curves were found to be linear over the range 0 - 5 kN but there was approximately 6 per cent interaction on the feed force component and 4 per cent on the thrust force. However, as the forces were only assessed independently this was neglected.

2.6. QUICK STOP DEVICES

Much evidence can be obtained from microscopic observation of the chip formation process. This can be accomplished by effectively "freezing" the cutting action enabling the chip and chip root to be removed from the workpiece and prepared for metallographic examination. It is to this end that the quick-stop device has been developed as it is important that the specimen is representative of the steady state cutting condition. For this to be so the separation distance must be small, as during separation the cutting speed, and in some cases the undeformed chip thickness, is continually changing. Fig.2.12. shows how a knowledge of the average acceleration enables approximate values of stopping time and stopping distance to be obtained.

Separation can be achieved by either accelerating the workpiece away from the tool or the tool away from the workpiece. As the tool is likely to have less mass than the workpiece and chuck assembly, it is usually more appropriate to accelerate the tool from the workpiece. This is the case with a lathe as the chuck and spindle also have considerable momentum, when machining at normal cutting speeds.

The basic requirements of a quick-stop device are:

1. The separation time, and therefore distance travelled by tool relative to the workpiece, should be small.
2. Geometrical and metallurgical changes in the chip and workpiece surface introduced by the action of the device, should be insignificant.
3. The dynamic performance of the device should be at least equivalent to a conventional toolholder.

4. It should be safe and easy to use.

2.6.1. Design of Quick Stop Devices

The performance is generally assessed in terms of either the time to reach a particular velocity, the separating time, or the average acceleration over the separating distance. Devices that have been developed recently (11,12,13) have usually used either an explosive or mechanically applied high impacting force to accelerate the toolholder in the direction of, but in opposite sense to, the workpiece-tool relative motion, or in a circular path away from the cutting edge.

A device of the pivoted tool type and using a captive bolt pistol to provide the impacting force, was designed and manufactured. It was thought that any variation in geometry during separation which is inherent in this type, is compensated by the simplicity in design. It may be seen from Fig.2.13. that the toolholder is hinged at one end and at the other supported by a pin. The pin is notched at either end to ensure failure occurred in the appropriate position; the combined areas at the root being 20% higher than that necessary to support the maximum cutting force.

In the initial design a modified commercial toolholder was utilised but this was found to be unsatisfactory as the clamping arrangement of the tip proved to be inadequate and the tip moved laterally on firing. The mass of the toolholder should not be excessive as the acceleration is inversely proportional to the mass. However, it was found necessary to make the toolholder of fairly large cross section and from a nickel-chrome steel, to minimise bending on impact. The existing toolholder has also a much sturdier combined clamp and chip former which has so far proved adequate.

The gun was a [REDACTED] captive bolt pistol humane killer, manufactured by [REDACTED] [REDACTED]. The original bolt was only 7.5 mm diameter and was replaced by a bolt 15 mm diameter in a nickel-chrome steel and

was mounted to provide 50mm of free flight.

2.6.2. Performance and Measurement

Brown R.H. et al (14) in a recent paper critically appraised the reported performance claims of a number of quick-stop devices, the performance of these devices being measured using accelerometers, high speed photography and a number of types of displacement transducer. Brown suggested the use of a fibre optic displacement transducer had advantages over the methods previously employed, and used the method to assess the performance of his quick-stop device. The main criticism of other techniques was that insufficient information was obtained in the first few micro seconds after impact.

Tests using a Fotonic sensor and auxilliary equipment by 'M.T.I. Instruments Ltd.' America, measuring the displacement of the polished surface of the tool tip clamp, had to be discontinued as part of the equipment became damaged when being used elsewhere and imminent replacement or repair was unlikely. It was therefore decided to use a shock accelerometer by 'Endevco Products Ltd.' attached to the underside of the toolholder and used in conjunction with an oscilloscope.

Although photographs of the oscilloscope traces of acceleration were obtained, the image was somewhat blurred by high frequency accelerations resulting from the impact causing stress waves to be propagated, the pattern of these waves being complex due to reflection of the waves from the surfaces of the toolholder. In steel the stress wave travels at approximately 6000 m/sec and therefore it takes only 5 micro seconds to travel across the toolholder.

An idea of the magnitude of the acceleration was obtained by examination of the envelope of the trace but some uncertainty remained concerning the maximum value of acceleration at the beginning of the movement. The acceleration was calculated, knowing the capacitance of the circuit and the charge sensitivity of the accelerometer, as follows:

Total circuit capacitance = 982 pF

Charge sensitivity of accelerometer = 0.645 pC/g

Therefore Voltage sensitivity of accelerometer = $\frac{.645}{982} = .655 \times 10^{-3} \text{ V/g}$

Maximum voltage ≈ 40

Therefore acceleration = $\frac{40}{.655 \times 10^{-3}} = 6.1 \times 10^4 \text{ g}$

The main criticism of the arrangement described is that it does not measure the acceleration at the cutting edge and it is possible that this could be different to that measured by the accelerometer.

Further tests were performed with the arrangement as described above but with the output connected to a Tektronix plug in type operational amplifier used as an integrator. It was thought that a clearer velocity envelope would have resulted and although this was the case, the results were treated with some scepticism as the criticism above still applies, namely the accelerometer is some distance from the cutting edge. It is proposed to repeat the tests with the Fotonic sensor as a displacement transducer.

2.6.3. The Natural Frequency

The device was mounted on the lathe cross-slide in its normal cutting attitude and excited in a vertical direction by an electromagnetic exciter at a point near the cutting edge. The output from the accelerometer was displayed on the oscilloscope and the frequency at which the amplitude was at a maximum was taken as the natural frequency. This procedure was repeated at different pressures on the toolholder. The frequency was found to vary from 840 to 1000 Hz.

2.6.4. Procedure When Using the Device

When machining the end of a tube the device was rotated on the cross-slide to provide a cant angle of 3° so that as the tool swung on the hinge pin there was a component of the movement in the Z direction, the spindle axis, away from the cut surface. The tip seating was also machined at this angle so that cutting was still orthogonal.

Approximately fifty test firings were made and observation of micro-specimens of chips roots using an optical microscope and an electron scanning microscope indicated that there was a reasonably high proportion of successful firings; however not less than three specimens were produced for each test. As there remained some uncertainty regarding the separation performance of the quick-stop device a cutting speed of 160 m/min was not exceeded, this being well below the cutting speed at which devices of similar design are claimed to work satisfactorily.

2.7. LIGHT SECTIONING MICROSCOPE

The light sectioning microscope utilises a narrow strip of light which is obtained by passing a collimated beam of light through a slit. This strip intersects the surface of the specimen at an angle of 45° , and illuminates the surface irregularities. An objective situated at 90° to the beam of light produces an image of the slit. The optical principle of this microscope is illustrated in Fig.2.14. The particular instrument used was a Carl Zeiss Light Sectioning Tester which could be used at four different overall magnifications, namely 60, 120, 260 and 520 times.

The method has certain advantages over other methods of surface assessment. The specimen does not require any preparation treatment, for example, sectioning and polishing, and no physical contact is made with the specimen. Furthermore, the contour obtained is not distorted, as is the trace obtained from a stylus type instrument which invariably uses different magnifications in the x and y directions. It is a quick and easy means of obtaining a visual assessment of the surface topography and, although means are provided by which measurement can be made, it is doubtful whether numerical assessment of say peak to valley height is reliable unless a great number of readings are taken.

2.8. HIGH SPEED PHOTOGRAPHY

Examination of the chip forming process when using chip forming grooves was also performed using a high speed camera. The frame speed selected was 750 frames/s. This caused a movement of the workpiece of approximately 2.5 mm at the cutting speed used, 120 m/min. The movement of the chip during the exposure of each frame was approximately 1 mm. For better definition a higher frame speed must be used but there is then difficulty in providing enough light. Using two photofloods and a white back cloth to provide a silhouette effect and with the largest aperture setting, F3.5, a frame speed of 750 frames/s was found to provide sufficient detail to enable the chip curvature and the position of the chip relative to the groove to be determined. The film used was Ilford Mark V 16 mm Type 794.

It was found necessary to use a telephoto lens with 70 mm extension tubes to provide an image of the appropriate size. The camera was situated at the rear of the lathe with the lens system and axis of the groove collinear. The cutting tool was presented at a cutting edge angle just large enough to cause the chip to spiral and miss the workpiece.

2.9. THE SCANNING ELECTRON MICROSCOPE

A scanning electron microscope differs from a conventional direct microscope in that instead of taking radiation from all over the object it takes radiation from a source and focuses it into a spot. This is scanned across a specimen and then forms an image by monitoring some specimen response on a screen scanned synchronously with input. Since the individual parts of the object are involved in the image making process only at any one instant it is possible to produce an image with a much greater depth of field than a conventional microscope. This means that much higher magnifications become practical and thus provides a valuable instrument for studying surface topography. In order to

prevent the bombarding electrons from charging up the specimen it must be either itself a conducting material or alternatively vacuum coated with a conducting material.

In 1974 the City University purchased a 'Jena' model MSM-2 "MINI-SEM" scanning electron microscope and this was used to examine the topography of surfaces produced when obliquely machining En 8 with double rake angle tools. The chip roots of the quickly stopped specimens were also examined in order to learn more about the separation process. The instrument proved useful but lacked the range and flexibility of larger models. These would seem more appropriate for low magnification work, the iris range enabling greater depths of field to be obtained.

2.10. TERMINOLOGY

The terminology and nomenclature used in metal cutting research has for many years often varied in different countries and sometimes individual researches have devised their own systems. The basis for the terminology and notation used in this thesis is the C.I.R.P. document "Terminology and Procedures for Turning Research" (8). As there is close co-operation between C.I.R.P. and I.S.O., most of the international standards on the subject use identical terminology.

In the text, cutting situations are sometimes referred to in a general manner as high or low speed machining. In general low speed machining is regarded as being below 20m/min and high speed machining above.

CHAPTER 3

A CRITICAL APPRAISAL OF PREVIOUSLY PUBLISHED WORK ON CHIP

CONTROL AND CHIP FORMING DEVICES

3.1. INTRODUCTION

Chip breaking may be defined as breaking up the chip into a size that can be easily handled, in a metal removal process where a continuous chip is being formed and can be achieved in a number of different ways. It is proposed that these are examined under three headings:

3.2. CHIP FORMING DEVICES

By far the major part of chip control today is achieved by using either obstruction or groove type chip forming devices, and a variety of these is shown in Fig.1.4. Most practical metal cutting operations are performed under conditions of oblique cutting where the straight cutting edge of the tool is inclined at some angle to the direction of work-tool motion as shown in Fig.3.1. The work of previous investigators which will be reviewed was performed under these conditions, as the most desirable form of chip breaking can only be effected when obliquely machining.

With both the above-mentioned types of chip forming device, the chip is formed into an approximately circular arc. Nakayama (16) suggests that the formed chip may then be broken in the four possible ways as illustrated in Fig.3.2. Observation supports this view and indicates that the breaking shown in Fig.3.2a. is the most common and desirable - most analyses on chip breaking assume this breaking action.

Although the work performed previously has mostly been concerned with the obstruction type chip former, once the chip has been formed, the breaking of the formed chip occurs in an almost identical manner with both devices. Each of the chip breaking actions shown in Fig.3.2. is therefore described.

TYPE A

The combined effect of the tool corner radius, cutting edge inclination angle and cutting edge angle on the direction of chip flow, causes the chip after being deflected by the obstruction, to be formed into a helix. Consequently it misses the workpiece at A. With continued curling it then strikes the tool shank below the cutting edge. Further chip production with the end effectively fixed at B increases the radius of curvature, and hence the stresses in the chip, until it breaks, at a point above B. However, the chip after contacting the workpiece at A, sometimes slides along the workpiece away from the tool and is carried down due to its own weight. This results in the chip forming a much larger radius of curl and the end of the chip is not fixed in any way. As the length of the chip increases it usually becomes entangled and snarled around the tool and tool post.

TYPE B

The chip, after being formed by the chip breaker strikes the shoulder of the uncut part of the workpiece and often spirals as in orthogonal cutting. The chip breaks usually at its root and, prior to breaking, the side of the chip often marks the new workpiece surface. This action also creates high intermittent cutting forces and the chip, when it does break, flies off at much higher speeds than those broken in the desirable manner. The likelihood of the chip breaking as in (A) or (B) depends principally upon the direction of the chip flow which can be calculated using Stabler's Law (3).

TYPE C

The chip either contacts the corner of the workpiece shoulder which causes it to curl too tightly for the free end to contact the tool flank or alternatively the free end of the chip may slide upwards and away from the workpiece on striking the tool flank. The chip thus formed is in the form of a continuous helical ribbon as shown in the figure.

Nakayama (16) suggests that if breaking does occur with this action, it is due to stresses produced in the root of the chip which are caused by its own weight and vibrations.

TYPE D

The chip strikes the workpiece shoulder and is immediately broken.

Spaans et al (17) in another investigation into break mechanisms, agrees mainly with the findings of Nakayama, but in addition stresses the importance of the chip's history. It is shown that the behaviour of the chip formed during the first revolution, before the feed has reached its steady state value, may have a decisive influence on all further chips.

3.3. NATURAL CHIP BREAKING

In many practical metal cutting operations the chip may be naturally formed into a circular or helical shape and then break in the manner described in section 3.2. The natural chip curl radius is determined by the cutting conditions and the workpiece material (18,19) therefore it is possible to achieve some degree of chip control by suitable choice of cutting conditions. However, this may necessitate the use of uneconomical speeds and feeds or impractical tool geometries.

3.4. OTHER METHODS

A variety of other methods have been developed, none of which have been used extensively. They include:

a) Varying and interrupted feed devices, which operate on the principle of causing a periodically thin spot in the chip which induces it to break at regular intervals. The feed variation is usually accomplished by one of the two following methods.

i) by applying a vibration to the tool in the direction of the feed as described by V.N. Baranov et al (20), or

ii) mechanical devices such as eccentric cams in the feed gear box.

b) Mechanical methods as described by Ioffe, Kundratov, and Kiselev

(21,22,23). Fig.3.3. shows an example which although limited to turning operations is said to efficiently chip break over a wide range of conditions. There is some similarity between this method and the chip forming methods previously described.

3.5. THE CHIP BREAKING ACTION OF CHIP FORMING DEVICES

From the discussion in section 3.2. it may be seen that the chip breaking action of both obstruction and groove type chip formers may be subdivided into four parts.

3.5.1. The Direction of Flow of the Chip from the Cutting Edge.

During an oblique machining operation the chip flows at some angle to the normal to the cutting edge as may be seen in Fig.3.1. Stabler (2) originated the chip flow law which states that the angle of obliquity (λ_s), now called the cutting edge inclination, equals the inclination of the direction of chip flow (v_c) perpendicular to the cutting edge, lying on the tool face as shown in Fig.3.1. that is:

$$v_c = \lambda_s \quad (3.1.)$$

Most of Stabler's early work was concerned with conditions of free cutting, namely where there was no secondary cutting edge. In a later work (24) after suggestions that the law did not always apply and did not take into account cutting speed it was modified to

$$v_c = a_s \lambda_s \quad (3.2.)$$

where ' a_s ' varies between 0.9 and 1 under a wide range of cutting conditions.

The observed variations from the law occurred when cutting under non free cutting conditions, that is with a secondary cutting edge. The law is therefore more accurate when the ratio of the length of the major cutting edge to the length of the minor cutting edge is high, say > 5 .

Okushima et al (25) also investigated the direction of chip flow and concluded that the significant parameters were the tool corner radius, width of cut and feed; although it was stated that the effect of the

latter was small compared with other factors. It was also concluded that the effect of changes in cutting speed was negligible. As the implementation of Okushima's theory involved considerable computation, nomograms were drawn to facilitate data retrieval. Okushima did not investigate the effect of cutting edge inclination which to some extent invalidates his work.

Spaans (17) showed experimentally that the chip flow angle was uniquely related to the ratio of width of cut to tool corner radius as illustrated in Fig.3.4. but did not quantify the relationship.

Much of the disagreement between the findings of different workers has arisen from the definition of the chip flow angle and the plane in which it is measured. Unfortunately, Spaans does not define his chip flow angle but assuming it is the same as that defined by Stabler then there is some measure of agreement between the results of these investigations and Stabler's law as may be seen in Fig.3.4. The work reported above was mainly of an experimental nature and the relationships thus obtained are empirical.

Zorev (26) conducted a much more rigorous analysis in which he considered the effect of the secondary cutting edge causing the existence of a secondary shear plane. It was suggested that the chip flow direction is determined by the normal forces on the shear planes and coincided with the resultant of the normal forces in the plane perpendicular to the direction of the cutting velocity. It was shown that

$$\rho_o = \eta + \nu_{ae} \quad (3.3)$$

where ρ_o is the angle measured in the normal plane between the direction of departure of the chip and the normal to the longer cutting edge when the rake angle is not zero.

η is the angle of deflection of the chip from the main normal plane.

ν_{ae} is the additional angular deflection due to the cutting edge inclination angle and may be obtained from

$$\nu_{ae} = \arctan(\tan \lambda_s \cos \eta - \tan \gamma_n \sin \eta) \quad (3.4.)$$

where γ_n is the rake angle in the normal plane. When examining the case of free cutting, the effect of the secondary cutting edge can be neglected and

$$\rho_o = \nu_{ae}$$

that is, Stabler's law applies. However, it is obvious that the secondary cutting edge has a significant effect on the direction of the chip flow as is evidenced by the fact that if each of the two edges is made to work separately without the other edge, the chip formed will leave at right angles to the working edge.

Zorev extended his analysis to account for tools having a transition cutting edge, for example, tools with a corner radius.

Mention was made by some of the above workers of chips that formed a helix on leaving the cutting edge. Additional causes of this may be inhomogeneity of the workpiece and differences in the variation in diameter of the workpiece over the depth of cut used.

3.5.2. The Control of the Radius Imposed on the Chip

There are two basic theories concerning the curvature induced in the chip by the obstruction. The first suggests that the curvature is determined geometrically from the configuration of the chip former.

Henriksen (27) introduced the parameter chip flow circle Fig.3.5. for obstruction type chip formers. The radius of the chip flow circle being obtained from

$$R_T = w \cot(\theta/2) \quad (3.5.)$$

for the chip former shown in Fig.3.5.(a)

and

$$R_T = (w^2 + H^2)/2H \quad (3.6.)$$

for the chip former shown in Fig.3.5.(b).

Although it was recognised that the radius of the chip after it loses contact with the obstruction R_o , was likely to be greater than

R_T , the difference was neglected in the analysis. It was also considered that the radius of the formed chip was determined solely by the chip former dimensions and unaffected by cutting conditions.

Nakayama (28) in a more comprehensive study also used the chip flow circle but indicated that this parameter was likely to be affected by the chip-tool contact length, KB_o , where KB_o could be calculated using

$$KB_o = K_m h_c \frac{2 \sin \omega}{[\cos \omega + \cos(\omega - 2\beta)]} \quad (3.7.)$$

where K_m is a constant, ω is the angle between the resultant cutting force and the shear plane and β is the friction angle and that R_T would be more accurately given by

$$R_T = (W - KB_o) \cot(\theta/2) \quad (3.8.)$$

It was also suggested that R_o would be affected by the chip thickness and therefore by parameters influencing this, such as cutting speed. Allowing for both these factors R_o was said to be a "function" of the chip flow circle and chip thickness for a particular workpiece material.

Trim and Boothroyd (29) in a study of the formed chip radius included the effect of the length of the chip-tool contact length as did Nakayama and found that the experimental results were very close to the predicted values. Assuming that the chips were measured after they were formed the implication of the results is that the elastic recovery is negligible. Trim's expression for calculating the chip flow circle radius was a modified version of Henriksen's, but assumed that the chip was tangential to the point at which the chip lost contact with the tool face. Assuming that the chip-tool contact length equals chip thickness this yields:

$$R_T = (W - h_c)/2h_c + h_c/2 \quad (3.9.)$$

The second theory is that the curvature is due to the bending moment at the obstruction causing plastic bending of the chip and regards the chip as a rectangular section beam. Okushima et al (30) considered that the bending was as shown in Fig.3.6. and that the

bending moment was sufficient to cause the chip to be fully plastic at least for some distance from the cutting edge. The amount of bending was a function of the time for which it was subjected to plastic bending, this being a function of chip velocity. At some distance from the cutting edge the beam changed from the plastic to the elastic state and began to recover elastically as it approached the heel. The following expression for the radius of the formed chip measured at the neutral surface was obtained.

$$1/R_n = c_1 H/W^2 - c_2/S \quad (3.10)$$

where S is the feed and c_1 and c_2 are constants depending upon the work material, the tool geometry and the cutting speed. After a series of tests c_1 and c_2 were obtained by equating theoretical and experimental results. The above analysis neglected the chip-tool contact length.

Subramaniam and Bhattacharyya (31) used the analysis of Okushima but attempted to include the chip-tool contact length. Unfortunately their results were somewhat inconclusive.

Al-Mandalawi (32) presented an experimental relationship between measured chip curl radius and chip thickness for a particular chip former geometry and cutting conditions, the chip curl radius being apparently measured after fracture. The results are compared in Fig.3.7. between equation (3.5.) equating KB_o to h_c , equation (3.8.) and the equation

$$1/R = 1/[(W-h_c) \cot(\theta/2)] - 2\varepsilon_f/h_c \quad (3.11)$$

where ε_f is the strain at fracture and was assumed to be 0.01 and R is the chip curl radius at fracture. Equation 3.11 is obtained by substituting equation 3.8. into equation 3.16. It is implicit that the chip curl radius is increased from R_n to R elastically and then does not recover after fracture.

This reasoning contradicts an earlier statement which suggests that the final chip curl radius varies negligibly from the chip flow circle radius. In order to justify this claim, R was calculated from equation

3.11. when $\sigma = 100,000 \text{ lbf/in}^2$. $E = 30 \cdot 10^6 \text{ lbf/in}^2$ $h_c = 0.005 \text{ in}$ and $R_T = (w-h_c) \cot (\theta/2) = 0.020 \text{ in (0.5 mm)}$.

This yielded a value of R of 0.0205 in , that is 2.5 percentage increase. It was thus suggested that the elastic expansion could be neglected. If this is so the term $2\varepsilon/h_c$ in equation 3.11 should be neglected, which invalidates the presentation of two different curves in the figure. In fact the value of R used in the calculation is not realistic; it is more likely that the chip thickness was 1.25 mm (0.050 in) and with values of this magnitude little elastic recovery is inevitable. Using the chip former dimensions quoted R_T calculated from equation 3.8. is 3.33 mm and substituting the figures above in equation 3.11. provides a value of R of 4.05 mm , that is, a 22 percentage increase, more in agreement with the figure.

A more likely explanation of the break mechanism is that the chip is formed to a radius, as numerically predicted by Trim. On leaving the obstruction it recovers to a slightly larger radius and eventually contacts the tool flank. With continued chip production it expands to a larger radius, as predicted by equation 3.16, and then breaks. The broken chip then recovers to approximately the original radius. The amount of elastic recovery is determined primarily by the magnitude of the chip thickness but some idea of the magnitude can be obtained from a comparison of the two curves in Figure 3.7.

3.5.3. The Relationship between the Radius of the Formed Chip and the Degree of Chip Breaking

Before being able to discuss the degree of chip breaking it is useful to have a systematic classification of the types of broken chips. Henriksen extracted a simple classification table out of a more comprehensive system by Schallbrook (33). The table shown in Fig.3.8. indicates a "preferred" and a "useable" range of chip types with respect to chip control and handling.

Henriksen assumed the formed chip to be broken as an open elastic ring and that $R_o = R_T$ (Fig.3.5.) it was shown that

$$h = 3\sigma \cdot c \cdot R_T / K_h \cdot E(c^2 - 1) \quad (3.12)$$

where σ = nominal stress

$c = R/R_T$ - indicating the degree of chip breaking

K_h is a constant relating feed to chip thickness and

h is the feed.

For swarf handling a full turn chip is convenient, for a full turn chip $R = 2R_T$ that is $c = 2$ substituting in equation (3.12) yields

$$h_c = 2\sigma \cdot R_o / E \quad (3.13)$$

This indicates a linear relationship between the chip breaking feed and the chip flow circle, when σ is the ultimate tensile strength of the chip. The experimental results presented by Henriksen reveal a parabolic relationship between the feed at which acceptable chip breaking occurs and the chip flow circle radius as shown in Fig.3.9, the difference between theory and practice being accounted for by such factors as:

- (a) The effect of neglecting the contact length when calculating the chip flow circle radius.
- (b) The chip flow circle radius may be effected by the chip thickness.

Another likely cause of error is the assumption that $S = K \cdot h$ where K is a constant. In fact K is likely to vary with cutting conditions, particularly changes in cutting speed.

A criticism of this analysis which is shown in Appendix A., is that it does not really represent the chip breaking action. The analysis assumes that the gap widens until the chip breaks; in practice the gap remains constant and the expansion of the chip occurs because the chip is being continually produced.

Nakayama (28) overcame some of the problems associated with Henriksen's analysis by relating the chip thickness not the feed to

the chip flow circle radius. This eliminates the problem of other factors influencing the relationship between the feed and the chip thickness and to some extent the effect of neglecting the contact length, as this was assumed to be approximately proportional to the chip thickness. To account for this and also elastic recovery, causing the radius of the formed chip to be greater than the chip flow circle radius, it was merely stated that for a given workpiece material the chip breaking feed was "a function of" the chip flow circle radius. Although a range of steels were tested little difference was found in their chip breaking properties. No analysis was presented but it was stated that breaking would occur according to the relationship.

$$\epsilon_f = h_c/2 (1/R - 1/R_T) \quad (3.14)$$

where ϵ_f is the strain at which the chip material is ruptured. This is obtained from classical theory of bending a curved beam.

If this relationship is developed it is shown in Appendix B that the predicted relationship between the beam thickness and the original radius of curvature, assuming $R = 2R_o$, is:

$$h_c = 4\sigma R_o/E \quad (3.15)$$

It is also possible to take into account the elastic recovery of the chip after it leaves the chip former. In this case it is shown in Appendix C that

$$h_c = 6w\sigma \cot(\frac{\theta}{2})/E + 6\sigma \cot(\frac{\theta}{2}) \quad (3.16)$$

The equations 3.15 and 3.16 both indicate a linear relationship between the chip thickness to cause fracture and the original chip curl radius. Nakayama's experimental results also show the above relationship to be linear. It is suggested that equation 3.16 is more representative of the breaking mechanism. However, accurate quantitative comparison is limited by the obtainable accuracy of the values of E and σ for the material of the chip. Nakayama assumed that the end of the chip slipped down the tool flank as shown in Fig. 3.10a, where it also may be seen

that $R_L \gg R_0$ although it was suggested R_L is difficult to calculate.

If typical values of h_c , R_T and ϵ_f are substituted in equation 3.16 the radius of the chip at fracture R is only slightly larger than R_0 therefore the height of the tool flank was not considered critical. However, tests were performed using an obstacle plate which in effect trebled the height of the tool flank, but no change in chip breaking was observed.

Summarising Nakayama's study, it was concluded that the limiting condition for chip breaking was affected by the workpiece material, the chip thickness and the chip flow circle radius and only affected by other metal cutting parameters in as much as they affect the chip thickness.

In a further work Nakayama (34) examined the mechanical properties of the chip. After measuring yield stress, ultimate tensile stress and hardness, it was concluded that the chips produced when cutting steel were often ideally plastic materials and that the ultimate tensile stress was twice that of the parent material. Bend tests were performed on identical chips where the uppermost side of the chip was

- 1) in tension
- 2) in compression.

In every case the chips break when the uppermost surface was in tension and as this is the situation which exists for the type of chip breaking described the remaining tests were performed with the chips being bent in this way.

The irregularity of the uppermost surface of the chip as shown in Fig.3.10b and the value of E obtained from the bend test using values of chip thickness measured with a ball and micrometer prompted Nakayama to conclude that the chips failed where the chip thickness is at its smallest. Although perhaps an obvious conclusion it highlights the importance of the ratio h_e/h_m where h_e is the effective chip thickness

and h_m is the mean chip thickness. Therefore, for chips of the same nominal thickness the chips will break easier where the uppermost side of the chip is rougher.

Okushima et al (30) suggested that the degree of chip breaking was determined by the radius of the formed chip and the feed (this really implied the undeformed chip thickness). Experimental results presented by Okushima showed the relationship between the feed and the radius of curvature of the neutral layer of the chip to be parabolic, and the equations to the curves which indicated the chip breaking range was obtained, and is shown in Fig.3.11. The main criticism of this work is that it neglects the chip-tool contact length.

3.5.4. The Effect on Metal Cutting Efficiency of Using a Chip Forming Device

Subramaniam and Bhattacharrya (35) found that as the width of the chip breaking step is increased, for a variety of heights of step, the cutting forces pass through a minimum. Although the chip former imposes additional deformation it was found that under certain conditions cutting forces were reduced compared with a plane tool without an obstruction. It was suggested that this was because the contact length was reduced by the action of the obstruction lifting the chip, and causing a reduction in the friction force on the face.

Nakayama (28) had also previously noticed that the correct choice of chip flow circle radius R_T decreased cutting force, thrust force and chip thickness but that an excessively small value of R_T increased them.

The previous work described above has all been concerned with obstruction type chip formers. It is shown in Chapter 6 that, except for the determination of the radius of the formed chip, the chip breaking action of the groove type chip former is the same as that of the obstruction type.

There is little published work of a theoretical nature concerning the groove type chip former. Henriksen in his paper on obstruction

type chip formers, implied that the groove type chip former operates in a similar manner, and that the chip curl radius before elastic recovery is 1.75 times the effective groove radius.

Some work concerning groove type chip formers, mostly of an empirical nature, has been reported by a number of Russian workers. Lutov (36) suggested that the important parameters with respect to chip control were the groove radius, land length and groove depth and conducted a series of tests on a steel. The conditions were typically:

$$V = 200\text{m/min}$$

$$a = 2.0 \text{ mm}$$

$$s = 0.5 - 1.0 \text{ mm}$$

$$\gamma_n = -5^\circ$$

and each of these parameters was varied independently. From the results the following conclusions were drawn:

Groove Radius R_g - As the chip thickness is reduced, to maintain effective breaking R_g should be reduced. It was suggested that as R_g is reduced the chip curl radius is reduced which increases the effective rake angle. This beneficial effect is nullified by the increase in force required to bend the chip. As a compromise it was suggested that the maximum groove radius consistent with effective chip breaking should be selected and the following values were recommended:

		over	over	over	over
<u>Land length - mm</u>	0.05-0.1	0.1	0.2	0.3	0.5
Groove radius - mm	0.5	1.0	2.0	3.0	4.0

Land Length - should be smaller than the chip-tool contact length. The chip-tool contact length for the conditions under test was found to be twice the chip thickness. It was recommended that

$$b_{\gamma r} \leq (0.5 - 0.7)h_c$$

where $b_{\gamma r}$ is the length of the land and h_c is the chip thickness.

Groove depth - had little effect on chip breaking. It was observed

that depths as low as 0.03 mm were effective but because of manufacturing difficulty depths of 0.1 - 0.2 mm were recommended.

Proskuryakou et al (37) used a volumetric coefficient to measure chip breaking efficiency where

$$\text{Volumetric coefficient} - W_v = \frac{\text{Volume of chips}}{\text{Volume of metal removed}}$$

and suggested $W = 30$ to be the upper limit of stable chip breaking.

From the results of tests it was concluded that the land length, b_{gr} and groove radius R_g , depth h_g and width W , were the important parameters and that $b_{gr} = (S - 0.2)$ mm for feeds from 0.3 - 0.9 mm/rev.

$$h_g = 0.2 - 0.3 \text{ mm}$$

$$R_g = 1.5 - 2 \text{ mm}$$

$$W = 1.2 - 2 \text{ mm}$$

for the particular steel under test.

It was claimed that suitable choice of groove configuration increased tool life 1.5 - 2.0 times.

Nodelman (38) provides a table of tool and groove configurations which is reproduced in Fig.3.12. In a further work on the effect of wear on chip breaker-grooved tools (39) it is suggested that with increase in flank wear there is an increase in the reliability of chip breaking. This is presumably due to the reduction on land length. If face wear occurs the groove width is generally increased and this causes the degree of fracture to decrease, that is the chip breaks less frequently. However, face wear is usually accompanied by flank wear which compensates this effect.

The effect of varying the orientation of the grooves and of using grooves with a non radial form as shown in Fig.3.13 has been examined by Skuratov (40) and Igoshin (41). Although little data is available it is suggested that with both types there is effective chip breaking and increased tool life.

Dzanashvili et al (42) claimed that chip breaking effectiveness is greater when the grooves have been manufactured with a diamond lap instead of a cast iron lap.

3.6. RECENT COMMERCIAL DEVELOPMENTS

'Sandvik' have introduced a three stage chipbreaker as illustrated in Fig.3.14a. The performance of this type of chipbreaker is described by Lundgren (43), and it is claimed that efficient chip breaking is obtainable over a wide range of feeds. At small values of feed the chip is formed by the mini chipbreaker. As the feed is increased the second groove forms the chip and finally with further increase in feed the third groove operates. In each case the effects of redundant grooves are said to be insignificant. There appears to be no published evidence as to how the groove dimensions are optimised for example in terms of chip breaking performance, cutting efficiency or tool life. Also, it appears that the tips with the mini groove are no longer manufactured.

A recent innovation by 'Hertel' provides tips of rather complex shape in order to provide up to eight positive rake cutting edges. These tips are manufactured with or without chipbreaker grooves. The contour of the grooves are shown in Fig.3.14b. Land lengths of up to 0.3 mm are provided at a rake angle of -30° ; again little is mentioned of chip breaking performance.

An adjustable clamp type chipbreaker is manufactured by 'Wimet' in their 'Econodex' range, an example of which is shown in Fig.3.14c. Clearly with this type of chip former it is left to the operator to determine the appropriate position of the chip former for efficient chip breaking.

'Valenite Modco' have introduced an extra wide groove type chip forming tool as shown in Fig.3.14d. There are two interesting aspects of this tool;

(a) There is no land on the tool. The effect of this is to decrease the minimum feed at which chip breaking commences but the edge strength is reduced. The latter is compensated somewhat by honing a small radius on the cutting edge.

(b) The shape of the groove causes the chip to be formed barrel shaped. This could be disadvantageous as it causes an increase in the moment of inertia of the chip, for a constant chip thickness, thus increasing its resistance to bending. However, for small values of undeformed chip thickness where the chip radius has to increase considerably to cause fracture, it could be advantageous since an increase in the moment of inertia of the chip would result in an increase in the radius required to cause fracture.

CHAPTER 4

THE EFFECT OF RAKE FACE CONFIGURATION ON THE CURVATURE OF THE CHIP

4.1. INTRODUCTION

With the increasing use of harder, more brittle cutting tool materials a need has arisen to discover methods of increasing the strength of the cutting edge of the tool and of reducing cutting forces. Also with increasingly higher cutting speeds, effective chip control becomes essential. In this chapter it is shown that in many circumstances these problems may be interrelated.

In recent years much work has been performed using unconventionally shaped cutting tools; often the difference takes the form of a rounded cutting edge or providing face or flank lands on the tool. The problems encountered with difficult to machine workpiece materials has often prompted this work, but it will be shown that there may be advantages in using tools with non-plane rake face configurations even when machining more common workpiece materials.

4.2. EXPERIMENTAL TECHNIQUE

Low speed tests were performed on the shaper and high speed tests on the lathe, in both cases with the two component dynamometer, in order to determine the effect of changes in rake face configuration on chip curvature and cutting forces. The equipment mentioned is described in Chapter 2. Quickly stopped specimens at low cutting speeds were obtained on the shaper by reversing the machine ram and were only obtained at a speed of 2.5m/min. The stopping time was considered to be the time taken for the cutting force trace to reduce to 80% of its steady state value. In general it did not exceed 4 ms which represents a distance travelled of not more than $1/3$ of the undeformed chip thickness. The quick-stop process used on the lathe has been described in

Chapter 2 and this was used exclusively for the high cutting speed tests. In every case not less than three quick-stop specimens were prepared.

The chip length was controlled by castellating the workpiece with sawcuts using a small hacksaw; this prevented the chip interfering with the dynamometer or uncut workpiece surface. In all cases the first chip was ignored as it was not representative of steady state cutting. This was thought to be because the oxide film which forms on the tool and which is removed in the first few millimetres of cut, acts as a lubricant. Also because of the design of the dynamometer some initial dig-in was encountered on impact, caused by the tool rotating about an axis situated behind the cutting edge.

Chip curl radius measurement was performed with radius gauges and was estimated by checking the same chips on an optical projector, to be accurate to within ± 0.2 mm. This was not necessarily the formed radius but the radius obtained after any elastic recovery had occurred. Two general observations concerning previous work on the determination of the chip curl radius when using chip forming devices are as follows:

(a) Information is rarely provided to indicate which radius is being measured that before, or after, elastic recovery, or even the radius of the broken chip.

(b) By implication the chip curl radius is quoted to a high degree of accuracy. In most cases the chip is not truly circular in form and thus a mean radius must be used. This being so a fairly broad tolerance should be allowed on quoted values of chip curl radius.

The length of the zone of sticking friction was regarded as being equal to the land length of the tool at the value of undeformed chip thickness (U.C.T.) which caused the chip to be formed straight and at which a discontinuity occurred in the cutting force - U.C.T. relationship.

4.3. FRICTION CONDITIONS ON THE RAKE FACE

The work of Bowden and Tabor (44) has done much to provide an understanding of the mechanism of friction between sliding pairs and the laws of Coulomb (45) and Amonton (46). They have shown that actual contact only occurs between a few surface asperities, the area of this contact being called the 'real' area of contact and is proportional to the normal force and inversely proportional to the yield pressure of the softer material. The tangential or friction force is the force required to shear the asperities, and is the product of the real area of contact and the shear strength of the softer material. Therefore

$$F_f = \frac{F_n \cdot k}{p}$$

where F_n is the normal force, k is the shear strength of the softer material and p is yield pressure of the asperities. The ratio k/p is found to remain approximately constant for a given material under a wide range of conditions. Therefore the frictional force is proportional to the applied load provided the real area of contact is less than the apparent or projected area of contact, the mode of friction described being known as Coulomb or Amonton's friction.

In a conventional metal cutting process the mode of friction suggested by Zorev (47) indicates that the pressures near the cutting edge are high enough to cause the real and apparent areas of contact to become equal for some distance along the tool face. In this zone the friction force must equal the shear strength of the softer material, the chip, and the laws for dry sliding friction do not apply. For the remaining contact area the pressure is reduced sufficiently to cause the friction to be Coulomb friction. These two zones are known generally as the zones of sticking and sliding friction.

4.4. PREVIOUS WORK CONCERNING CUTTING WITH CONTROLLED CONTACT LENGTH TOOLS

With plane rake face cutting tools it has been established that

for a given workpiece - tool combination there is an optimum value of rake angle for maximum tool life. Fundamentally this is because as rake angle is increased cutting forces decrease but at the same time the tool strength decreases.

Early work (48,49,50,51) performed on positive rake tools having a small land of different rake angle, was mostly concerned with cutting under conditions that caused the natural contact length, that is, the length of contact between the chip and a tool without appreciable wear and measured along the face, KB_0 , to be greater than the land length of the tool, b_{yr} . As might be expected, under those cutting conditions, rake face friction and cutting temperatures were found to be reduced whilst tool life increased.

Usui et al (52) showed that a special plastic field is formed when using the above type of tools and used slip line field theory to analyse the variation of the coefficient of rake face friction with reduction in chip-tool contact area. Usui stated that the special plastic field is only formed when the restricted contact length is less than the natural contact length. Rubenstein (53) has suggested that with a tool of given dimensions, three different conditions can exist namely:

(a) When the value of the undeformed chip thickness, h , causes the natural contact length to be less than the length of the primary land and where the tool behaves as a plane rake face tool.

(b) When the length of the primary land is greater than the length of the sticking friction zone, l_s , but less than the natural contact length. For this condition, although it has been established that the cutting forces and temperature at the chip tool interface decrease (51), there is little evidence concerning chip formation.

(c) When the length of the sticking friction zone is equal to or greater than the length of the primary land.

It has been shown (54) that when the conditions are as in (c) above

and where a special plastic field exists, the chip is formed straight and the increase in cutting force with undeformed chip thickness is at a slower rate.

4.4.1. The Length of the Sticking Friction Zone

As mentioned above an understanding of the influences which determine the length of the sticking friction zone is important in the control of the cutting process. A number of analyses, for example, Zorev (55), predicting the total length of contact between chip and tool, have been performed and other similar analyses, that of Abuladze (56) possibly being the first, predict the length of the zone of sticking friction. Most of these analyses and other empirical relationships (57) suggest that both of these lengths are a function of the chip thickness and, in some cases, it is suggested that the lengths are also influenced by other parameters, for example the mean coefficient of friction between the chip and the tool. It is therefore appropriate to consider the factors which influence these parameters.

For a particular workpiece-tool combination the chip thickness decreases with positive increase in rake angle and in the practical speed range decreases slightly with increase in cutting speed. The speed effect is due to the lowering of the yield stress caused by increase in temperature, predominating over the effect of increasing strain rate increasing the yield stress (58). At low cutting speeds conventional built-up-edge formation, as mentioned later, may also have to be taken into account. However for a given rake angle the chip thickness is directly proportional to the undeformed chip thickness over a fairly wide practical speed range.

The parameter mean coefficient of friction $\mu = F_r / F_{rn}$ does not adequately represent the friction conditions at the chip-tool interface but it is often used to indicate the effect of variations in chip-tool friction. In general it is found to be unaffected by cutting

speed, decreases only slightly at small values of undeformed chip thickness but is significantly affected by rake angle. The latter is due to the resultant cutting force reducing as rake is increased positively and although the normal force on the face of the tool F_{yn} decreases, the tangential force F_y , decreases at a much slower rate, therefore the mean coefficient of friction increases.

The ratio of the undeformed chip thickness to the chip thickness is known as the chip thickness ratio and is found to remain essentially constant with variation in undeformed chip thickness except at small values of the latter at which it is influenced by the ploughing force effect (59). It is suggested then, that for a particular range of cutting speed and workpiece material, the length of sticking friction zone is determined only by the tool rake angle and the undeformed chip thickness.

One other significant effect of variation in cutting speed is concerning conventional built-up-edge (b.u.e.) formation. There is much documented evidence (60,61,62) to show that as cutting speed is increased, at very low cutting speeds the size of the built-up-edge increases causing the effective rake angle to increase. With further increase in speed the built-up-edge angle increases to a maximum and then decreases until it is almost non existent. It may be obvious that cutting forces are influenced accordingly.

4.5. EXPERIMENTAL WORK CONCERNED WITH THE STICKING FRICTION ZONE

From the above discussion it would follow that the ratio of the undeformed chip thickness to the length of the sticking friction zone, Z_0 , remains constant for tools of differing land length, assuming a constant workpiece-tool combination, rake angle and cutting speed. More precisely this is the ratio of the U.C.T. at which the chip is formed straight, or the discontinuity occurs in the cutting force curve as shown in Fig.4.1, to the length of the land of a controlled

contact length tool. The effect of variation in cutting speed on Z_0 was expected to be more significant at low cutting speed. In order to confirm this and to establish the effect of variation in primary rake angle on Z_0 tests were therefore performed with high speed steel tools of varying land length and rake angle over a range of low cutting speeds for an En1A workpiece material. The above-mentioned experimental relationships are shown in Fig.4.2. and 4.3. Fig.4.4. illustrates the constancy of the ratio Z_0 .

Tests at higher speeds were performed with P30 carbide inserts for primary rake angles from 0° to -53° . It was found more convenient to obtain the length of the sticking friction zone from just the discontinuity in the cutting force-undeformed chip thickness curve as shown in Fig.4.5. because at higher speeds the chips were either too long or, if shortened by slotting the end of the tube, not representative of steady state cutting. The relationship between the ratio Z_0 and the primary rake angle is shown in Fig.4.6. for values from 0° to -23° . It may be seen that the predicted ratio by extrapolation for a -38° P.R.A. tool was 0.1 which meant that unless the primary land length was not less than 2 mm long the range of undeformed chip thickness values below the discontinuity was too small to provide a meaningful relationship. This was found to be the case in practice as no discontinuity was observed in the curves for the -38° and -53° P.R.A. tools.

In order to compare the experimental results with the values predicted by Abuladze's equation

$$h_s = h_c [1 + \tan (\Phi - \gamma)]$$

the shear angle was calculated, assuming the Merchant shear plane model, for values of undeformed chip thickness below that at which the discontinuity occurred and using measured values of the chip thickness. Using the calculated shear angle and the measured chip thickness the

length of the sticking friction zone as predicted by Abuladze's equation for tools having primary rake angles of 0° , -8° and -23° , was calculated; its relationship with undeformed chip thickness is shown in Fig.4.7. The theoretical curves were extrapolated in order to obtain the value of undeformed chip thickness at which the theoretical length of the sticking friction zone is equal to the land length of the tools used. From these values the relationship between the ratio Z_0 and undeformed chip thickness was obtained and is compared in Fig.4.6. with experimental relationship.

4.6. THE BEHAVIOUR OF A RESTRICTED CONTACT LENGTH TOOL - EXPERIMENTAL WORK AND DISCUSSION

Comparison of chip curvature and cutting forces when using a plane rake face tool and a restricted contact length tool with increase in undeformed chip thickness as shown in Fig.4.1. illustrates the three phases described in Section 4.4. That is, the restricted contact length tool initially behaves as a plane rake tool; this is followed by a small transition stage, as described in (b) Section 4.4. where the chip curl radius rapidly increases in value. Finally, when phase (c) is reached the chip is formed straight and the cutting forces increase less rapidly. Further increase in undeformed chip thickness initially induces no curvature but with continued increase the chip is again produced curled. Fig.4.8. shows that the value of undeformed chip thickness at which this occurs and the subsequent radius of the chip is dependent on the secondary rake angle, and the workpiece material. Fig.4.9a. shows photomicrographs of the quickly stopped cutting action when cutting with a tool having a zero rake angle with increasing values of undeformed chip thickness which illustrates the phases (a), (b) and (c) described above. Fig.4.9a. shows that the special built-up-edge (b.u.e.) formed at approximately the chip stream angle (γ_u Fig.4.9b. and 4.10a.) irrespective of the value of the primary rake angle. This

implies that the b.u.e. angle β Fig.4.9b. exceeds the chip stream angle if the primary rake angle (P.R.A.) is negative. It is also interesting to note that the chip which is formed at the straightening feed is almost discontinuous. This seems to be due to the rather unusual deformation pattern. The primary shear plane appears to form at a very small angle and there is a large secondary deformation zone which, unlike the special b.u.e. that forms at slightly higher values of undeformed chip thickness, is unstable and mostly becomes part of the chip, although some material is squeezed under the tool nose to form part of the workpiece surface. This means that at this stage the effective rake angle is somewhat indeterminate but is certainly much smaller than the secondary rake angle. Also the chip thickness ratio is similar to that at smaller values of undeformed chip thickness, whereas at higher values the chip thickness ratio, c_h , is much higher. Under the conditions shown in Fig.4.9a., c_h approximately doubles; this again gives some indication of the value of the effective rake angle. It is emphasised that, as is mentioned elsewhere, the transition range of U.C.T. is usually small although the range increases at smaller rake angles and lower cutting speeds, that is, under conditions which promote discontinuous chip formation.

When cutting with double rake angle tools some difficulty is usually encountered in determining the chip stream angle when the chip is formed straight. This is because some negative curvature is initially imparted to the chip during the finite time required for the special plastic field to form, and the end of the chip, impinging on the secondary rake face, alters the chip stream angle as shown diagrammatically in Fig.4.10b.

It has previously been stated by Zorev that the angle of the built-up-edge cannot exceed 45° . In order to establish the value of the

chip stream angle and to observe the b.u.e. angle in these circumstances a special tool was designed, which is shown in Fig.4.11a and b, and quickly stopped specimens were obtained indicating the chip stream angle was in all cases not greater than 45° . Therefore, when cutting with positive rake tools, as in Zorev's work, the built-up-edge angle cannot exceed 45° .

4.7. SOME PREVIOUS WORK CONCERNING CHIP FORMATION

Most early analyses on conventional metal cutting with a single point tool assumed the model shown in Fig.4.12a., that is a tool with an infinitely sharp cutting edge. Masuku (63) in 1953 and Albrect (59) in 1960 introduced the concept of the "ploughing force". The tool is assumed to have a finite radius at the cutting edge as illustrated in Fig.4.12b. It was suggested that this causes a small force to exist which does not contribute towards the removal of metal. This is due to the small area of metal ahead of the tool, where the edge is radiused, being compressed before becoming part of the chip. The model shown in Fig.4.12a. is therefore modified.

Rubenstein et al (64) suggested that the "ploughing" resulted from the fact that as the rake angle round the edge becomes more negative the shear angle decreases at a slower rate than the rake angle. Fig.4.13. indicates that when cutting with plane tools, at a particular value of rake angle the plane of the tool face and the shear plane coincide, that is, the angle Φ becomes zero. At this point shear can no longer occur and the metal ahead of the tool is "ploughed". The value of rake angle at which this occurs was obtained by extrapolating back the curves representing the relationship between Φ and the rake angle γ . The value of γ at which Φ was found to be zero was typically in the range -50° to -70° , and was referred to as the critical rake angle.

The ploughing action causes some material to be plastically compressed into the left or machined surface.. On passing the cutting

edge this material is allowed to recover elastically as the tool flank is always presented at a clearance angle. This causes rubbing or friction on the flank causing further work to be done. The sum of these two effects is called the ploughing force effect.

More recent work by Takeyama and Usui (65) and Wallace and Boothroyd (66) has attempted to quantify the ploughing force. The former authors suggested that the intercept of normal and tangential components of the resultant cutting force when plotted against contact area, that is, when the contact area is zero, are the normal and tangential components of the ploughing force. The latter authors suggested that this analysis did not take into account the undeformed chip thickness, and therefore they obtained the relationship between the normal and tangential cutting force components and undeformed chip thickness for constant values of the ratio of undeformed chip thickness/contact length; the intercepts on the force axis, that is, when the U.C.T. was zero, being assumed to be the components of the ploughing force.

When cutting with controlled contact length tools at values of undeformed chip thickness above that which causes the length of the sticking friction zone to equal the controlled contact length, a dead metal zone is formed as described in Section 4.5. This behaves as an extension to the tool and, if the chip is not obstructed by the secondary face, adopts an angle of 45° .

Johnson (67) used patterns of tangential velocity discontinuities to provide models of chip formation when cutting with controlled contact length cutting tools, from which upper-bound estimates of the shear plane angle were obtained. When using this theory a number of simplifying assumptions are made, namely:

1. It is implicit that when a displacement occurs in a plastically deforming material there may be a change in magnitude of the displacement component tangential to certain surfaces, but there is no change in the

component normal to the surface.

2. Body forces such as gravitational or inertia forces are ignored.
3. The effect of strain hardening is neglected.
4. Temperature gradients are neglected.

The study is therefore restricted to the quasi-static plane strain deformation of a rigid-perfectly plastic material.

4.8. A PROPOSED MODEL OF CHIP FORMATION

From examination of a photomicrograph of the quickly stopped cutting action a model was assumed. Both are shown with the resulting hodograph in Fig.4.14. Applying the upper bound estimate and assuming that the chip flow direction is 45° from the direction of workpiece-tool relative motion, it is shown in Appendix D that $\Phi = 45^\circ$.

It may be seen from the photograph in Fig.4.14. that the dead metal zone has effectively a round edge of bigger proportions than the edge rounding that is usually encountered with plane tools. This means that the model should take into account the ploughing force introduced by the existence of a radiused dead metal zone.

A model which closely approximates to the observed deformation pattern is shown in Fig.4.15. with the associated hodograph. An expression for the external work done is derived in Appendix E. By substituting a range of values of shear angle Φ the relationship between $\dot{w}/k$ and Φ for a particular value of undeformed chip thickness, h , can be obtained as is shown in Fig.4.16.

$\dot{w}$ is the rate of change of external work done

and k is the yield shear stress of the material.

From Fig.4.16. Φ for the minimum value of $\dot{w}/k$ can be obtained for the value of h used and the procedure repeated for a range of values of h .

Fig.4.17 shows both the theoretical and experimental relationship between the U.C.T. - h and shear angle Φ ; the experimental values being obtained when machining orthogonally with a controlled contact

length tool of 0° P.R.A. and 0.6 mm land length at a cutting speed of 2.5 m/min.

The model proposed can also be used to explain why cutting forces do not decrease substantially and plastic deformation of the machined surface increases, at high cutting speeds. These effects are due to the increasing effect of the ploughing force with increase in cutting speed. At much higher speeds the effective rake angle of the special built-up-edge is also reduced. Fig.4.18. shows the increase in the corner radius of the D.M.Z. with increase in cutting speed. The lower curve in Fig.4.17. represents the theoretical relationship between h and Φ calculated for the tool with the bluntest corner, as shown in the figure. It may be seen that the shear angle is smaller with the blunt tool indicating a decrease in the efficiency of the cutting process.

4.9. FORMATION OF THE CHIP WHEN USING A GROOVE ON THE FACE

If the undeformed chip thickness is large enough to cause the sticking length to exceed the land length of the tool then the chip is formed straight with a special built-up-edge. It then contacts the groove and is guided by the groove to the point at which the rear of the groove intersects the plane of the secondary rake face, (point A, Fig.4.19.). It has been shown previously (6) that the special b.u.e. then reaches a stable shape, which for a given primary face configuration and workpiece material, is determined solely by the width of the groove, provided that the groove contour does not interfere with the chip. The chip is thus form curled to a particular radius, determined by the undeformed chip thickness. This is illustrated in Fig.4.19. which shows the experimental relationship between the undeformed chip thickness and the chip curl radius, for tools of different groove width and constant land configuration.

4.10. THE EFFECT ON CHIP FORMATION OF THE PRIMARY LAND LENGTH

Dzanashvili (68) has reported increased tool life when using

negative face lands to machine difficult workpiece materials. However, there appears to be little published work on the effect of the configuration of the primary land on chip formation and chip curl radius.

It has been suggested by the author (54) that a curve fitting the results shown in Fig.4.19. should be asymptotic to the undeformed chip thickness at which the chip is formed straight (length of the sticking friction zone equals land length) and that there should also be a minimum value of chip curl radius, $R_{\min}$ determined by the groove width W and given by

$$R_{\min} = W / \sqrt{2} \quad (4.1.)$$

which assumes a maximum chip stream angle of 45° .

The value of undeformed chip thickness for this minimum is dependent on the chip thickness ratio. If a chip thickness ratio of 0.5 is assumed the undeformed chip thickness at which the chip curl radius is a minimum is $W/(2\sqrt{2})$. With the grooves shown in Fig.4.19. the calculated value of undeformed chip thickness for $R_{\min}$ is very high and was never reached.

When determining the equations representing the experimental relationships between the chip curl radius and undeformed chip thickness, the following points were considered:

1. The proposed theory predicts a linear relationship between $h-h_s$ and $1/(R_1-R_{\min})$, where R_1 is the chip curl radius before elastic recovery. In practice R_0 was measured and not R_1 .
2. The elastic recovery of the chip varies with undeformed chip thickness.

Previous work (6) has indicated that the resulting deviation caused by these effects is relatively small. It was therefore decided that least error would be introduced by drawing a straight line by eye through the experimental points and passing through the origin, rather than perform a regression analysis.

It may be seen that the curves representing the relationship between the chip curl radius, R_o , and the undeformed chip thickness, h , were in close agreement with the curves obtained if R_o was regarded as approaching R_{min} asymptotically. Therefore, for the practical range of undeformed chip thickness values used, the curve was considered to be a rectangular hyperbola, that is:

$$h-h_s = \frac{K}{R_o - R_{min}} \quad (4.2.)$$

where K is the tangent of the line

$$K = (h-h_s) (R_o - R_{min}) \quad (4.3.)$$

Further, the equation to this line for a particular workpiece material is the same for different groove widths. If it is assumed that at high speeds the speed effect will be small this means that for a particular workpiece material and provided the groove does not interfere with the chip, then for a constant land configuration, the above linear relationship will still be valid. The former point is illustrated in Fig.4.20. which also includes the results obtained when reducing the land length of the tool.

Fig.4.20. also indicates that the slope of the line representing the relationship expressed in equation 4.2. varies with change in primary land length despite the fact that some correction has already been applied because h_s will have changed with land length. Fig.4.21. shows the results when using the same tools but with various land lengths. However it can be seen that the relationship between the slope of the line K , and the land length is approximately linear over a wide range of cutting conditions, indicating that for otherwise constant conditions, the chip curl radius reduces as the land length is reduced. This implies that the chip stream angle and hence the b.u.e. increases more rapidly when the land length is reduced. The results of a test with a grooved tool having no land are shown in Fig.4.22. where it may be seen that chips were produced of consistent radius for values of undeformed chip

thickness within the range 0.05 - 0.4mm. This suggested that the rake angle of the b.u.e., γ_u Fig.4.9b., for tools having a very small land reaches a value of 45° at very small values of undeformed chip thickness and as this angle cannot be exceeded the chip curl radius remains constant with varying undeformed chip thickness. When using this tool, the chip curl radius should be R_{min} but as the chip is measured after it has left the groove some elastic recovery has taken place and this accounts for the constant value of R being slightly greater than R_{min} . At the highest value of U.C.T. the observed decrease in R is likely to be due to the elastic recovery being less in the thicker chip.

A possible explanation for the chip curl radius at the U.C.T. of 0.045 mm being less than R_{min} is that a finite land or radius existed at the cutting edge and the length of the zone of sticking friction at this value of U.C.T. did not exceed the land length and the chip curled naturally. This implies that the chip did not use the groove and the visual evidence supports this view.

4.11. PREDICTION OF CHIP CURL RADIUS

The above observed relationships are extremely important with regard to the prediction of the chip curl radius. From a single test with a grooved tool and with a knowledge of the primary rake angle-sticking length relationship, which can be obtained as described in Section 4.4.1., it is possible to predict the chip curl radius for any given value of U.C.T. provided that the groove does not interfere with the chip. The following outlines the procedure assuming a single tool configuration and workpiece material.

1. A test is performed as described in Section 4.4.1. in order to obtain the relationship between the primary rake angle and the length of sticking friction zone to land length ratio. The relationship for a C.D.S.1 workpiece material is shown in Fig.4.6.
2. A test is performed to determine the relationship between the

undeformed chip thickness and chip curl radius.

3. From the relationship obtained in (2) and the length of the sticking friction zone obtained in (1) and the minimum chip curl radius from equation 4.1. the relationship between $h-h_s$ and $1/(R_o-R_{min})$ is obtained as is shown in Fig.4.20. The slope K can be obtained from the graph.

4. It has been shown above and in Fig.4.21. that the relationship between K and the land length $b_{\gamma r}$, is linear, that is

$$b_{\gamma r} = C.K. \quad (4.4.)$$

where C is a constant and can be obtained from Fig.4.21.

5. From the test described in (1) above, the relationship

$$h_s/b_{\gamma r} = \gamma_1 Z + P_1 \quad (4.5.)$$

is obtained and the constants Z and P_1 evaluated for the speed range selected.

6. Equation 4.2. can be rewritten in terms of R_o and substituting K from equation 4.4. and h_s from equation 4.5. yields

$$R_o = b_{\gamma r} / \left[C \left\{ h - b_{\gamma r} (\gamma_1 Z + P_1) \right\} \right] + W/\sqrt{2} \quad (4.6.)$$

Note the relationship only holds true if the primary rake angle has no effect on chip curvature.

For a particular tool configuration, workpiece material and cutting speed range

$$R_o = b_{\gamma r} / \left[C (h-Q) \right] + R_{min} \quad (4.7.)$$

$$\text{where } Q = b_{\gamma r} (\gamma_1 Z + P_1)$$

4.12. EFFECT OF THE PRIMARY RAKE ANGLE

Although it has been established by the author that the feed at which the chip straightens (h_s) is proportional to the land length, (54), there is less evidence concerning the effect the primary rake angle γ_1 has on h_s and on the subsequent curvature of the chip, when using a tool with a chip forming groove. As mentioned in Section 4.4.1. and shown in Fig.4.3. the P.R.A. has a considerable effect on the length

of the sticking friction zone. In order to determine whether chip curvature was also affected by variation in P.R.A., tests were performed with grooved tools of differing groove widths and primary rake angles varying from $+12^{\circ}$ to -15° . The length of the zone of sticking friction and the minimum chip curl radius were obtained as previously described and the experimental relationship between $h-h_s$ and $1/(R_o-R_{min})$ was obtained and is shown in Fig.4.23. It may be seen that, although there is some scatter, the variation in P.R.A. does not appear to have a significant effect on chip curvature, other than that caused by an alteration in the length of the zone of sticking friction. This means that for a given value of undeformed chip thickness and land length, the chip curl radius reduces as the primary rake angle is made more negative.

4.13. THE EFFECT ON CHIP CURVATURE OF VARIATION IN CUTTING SPEED

The effect of cutting speed on the length of the zone of sticking friction was described in Section 4.4.1. Therefore, for tests previously described the cutting speed was kept constant unless otherwise stated. In order to investigate the effect on chip curvature of variation in cutting speed other than that caused by alterations to the length of the sticking friction zone, a test was performed over a speed range of 2.5 to 20 m/min. The relationship between h and R_o over a small range of feeds is shown in Fig.4.24. If the results are presented as before, that is, taking into account the variation of h_s with cutting speed it may be seen from Fig.4.25. that the equation to the straight line is the same for each speed. This indicates that for this speed range the only effect of speed, for a particular configuration of primary land, is that caused by a change in the value of h_s .

The length of the sticking friction zone for the 2.5 m/min cutting speed was slightly less than for the 5.0 m/min cutting speed indicating that the strain-rate effect predominated; for speeds of 10 and 20 m/min

there was a reduction in the sticking length. The straight line of Fig.4.25. should according to the theory pass through the origin but in fact it intersects the $1/(R_o - R_{min})$ axis at -0.032 mm indicating a very small discrepancy. This could be due to slight errors in the measurement of undeformed chip thickness and chip curl radius, the small range over which readings were taken, or the effect of measuring the chip radius after elastic recovery has taken place.

It should be pointed out that the speed range selected was fairly narrow and was at the low end of the speed range encountered in practical turning operations. At higher speeds it is possible that there will be a greater temperature gradient across the chip creating a greater contraction on the tool side of the chip causing a straightening effect.

4.14. THE EFFECT OF CUTTING WITH A TAPERED LAND

In order to determine the effect, on chip formation and curvature, of cutting with a tapered land, an orthogonal test was performed using a tool having a primary land of zero rake angle but varying in length from 0.15 - 0.6 mm. The cutting speed selected was 2.5 m/min. The chips produced with increasing U.C.T. are shown in Fig.4.26. It may be seen that at the lowest feed the chips were produced with some curvature in the orthogonal plane. With increase in U.C.T. the chip was produced without curvature but further increase in U.C.T. produced a chip with curvature in two planes, that is the chip spiralled. Still further increase in U.C.T. was found to produce chips with decreasing two dimensional curvature until finally the chip was again formed with only a small amount of curvature in the orthogonal plane.

Quickly stopped specimens of the cutting action when the chip was produced in spiral form were obtained and photomicrographs at different positions across the section of the chip are shown in Fig.4.27.

4.14.1. Discussion

An explanation as to the causes of the effect of increase in

undeformed chip thickness on chip curvature described above is as follows.

At very small values of U.C.T. the tool behaves as a plane rake tool, since the length of the sticking contact zone does not exceed the minimum land length. With the primary rake angle of 0° and the small value of U.C.T. the natural curvature induced is quite significant. With increase in U.C.T. the curvature decreases as is the case when cutting with a plane tool. Further U.C.T. increase causes the length of the sticking friction zone to exceed the minimum land length and the part of the chip over which this occurs forms with a built-up-edge and therefore the effective rake angle is 45° . The efficiency of the cutting action and therefore the chip thickness varies considerably between the two parts of the chip. For volume constancy the length of the chip is much greater on one side than the other and therefore the chip spirals. This spiralling gradually diminishes as with further increase in U.C.T. a greater proportion of the chip is being formed with a special b.u.e., until eventually this occurs right across the section of the chip at which point the chip is produced with a slight amount of curvature in only the orthogonal plane. This curvature is probably due to the planes of the built-up-layer and the secondary rake face being non collinear. The lack of two dimensional curvature seems to indicate that even though the land length varies across the width of cut, the cutting efficiency is constant across the width for the cutting conditions used, that is the "ploughing" effect of the special built-up-edge is constant irrespective of land length, providing the length of the sticking friction zone exceeds the maximum land length.

4.15. THE EFFECT OF VARIATION IN THE WIDTH OF CUT

It was anticipated that variation in width cut had no effect on chip curvature as the accompanying increase in force is approximately linear, as is also the increase in bending resistance. This was found

to be the case when machining an En1A workpiece at 2.5 m/min with variation in width of cut from 3 to 8 mm, as is shown in Fig.4.28.

4.16. CONCLUSIONS

1. It has been shown that the value of undeformed chip thickness that causes the length of the zone of sticking friction to equal the land length is the same as that which causes the chip to be formed straight. Alternatively, the value can be taken as the value at which the slope of the undeformed chip thickness-cutting force relationship decreases.
2. When cutting with a restricted contact length tool the special b.u.e. may be formed with a b.u.e. angle exceeding 45° but the rake angle of the b.u.e., γ_u , as shown in Fig.4.9b., cannot exceed 45° , that is, the chip stream angle cannot exceed 45° .
3. The influence of the configuration of the primary land on the length of the sticking friction zone for a single workpiece material is determined. As the primary rake angle is made more negative the length of the sticking friction zone is increased. With land lengths normally encountered in practice, when $h > h_s$, there is often a range of undeformed chip thickness values for which the chip is discontinuous. This range appeared to increase as the primary rake angle is made more negative.
4. For a given workpiece material it is possible, after a short series of tests, to predict the relationship between the chip curl radius and the undeformed chip thickness for any value of primary rake angle, primary land length and groove width, within a prescribed speed range, providing the groove operates.
5. The work that has been described in Chapter 4 is concerned almost exclusively with relatively slow speed machining. However, it was mentioned that at high speeds the special built-up-edge angle decreased. When machining at high speeds and in particular with negative rake angles, it is possible that the chip stream angle is not large enough

to cause the chip to contact the secondary face. In such cases the relationships obtained in Section 4.9. do not apply.

CHAPTER 5

SURFACE INTEGRITY, CUTTING FORCE AND CHIP FORMATION WHEN MACHINING WITH DOUBLE RAKE ANGLE TOOLS

5.1. INTRODUCTION

In a conventional metal cutting operation shear takes place in the primary deformation zone causing the thickness of the formed chip to be greater than the undeformed chip thickness. Further plastic deformation, caused by the friction conditions at the chip-tool interface, occurs in the secondary deformation zone as illustrated in Fig.1.2. and also influences the thickness of the chip. The rake angle, the inclination of the tool face from a normal to the direction of the workpiece-tool relative motion, has considerable influence on both the efficiency of the cutting action and the strength of the cutting edge. The value assigned to the rake angle in conventional cutting is usually a compromise taking into account both strength and efficiency considerations and will vary with different workpiece-tool combinations. The efficiency may be assessed by examination of the chip thickness ratio, that is, the undeformed chip thickness/chip thickness. An increase in this parameter, indicating greater efficiency, will usually occur with increase in rake angle and decrease in friction at the chip-tool interface.

A method of improving the efficiency of the cutting process is to use a double rake angle, or controlled contact length (C.C.L.) tool, which is shown in Fig.1.2. Under most cutting conditions this provides a cutting action approximating to that using a plane tool of rake angle equal to the secondary rake angle. If a negative primary land is used then additional strength is provided at the cutting edge. This is extremely advantageous, with brittle tool materials and difficult to machine workpiece materials, where cutting edge chipping is a problem, and may also be beneficial when machining free cutting materials.

When cutting with the tools described it has been demonstrated in Chapter 4 that, generally, a special plastic field is formed above the tool face. Within this field is a dead metal zone which in appearance resembles a built-up-edge (b.u.e.), and it is suggested that the stability of this special b.u.e. is influenced by temperature as is the normal built-up-edge. A consequence of this is the considerable effect changes in the cutting conditions can have on the surface roughness of the machined surface. Two other effects of this special b.u.e. have been observed for particular cutting conditions. These are the formation of a transverse chip, in addition to the main chip, as may be seen in Fig.5.1a. and an increase in the depth of the plastically deformed layer on the workpiece surface. Also, a variation in the primary rake angle may under some conditions have considerable effect on the cutting forces and therefore on the efficiency of the process, for example, when using low cutting speeds.

The work reported in this Chapter is the result of experimental work when cutting with controlled contact length tools, and the effect of changes in the primary rake angle (P.R.A.) on:

1. The surface roughness of the primary cut surface and machined surface.
2. Cutting forces, and
3. The plastic deformation and depth of the work hardened layer on the machined surface.

is established. It must be stressed that in all cases the tools used had a plane secondary face, that is, there was no chip forming groove.

5.2. PREVIOUS WORK

5.2.1. Cutting with Controlled Contact Length Tools

Some previous work concerning the mechanics of cutting with controlled contact length tools has been described in Chapter 4. Other more recent slip line field solutions have been presented by Childs et

al (69) and tend to agree with earlier slip line solutions proposed by Kudo (70). A more empirical approach was adopted by Dzanashvili (68) who conducted tests involving a variety of land configurations with a view to determining optimum land design in order to inhibit cutting edge chipping.

With the exception of Dzanashvili's work, the work previously performed was at only moderate cutting speeds, and at positive or small negative rake angles. The effect of cutting at extreme speeds and with high negative rake angles with plane cutting tools, was investigated by Findley and Reed (71). They showed that when cutting a lead-antimony alloy the cutting forces passed through a maximum with increase in cutting speed and then decreased approximately exponentially. Also, with decrease in rake angle, cutting forces increased drastically at low cutting speeds. The main criticism of this work is that the results were obtained when cutting an uncommon workpiece material and may not be consistent with more typical workpiece materials.

5.2.2. Surface Integrity

In recent years the term surface integrity has been used (72) to describe the surface topography as well as the surface hardness, the presence of micro cracks, surface stresses etc. During the course of previous experiments by the author with C.C.L. tools it has been observed that the surface texture of the machined surface varied considerably with changes in cutting conditions.

Also, that under some conditions, there appeared to be a highly deformed plastic layer residual on the machined surface. It is therefore appropriate to examine the relevant previous work on surface roughness and the deformation of the machined surface.

5.2.3. Surface Roughness

Generally in turning operations two surfaces are generated simultaneously. These are shown in Fig.5.1b, and 5.2. to be (a) the major

cut surface produced by the action of the major cutting edge, and (b) the machined surface, created by the profiling edge. In some exceptional cases the machined surface may be produced by the primary cutting edge, for example, form turning. The nature and profile of the two surfaces is often quite different.

5.2.3a. Major cut surface

Ideally the major surface will reflect the profile of the major cutting edge but in practice it is also affected by built-up-edge formation. There is much documented evidence (60,61,62) which shows that often in a conventional metal cutting operation a built-up-edge forms on the face of the tool. Parts of this b.u.e. are unstable and are continually being detached to form part of the underside of the chip or the left surface. With brittle workpiece materials a built-up-edge rarely exists but with more ductile materials the size and stability of the built-up-edge has been shown to be temperature dependent. With these materials at very low temperatures the workpiece is usually too brittle for a b.u.e. to form; however with increase in temperature and ductility a built-up-edge is formed and increases in size with further increase in temperature until it reaches a maximum size. With still further temperature increase its size decreases due to a reduction in yield strength, and it is eventually manifest as a very thin built-up-layer. The significant cutting parameters with respect to temperature, will therefore have the most effect on b.u.e. formation. Cutting speed has by far the most influence on cutting temperature, and therefore b.u.e. behaviour with change in cutting speed, has been studied in a number of ways. These include examining the chip formation with the aid of quick-stop techniques, examination of the existence of b.u.e. on the underside of the chip and by measuring the roughness of the left surface. The surface roughness variation with cutting speed is typically as shown in Fig.5.3.

5.2.3b. Surface finish of the machined surface

Sata (73) suggests that surface roughness of surfaces produced under conditions where the b.u.e. has disappeared, is constituted of four parts namely,

- (i) Ideal roughness
- (ii) Vibration term
- (iii) Swelling term
- (iv) Groove wear

(i) The ideal surface roughness is that caused by the tool profile in the tool reference plane and the axial displacement of the tool per revolution or stroke, that is, the feed. Fig.5.4. shows the ideal surface profile when the machined surface is generated by the tool corner radius alone. It is possible, in cases where the corner radius is small or the feed is large, that the cutting edge angle may also have to be taken into account. In finish turning operations the ideal roughness profile is usually only affected by the tool corner radius. When this is so the ideal peak to valley height R_t is given by:

$$\begin{aligned} R_t &= r_\epsilon - y \\ &= r_\epsilon - \sqrt{r_\epsilon^2 - \frac{s^2}{4}} \\ &\approx \frac{s^2}{8r_\epsilon} \text{ mm} \end{aligned}$$

or in terms of C.L.A. value is found to be

$$R_a = \frac{32.1 s^2}{r_\epsilon} \mu\text{m}$$

(ii) The Vibration Term is a function of the dynamic performance of the workpiece-machine tool system and will therefore not be discussed, as cutting conditions during experimental work will be arranged so that forced or induced vibrations are eliminated.

(iii) The swelling effect is sometimes referred to as sidespread. When this occurs some workpiece material is forced out sideways as shown in Fig.5.5a. leaving a cusp on each peak of the machined surface. Sata suggests that as the cutting speed approaches the speed of plastic wave

propagation, sideflow diminishes. Pekelharing and Giezen (74) in a more exhaustive study attempted to establish whether the sideflow was caused by pressure on the flank (below the cutting edge) or by movement of the workpiece material ahead of the cutting edge. This could be supposed, as often the chip width is greater than the undeformed chip width. They concluded that due to the inefficiency of the cutting action, metal is squeezed out sideways above the cutting edge but the cusp thus formed is often extruded by the first wear groove that appears in the minor flank. It was suggested that tips that had been "tumbled", a common manufacturing operation with cemented carbide and ceramic tips which causes cutting edge rounding, may cause sideflow immediately the cut commences, whereas sharp tools cut initially without sideflow. However, in a further paper by Pekelharing and Van Luttervelt (75) it was suggested that although the cutting edge roundness had some effect on "squeezing", sharp tools were found to quickly wear blunt and rounded tools quickly wear sharp so that in both cases a "stabilised" radius was quickly acquired.

Selvam and Radhakrishnam (76) also investigated sideflow and suggested that it decreased with increase in cutting speed. In a further work by them (77) it is suggested that examination of the machined surface indicates that as the tool rake angle is increased from -10° to $+15^{\circ}$ sideflow is reduced. Also that as the chip flow direction becomes closer to the secondary cut surface the sideflow of metal is suppressed, as it is forced into the machined surface.

(iv) The effect of groove wear on surface texture has been investigated by several of the above-mentioned authors and is shown diagrammatically in Fig.5.4b. As the effect on surface roughness of cutting with worn tools is not being considered in the present work it may be just mentioned that the groove wear occurs because of either the extra hardness of the peaks on the machined surface, or because of the greater

movement between the chip and the tool at the extreme edge of the cut. It is also mentioned that where tool wear causes the tool profile to be modified, the machined surface profile is similarly modified.

Sokolowski (78) postulated that there is always a minimum undeformed chip thickness at which cutting will take place. Often this means that part of the uncut chip will always remain; this was called a "spanzipfel" and is shown in Fig. 5.5b. Brammertz (79) assuming the U.C.T. that could not be cut, to be 0.0001 in., modified the proposed ideal surface roughness value according to the new profile and found closer agreement with values of actual surface roughness. Shaw and Crowell (80) comment that even if a "spanzipfel" forms it is likely to be modified in shape by contact with the minor flank. This could also be said of the cusp caused by sideflow, unless it is extruded through a flank groove when groove wear has occurred.

There have been some differences of opinion regarding the cusp that is found on the peaks of the machined surface profile, as the Sokolowski effect and the effect of sideflow provides a cusp on opposite sides of the peak. It is possible that each effect may occur separately under particular cutting conditions or in some cases the "spanzipfel" may itself become part of the sideflow.

5.2.4. Surface Deformation

It has been long known that the chip is strain-hardened due to the shearing action in the primary and secondary deformation zones. There is less evidence, however, concerning the plastic deformation and strain hardening of the machined surface. Camatini (81) has investigated the effect of variations in the cutting conditions on the hardness at a given depth below the surface, and in some cases on the depth of the hardened layer, when cutting both a low carbon and a high carbon steel. It was concluded that in the range investigated the rake angle and the carbon content of the workpiece material were the only parameters of

real significance, although slight variations were observed with change in speed and feed.

An orthogonal model proposed by Haslam and Rubenstein (82) and developed further by Lau and Rubenstein (83), utilises a tool with finite cutting edge radius which causes workpiece material, below some value of depth of cut, to be "ploughed" under the tool nose. This effect is due to the critical rake angle, described in Section 4.6., being exceeded. A tensile stress is set up in the material ahead of the tool nose, causing strain-hardening. It is postulated that further hardening occurs due to frictional deformation as the workpiece is extruded under the tool nose and as it rubs against the flank on recovering elastically. These latter authors concluded that the hardness was a maximum at the surface and decreased, with increase in depth, to the hardness of the unworked specimen. Also that the hardness and depth of the hardened layer increased as undeformed chip thickness increased and rake angle decreased, and may be expected to increase as cutting edge radius and flank wear land increase and as flank clearance angle decreases. Hardness measurement in the above-mentioned work was by micro hardness testing.

Okushima and Kakino (84) used the finite element method to predict surface stresses in a machined surface and measured the stresses using X-ray diffraction techniques. They concluded that in the orthogonal case stresses were always tensile and that they increase as cutting conditions become more adverse. Therefore, to reduce surface stresses it was suggested that cuts should be light and cutting speeds high. In conventional cutting tests, oblique machining, it was discovered that at low speeds the residual stresses were compressive but decrease with increase in cutting speed, eventually becoming tensile. It was concluded that this was due to the effect of the minor cutting edge.

5.3. EXPERIMENTAL PROCEDURE

5.3.1. Cutting Conditions

When examining the behaviour of the b.u.e. an examination of the major cut surface is more appropriate than an examination of the machined surface as it eliminates the disturbing effect of the minor cutting edge, as is shown in Fig.5.2. When machining with double rake angle tools a special built-up-edge is formed which in many respects behaves in a similar manner to the conventional b.u.e. It was therefore considered more appropriate to investigate the major cut surface in order to simplify the assessment of the surface topography and resolve the problem into a two-dimensional case.

5.3.2. Orthogonal Machining Test

As it had been reported (68) that the susceptibility to chatter was much greater with tools having negative lands a preliminary test was performed to obtain the b_{lim} value, the length of the active cutting edge at the onset of chatter, at the greatest negative rake angle and the highest speed and feed. Although b_{lim} is known to increase with speed at high cutting speeds this was thought to provide a first approximation of b_{lim} without performing comprehensive tests. For the conditions described, b_{lim} was found to be approximately 5 mm when using a 350 mm long tube with a fixed steady, and varied only slightly when using a 50 mm long tube without a steady. For the orthogonal machining test the tube thickness was constant at 4 mm.

Profiles of the machined surface were obtained using a Mark 4 Talysurf, the maximum height obtainable under the stylus, 350 mm, determining the maximum length of the tube used. When cutting with a tube from 50 - 350 mm long, a three point fixed steady was used.

When orthogonal machining the terms undeformed chip thickness and feed are synonymous. As explained previously, at feeds which provide a sticking length equal to or less than the land length, the tool performs

as a plane rake tool. Therefore as the sticking length decreases with increase in rake angle and cutting speed, it was necessary to obtain the feed which provides a sticking length of 0.75 mm for the smallest negative P.R.A. at the maximum cutting speed for one workpiece material. The material used was a low carbon steel to C.D.S.1. The method of determining this feed has been described in detail in Section 4.4.1. Two feeds in excess of this were chosen namely 0.25 and 0.4 mm/rev., which means that under all conditions tested, the length of the sticking friction zone exceeds the land length. The carbide tips were lapped at the cutting edge to provide a land angle of -7° ; -30° ; -45° and -60° to the face. The tips were then presented in the toolholder at a positive rake of 7° thus providing primary rake angles of 0° , -23° , -38° and -53° , the land lengths being held constant at 0.75 mm.

Previous tests using high speed steel tools had indicated that the b.u.e. was a maximum with a feed of 0.4 mm/rev. and a speed of 12m/min. However, as it was the speed at which the built-up-edge stabilised that was under consideration, it was decided that a speed range from 16-160m/min. in the form of a geometric progression would be appropriate.

5.3.3. Oblique Machining Test

In a practical machining operation it is the surface roughness of the left or machined surface, and not the primary cut surface that is important. Therefore oblique machining tests were performed where the roughness of the left surface was assessed.

Cutting conditions were chosen such that the contact face of the tool was only with the primary face, as shown in Fig.5.2. The surface roughness is only of concern when finish machining, and as the "ideal" centre line average (C.L.A.) value using a round nose tool is given by:

$$R_a - \mu m = \frac{32.1 s^2}{r_e} \quad (5.1.)$$

where s is the feed/rev-mm and r_e is the tool corner radius - mm, it can be seen that the feeds used for finish turning will be relatively

small, therefore the maximum value chosen for the tests was 0.4 mm/rev.

The workpiece material was a medium carbon steel to B.S.S. En 8 in the form of 75 mm diameter round bar 300 mm long. Cutting speeds of 16, 31, 62.5, 130 and 160 m/min. were found to provide sufficient results.

A tool run-in distance was allowed as it has been suggested (85) that some variation in surface roughness occurs during the beginning of the cut. This was constant at a cutting distance of 40 m.

Examination of equation (5.1.) indicates the importance of maintaining r_c constant throughout the tests. Provisional tests indicated that each tool could be used to complete one set of feed tests without tool wear significantly affecting the surface roughness. As the manufacturer's tolerance on r_c is ± 0.1 mm the corner radius of each tip was measured using the projection microscope and the most accurate tips were selected; the maximum variation in r_c being less than 0.05 mm, that is approximately 5 per cent.

A further series of tests were performed with varying land lengths with both -53° and -23° P.R.A. tools, the length of the land being varied from 0.2 to 0.8 mm. For these tests the same tool was used in order to eliminate any variation due to corner radius, the land being progressively increased for each test by lapping. These last tests were performed at a single speed and feed, in each case the feed being high enough to cause the length of the sticking friction zone to be greater than the land length and the cutting speed being greater than the minimum speed at which the built-up-edge stabilised.

5.3.4. Assessment of Surface Texture

When cutting under conditions that cause an unstable built-up-edge to form, fragments of the b.u.e. are periodically detached and become embedded in the workpiece surface. The pitch of these irregularities varies with cutting conditions but is generally one order higher than the irregularities of the primary surface texture of the machined surface

in the direction normal to the lay; this is usually the value of the machine feed. When assessing the left surface on the tube it is therefore inappropriate to use the centre line average method at standard cut-off lengths, as with this method it is normal practice to use cut-off lengths of at least two or three times the pitch of the primary irregularities. As most instruments operate with a length of stroke of approximately six times the cut-off length this would be beyond the range of the instruments. With the surfaces tested the pitch of these irregularities was generally 0.5 to 1.0 mm.

The procedure adopted for the numerical assessment of surface roughness was to obtain a Talysurf trace at twenty times horizontal magnification at a sampling length of 11 mm, providing a trace 220 mm long. The centre 200 mm was divided into 50 mm lengths and the mean total height, R_{tm} , obtained as shown in Fig.5.6. Two traces were taken of each surface and the mean of the two values obtained. The vertical magnification used varied from 500 to 2,000 and the stylus radius was 2.5 μ m.

The machined surface roughness was taken as the mean of four Talysurf readings taken at 90° intervals with a 0.8 mm cut-off. Talysurf traces at 100 times horizontal magnification provided a visual record of the surface. Further visual examination was performed using the scanning electron microscope, the light sectioning microscope and using a conventional metallurgical microscope to view a section of the surface profile prepared using the edge retention technique described in Section 5.3.5.

5.3.5. Examination of the Plastically Deformed Layer on the Workpiece Surface

When preparing a metal specimen for microscopic examination the technique adopted is to remove damaged layers of metal by using a series of successively finer abrasives. This should result in a plane surface

free from flowed material and abrasive scratches.

With standard techniques the edge of the specimen often becomes rounded. If the specimen has been mounted - usually in a thermo setting phenolic resin, for example, bakelite - edge rounding still occurs due to the mounting medium wearing away more rapidly than the specimen.

The depth of the surface microstructural alterations due to machining may only be of the order of $50\mu\text{m}$ or less and hence a study of this zone requires an edge retention technique better than that obtained in normal practice. This is usually achieved by mounting the specimen in a hard wear resisting material (72) or by electroplating the specimen in order to protect the edge. This is then followed by grinding and polishing in the shortest possible time.

In order to determine a convenient but acceptable method of edge preparation, tests were performed using five different mounting media. Each specimen was ground on a flat plate grinding wheel to 400 grit and was rough polished, using a napless cloth and a six micron diamond abrasive, and fine polished using a napped cloth and a one micron diamond abrasive, both manually (unidirectionally) and mechanically (multi-directionally).

Examination of the edge to check for flatness was performed on an interference microscope using a mercury vapour light with green filter. The difference in height between successive fringes is one half wave length of the light source. The number of band deflections at the edge therefore gives a measure of edge rounding, also the point at which the interference fringes become non linear indicates where rounding of the edge commences.

The table shown in Fig.5.7. details the various mounting techniques and Fig.5.8a, b and c shows the best edge of each specimen. It was found that when unidirectionally polishing the amount of rounding on each edge varied considerably, the best edge being that normal to and

facing the approaching direction of polish. The method finally adopted was to mount in a glass fibre compound, diallyl phthalate, and manually polish to provide one good edge, that is the edge of the machined surface.

The depth of the plastically deformed layer was ascertained by microscopic examination of the etched specimen and further evidence was obtained by micro hardness testing with a 5g load, using a Vickers 55 projection microscope. Indentations were made at intervals of $8\mu\text{m}$ to within $8\mu\text{m}$ of the edge over a distance of $88\mu\text{m}$. Three adjacent series of readings were made and the specimen was then lightly etched to check if any abnormal hardness values could be accounted for by indenting of pearlite areas. The mean values of the three readings were obtained and the relationship between mean hardness value and distance from edge, together with a photograph of the etched microstructure is shown in Fig.5.9. It may be seen that there is close agreement between the visual evidence of plastic deformation and the point on the graph at which the hardness value becomes constant.

5.3.6. Examination of the Special Built-up-Edge

On occasions where the special built-up-edge configuration has been examined the specimens were obtained using the quick-stop device, described in Section 2.6. on the Lodge and Shipley lathe.

5.4. EXPERIMENTAL RESULTS AND DISCUSSION

The variation of cutting and feed forces with cutting speed when using tools of differing rake face configurations is shown in Fig.5.10. Although, in general, both these forces reduce with increase in cutting speed this is not the case for the -53° and in some cases the -38° primary rake angle tools. It can also be seen that the force increases almost exponentially with decrease in primary rake angle, that is, little increase from 0° to -23° , but a considerable increase from -23° to -53° .

Fig.5.11. shows the variation in surface roughness with cutting speed when orthogonally machining with tools of differing primary rake

angles. It may be seen that at low speeds the surface texture is poor. This is because the special built-up-edge is very unstable and fragments of it are continually becoming detached to form part of the workpiece surface. However, as the temperature is increased by increasing the cutting speed the surface finish rapidly improves. As the primary rake angle is made more negative the special built-up-edge stabilises at a lower cutting speed, as is evidenced by the rapid reduction in the surface roughness value.

Fig.5.12. indicates the relationship between the depth of the plastically deformed layer, the cutting speed and the primary rake angle. It can be seen that the depth of the layer is increased as the primary rake angle is made more negative, the depth is seen to pass through a minimum with increase in cutting speed and then increases with further increase in speed.

Examination of micrographs of the quickly-stopped cutting action as shown in Fig.4.18. indicate that a dead metal zone is formed on the tool land. This dead metal zone behaves in some respects in a similar manner to a conventional built-up-edge, in that it stabilises at high temperatures - high cutting speed, large negative primary rake angle - but unlike the conventional built-up-edge it does not disappear completely. The shape of the dead metal zone causes it to appear to be an extension of the cutting tool but with a rounded cutting edge, the size decreasing and the edge rounding increasing with temperature.

The configuration of the land and variation in cutting conditions have considerable effect on the shape of the secondary deformation zone ahead of the dead metal zone, but this has not been thoroughly investigated as it is considered beyond the range of the present investigation. It may be said, however, that as the primary rake angle is decreased the rounding of the dead metal zone becomes more pronounced and the size of the secondary deformation zone increases. This is seen

to occur at cutting speeds of both 2.5 and 32 m/min. as shown in Figs. 4.9b. and 5.13. respectively. Thus the process is less efficient and more heat is generated causing the dead metal zone to stabilise at a lower cutting speed. At the same time this causes the depth of the plastically deformed zone on the workpiece surface to be increased as mentioned above.

The shape of the dead metal zone is also affected by the land length as has been described in Section 4.8. That is, to a greater extent than that caused by the effective increase in undeformed chip thickness. The transition range of U.C.T. also appears to increase with land length. These effects are shown in Fig.5.14.a and b which illustrates the effect of land length on the shape of the dead metal zone at increasing values of undeformed chip thickness. The values of U.C.T. at which the length of the sticking friction zone equals the land length for the tools used was found from Fig.4.6. to be 0.045 and 0.09 mm respectively.

At high negative rake angles and high cutting speeds, the plasticity conditions in the secondary deformation zone are no longer those of plane strain. The deformation in the X-Y plane becomes manifest as either sidespread on the chip or workpiece, or as a transverse chip as illustrated in Fig.5.1b. It was also noted that under these conditions chatter was induced.

The variation of surface roughness with cutting speed when machining obliquely with both plane and controlled contact length tools is as shown in Fig.5.15. It can be seen that with increase in cutting speed the ideal surface roughness value is again approached more rapidly when cutting with a tool having a negative primary land than when cutting with a plane tool. This indicates that the phenomenon described above also occurs during oblique machining. It is further validated by the results shown in Fig.5.16. which indicate how the surface roughness is affected

by changes in land length and primary rake angle and Fig.5.17.a and b which shows Talysurf traces, photomicrographs of a section of the surface profile, and also light sectioning microscope and scanning electron microscope photographs of the surface. It is apparent that when the land length exceeds 0.2 mm the sidespread that occurs when using the -53° primary rake angle tool is manifest as an exaggeration of the cusp at the point at which the active cutting edge loses contact with the machined surface.

Also of interest is the improvement in surface finish when cutting with a -23° primary rake angle tool with increase in land length, as this may prove to be a further advantage of using tools with negative lands. It seems probable that the "smoothing" of the cusp on the machined surface profile is due to the cusp inhibiting the flow of the transverse chip, in the X-Z plane, towards the workpiece surface.

When cutting with tools with rake angles other than zero the ideal surface profile is modified due to the foreshortening of the depth of cut, see Appendix F. With the worst case, the -53° P.R.A. tool, the reduction in peak to valley height was found to be 0.04 per cent for the conditions used, and so was neglected. The modification of tool corner radius due to the flank angle of 7° causing the tool profile to be a conic section was also neglected.

5.5. CONCLUSIONS

1. Tools with negative primary lands will perform almost as efficiently as plane tools up to a particular value of negative primary rake angle and above a particular feed. The value for a particular workpiece material can be obtained as described in the text.
2. The value assigned to the primary rake angle should not exceed a particular value of negative rake, the value depending upon the workpiece material, as the following effects are induced.

(a) Considerable increase in cutting forces.

(b) Increase in cutting temperature, as observed from the colour of the chip.

(c) There is a decrease in the limiting chip width at which chatter occurs.

3. When cutting with tools with negative lands under conditions that cause the special built-up-edge to form, the special b.u.e. stabilises at a lower cutting speed than that at which the conventional built-up-edge disappears, when cutting under otherwise identical conditions.

Cutting below this speed results in high cutting forces and very poor surface finish.

4. When obliquely machining using tools with negative lands it is possible to produce surfaces having roughness values better (smaller) than the ideal C.L.A. value. The surface roughness is also affected by the length of the primary land.

5. The work hardening of the machined surface increases in depth as the primary rake angle is made more negative. Observation of the strain of the work hardened layer suggests that the stress state is primarily tensile in the direction of workpiece tool relative motion. This is in agreement with the findings of Connolly and Rubenstein (86).

CHAPTER 6

THE OPERATION AND PERFORMANCE OF A GROOVE TYPE

CHIP FORMING DEVICE

6.1. INTRODUCTION

It has been shown in Chapter 4 that when cutting at low speeds with tools having primary lands, chip formation will proceed with formation of a special built-up-edge if the length of the zone of sticking friction exceeds the land length. When cutting at slow speeds, if the chip is unobstructed by the secondary face, the special built-up-edge will form so that the plane of its uppermost surface makes an angle of 45° to the direction of workpiece-tool relative motion. The direction of chip flow is relative to the b.u.e. and therefore the chip stream angle will also be 45° . If the secondary face is provided with a groove, the chip will be directed into the groove and, provided that the groove does not obstruct the chip, the chip will flow round the groove until it exits at the groove heel. Whilst this is occurring the configuration of the built-up-edge changes as the direction of chip flow is constantly changing. However, as the chip exits from the groove, the b.u.e. reaches a stable configuration which it is suggested is determined by the resultant bending moment on the chip.

At higher, more practical cutting speeds in addition to an increase in rounding of the built-up-edge, the built-up-edge angle is also reduced due to the increase in temperature, as is a conventional b.u.e. This causes the maximum chip stream angle to be modified. The built-up-edge also reduces in size with increase in land length; this is again likely to cause a reduction in the maximum chip stream angle. Photomicrographs of the quickly stopped cutting action illustrating these effects are shown in Figs. 4.18. and 5.14.a and b. It has been demonstrated in Section 4.8. that the rate of increase of built-up-edge angle with increase in undeformed chip thickness decreases as land length is

increased. Also, there is always a small range of feed over which transition from plane face, to restricted contact length cutting takes place. An example showing a photograph of the quickly stopped cutting action in the transition range of undeformed chip thickness is shown in Fig.4.9a. It seems likely therefore that the value of U.C.T. which causes the groove to operate may need to be well in excess of that which causes the length of the sticking friction zone to equal the land length. The magnitude of this value depends upon workpiece material and cutting conditions but it is suggested a typical value is an approximate 20 per cent increase in undeformed chip thickness value for small land lengths, but increases as land length increases. If this value of U.C.T. is exceeded for the land length of the tool used, the groove is said to be operating. When operating there is a particular relationship between the groove width and the undeformed chip thickness which may be determined as described in Section 4.9.

It is worth noting that an increase in the height of the secondary face relative to the cutting edge has the same effect as reducing the groove width, and this is illustrated in Fig.6.1a.

6.2. THE CHIP BENDING ACTION

Attempts have been made (87) to analyse the chip formation when using an obstruction type chip former as pure plastic bending but this does not fully represent the complex bending action. For although the chip is fully plastic in the primary shear zone, account has to be taken that part of the chip is also fully plastic for some distance along the tool face. This means that the chip, or part of the chip, is being bent plastically over a period of time, that is dynamic bending. The present state of knowledge does not allow the solution of this problem, although an attempt was made by Okushima (30) by matching empirical and theoretical results.

When the chip is in the equilibrium position as shown in Fig.6.1b.

it is being supported by the reaction force R_L at the land and R_R at the chip former heel. The equilibrium force which is the resultant cutting force creates a bending moment on the chip. It is suggested that the magnitude of the equilibrium moment and the groove width determine the profile of the uppermost surface of the b.u.e. and the chip is thus formed curled.

6.2.1. The Effect of the Significant Parameters

It has been shown in Chapter 4, that for a particular workpiece material and cutting speed range the radius of the formed chip is affected by groove width, undeformed chip thickness, land length and primary rake angle.

6.2.1.(a). Groove width

As groove width increases, for otherwise identical conditions, chip curl radius increases.

When cutting with a controlled contact length tool it has been shown that when the 'sticking length' exceeds the land length the built-up-edge will form at 45° provided that the chip flow is unobstructed and that the built-up-edge is not modified by temperature. If cutting with a chip forming groove the built-up-edge is modified by the reaction at the groove heel. It has been shown that the chip curl radius is determined by the rake angle of the built-up-edge and the groove width, that is,

$$R_1 = W/2 \sin \gamma_u$$

and
$$R_o \approx W/2 \sin \gamma_u$$

Assuming the simplified bending moment diagram in Fig.6.1b. to be applicable then as the groove width increases the reaction at the heel decreases but the bending moment at F_v increases slightly, due to increase in W . This causes a small increase in the rake angle of the built-up-edge as is shown in Fig.6.2. The value of rake angle of the built-up-edge is the same as the chip stream angle and was calculated

from experimental values of R_o obtained when using grooves of different widths. Slight variations in the land lengths of the tools used may introduce small errors in Fig.6.2.

Despite this increase in chip stream angle, the chip curl radius still increases due to W increasing at a greater rate than $\sin \gamma_u$. This reasoning assumes that the effect of variation of groove width on the direction, magnitude and point of application of the cutting force will be small.

6.2.1.(b). Undeformed Chip Thickness

For a constant groove configuration, as undeformed chip thickness is increased chip curl radius decreases. Both the magnitude and position of the resultant cutting force change to cause an increase in the reactions at the tool, which increase the bending moment.

6.2.1.(c). Land Length

A decrease in land length, for otherwise constant conditions, causes a decrease in the chip curl radius.

It is again suggested that the change in position of the cutting force relative to the reaction at the land, R_L , causes the bending moment to increase. This has already been elaborated in Section 4.10. However, the point may be presented in a different manner. If the groove width is kept constant, provided the ratio of the undeformed chip thickness to cause the sticking length to equal the land length, to the land length, Z_o , is constant, the chip curl radius will be constant for all U.C.T. values above that at which the groove starts to operate. From equation 4.2.

$$h = K/(R_o - R_{min}) + h_s$$

as the land length varies, as has been demonstrated, K and h_s vary, therefore for constant $R_o - R_{min}$, h varies.

To illustrate this point Fig.6.3. shows the experimental relationship between the undeformed chip thickness and the chip curl radius for

tools of 0.51 and 0.25 mm land length having identical grooves. If it is assumed that the length of the sticking friction zone is proportional to the U.C.T., as has been previously established (54), since the land lengths are in the ratio 2:1 the values of h_s and K will vary in this ratio. Therefore the values of h to provide the same chip curl radius must also vary in the same ratio.

Values of curve 2 with undeformed chip thickness values doubled are shown to coincide with curve 1, showing close agreement with the experimental results.

6.2.1.(d). The effect of primary rake angle

It has been suggested in Section 4.8. that changes in primary rake angle only affect chip curvature inasmuch as they affect the value of undeformed chip thickness at which the length of the sticking friction zone equals the land length, h_s . Thus the relationship between $h - h_s$ and $1/(R_o - R_{min})$ shown in Fig.4.23. is unaffected by primary rake angle. The following explanation is proposed:

As primary rake angle is made more negative, for a given value of undeformed chip thickness and land length, the thrust force increases considerably but the increase in the component that causes bending, the cutting force, is much less. However, the point of application of this force is further from the front of the groove as is shown in Fig.6.1b. This causes the bending moment on the chip to increase and therefore the chip curl radius is reduced. However the value of h_s also decreases as the primary rake angle is more negative. That is, consider the chip curl radius produced when cutting with a tool of particular groove, and land configuration. Suppose the test to be repeated at the same value of undeformed chip thickness, but with a tool of more negative P.R.A., h_s will be smaller. Therefore, $h - h_s$ is increased and for the relationship between $h - h_s$ and $1/(R_o - R_{min})$ to be unchanged R_o is decreased. It is suggested that R_o is smaller because effectively, h , is increased by an

amount equal to the difference between the actual and projected land lengths.

Considering tools having 0° and -30° P.R.A. lands 1 mm long, according to Fig.4.6. the h_s values are 0.24 mm and 0.13 mm respectively, that is, a difference of 0.11 mm. The projected length of the -30° P.R.A. tool is:

$$\text{land length} \times \cos 30^\circ = 0.866 \text{ mm}$$

providing a difference of 0.134 mm, that is, very close agreement over the same range of primary rake angle as that shown in Fig.4.23. As mentioned previously in the range of P.R.A. quoted the increase in cutting force as the primary rake angle is made more negative is fairly small but does account for some of the scatter in the figure. However, under conditions where the change in cutting force is significant the chip curl radius is likely to be affected.

6.3. EXPERIMENTAL WORK ON CHIP FORMING AT HIGH CUTTING SPEEDS

Conventional cine photography at 16 frames/s had been used to observe the chip formation at low cutting speeds, up to 0.75 m/min. If a chip thickness ratio of 0.5 is assumed this results in a maximum movement of the chip of 0.4 mm. When observing the chip formation at high cutting speeds, 120 m/min, a similar amount of chip movement was thought to be appropriate. This necessitated the use of a high speed camera, which was found to give satisfactory results at a frame speed of 750 frames/s. The camera was situated at the rear of the lathe with the lens and groove axis collinear. The workpiece was in the form of a tube in order to provide an unobstructed view. Two photoflood lamps provided the illumination and a silhouette effect was obtained by using a white back-cloth to the tool and an aperture setting of f 3.5. The profile of both the tool, and the chip whilst in the vicinity of the tool, was quite clear and suitable magnification was obtained by using a telephoto lens and extension tubes. Although it was intended to accurately determine

the amount of elastic recovery from measurements taken from the projected film, the accuracy obtainable was only sufficient for a first approximation. However, a good estimation of the chip stream angle could be made and the clearance between the underside of the chip and the bottom of the groove was always visible. The grooves used for the filming tests were designed to provide an inlet angle of 45° . The mode of chip breaking was also observed and was found in general to be as that described in Section 3.5. for obstruction type formers.

A further series of tests were performed on the lathe using 6 in. diameter En 1B bar at a single cutting speed of 120 m/min. The tips were clamped, with the combined chip former-clamp in the rear position, in a "Sandvik" toolholder. This provided a cutting edge angle of $+75^{\circ}$ in order to cause the chip to miss the workpiece shoulder, and a positive normal rake of 7° . The toolholder was in turn clamped to a "Kistler" three component force measuring platform, as shown in Fig.2.11. The P30 grade tips were spark eroded to provide groove configurations as shown in Fig.6.4. and the land lengths were controlled by lapping the flank.

An oblique machining test was performed with each groove configuration and with two land lengths, 0.20 mm and 0.35 mm and four primary rake angles, $+7^{\circ}$, 0° , -15° and -30° , comprising 24 tests in all. Each test was conducted over a range of feeds and the chip formation was observed for evidence of transverse chip, built-up-edge and sidespread, as well as the type of chip produced; cutting forces and chip curl radius were also measured. In each case it was noted if the chip contacted the obstruction.

Values of undeformed chip thickness were calculated knowing the feed and the tool inclination angle. At high cutting speed the only way in which the original chip curl radius within the groove could be measured, was by high speed photography. As the number of tests performed was high it was decided, that provided the variation in elastic recovery was not

forgotten a close approximation of R_1 could be obtained by measuring the formed or broken chips.

6.4. ANALYSIS OF RESULTS

6.4.1. Cutting Force

Fig.6.5. shows the typical variation in cutting force with undeformed chip thickness. It may be seen that the cutting force-undeformed chip thickness relationship with the grooved tools when cutting at high speeds varies in a similar manner to that shown in Fig.4.5. and described in Section 4.4.1. for slow speed machining. It may also be seen that there is a general increase in cutting force as the primary rake angle is made more negative. A more significant increase in cutting force occurs with increase in the length of the primary land. It may be seen from Fig.6.5. that groove width may have a slight effect on cutting forces.

These trends are as expected, as at values of undeformed chip thickness in excess of that required to cause the length of the sticking friction zone to equal the land length, the special built-up-edge provides a positive rake angle and so in effect the tool changes from a negative to a positive rake tool. This is also illustrated visually by an examination of the swarf produced with increase in undeformed chip thickness, from values below the transition point to values above it. Fig.6.6a and b show how the chip is initially blue in colour and gradually changes to brown and straw and finally the natural colour of the workpiece. This indicates a higher temperature when cutting with the negative land, despite the reduction in undeformed chip thickness. With a plane tool, cutting temperature increases with undeformed chip thickness.

6.4.2. Feed Force

As may be seen from Fig.6.7. the feed force increases very slightly with increase in undeformed chip thickness up to a particular value, after which further increase is at a much higher rate. This is primarily a result of the increase in the rounding of the special built-up-edge, as

described in Section 4.6., caused by an increase in temperature due to increase in feed. This is further illustrated in Fig.6.8. where it is also shown that an increase in the ploughing force rotates the direction of the resultant cutting force in a clockwise direction and causes an increase in the feed force. A secondary effect is that at higher feeds the chip curl radius was reduced so that the chip did not clear the work-piece shoulder, and therefore spiralled. This in turn caused an increase in feed force which was shown from the force trace to be cyclic in nature, tending to promote chatter. It may also be seen that the feed force increases considerably with increase in primary rake angle. It is suggested that this is due to the increased ploughing caused by an increase in the radius of the built-up-edge as described in Section 5.4. and shown in Fig.5.13.

6.4.3. Sidespread, Built-up-edge and Transverse Chip Formation

During each test the chip formation was closely observed with respect to the occurrence of the formation of a transverse chip, and the existence of built-up-edge or sideflow on the chip or machined work-piece surface.

The following pattern was observed:

At values of undeformed chip thickness below the transition point there was some evidence of transverse chip and sidespread with the -15° P.R.A. tools but this was more pronounced with the -30° P.R.A. tools. At values of undeformed chip thickness above the transition point there was little evidence of sidespread in any of the tests but there was increasing evidence of transverse chip formation with increase in U.C.T. and with decrease in primary rake angle. At very small values of undeformed chip thickness there was some evidence of built-up-edge formation.

This is in accord with previous results on surface finish reported in Section 5.4. and with the suggested mechanism of chip formation outlined in Section 4.7. The dead metal zone although stable in the Y-Z

plane, or the plane of the major cutting edge when obliquely machining, is unstable in the X-Z plane. As its size increases with U.C.T. then more material becomes available to form the transverse chip; cutting with a more negative rake angle has a similar effect. It is therefore suggested that the transverse chip is the special built-up-edge being squeezed out in the X direction. In order to confirm this a transverse chip was mounted in 'Perspex' and a photomicrograph of its cross section is shown in Fig.6.9. It can be seen that the microstructure of its cross section is the same as that of the special built-up-edge, as illustrated, for example in Fig.4.9a and b.

As there was little evidence of sidespread when the groove was operating, this indicates that at the speed employed the dead metal zone performed as a reasonably efficient extension to the cutting tool at primary rake angles down to -30° with relative little ploughing. This was also the case when cutting the En 8 steel in the surface finish tests. At higher negative rake angles, the radius of the dead metal zone reaches such proportions as to cause a considerable amount of ploughing and consequently sidespread. As mentioned in Chapter 5 in some cases when cutting under conditions which cause the formation of a transverse chip the surface finish may be better than the 'ideal' due to the "smoothing" of the cusp by the action of the transverse chip.

The occurrence of built-up-edge at low values of undeformed chip thickness is due to the reduction in temperature causing the conventional built-up-edge, formed when the tool is performing as a plane tool, to become unstable.

6.4.4. Chip Curl Radius

As mentioned previously the curvature of the broken chip was used as the measured parameter. In order to test that the mechanism was the same as that proposed for slow cutting speeds the curve representing the relationship between $h - h_s$ and $R_o - R_{min}$ has also to be shown to be a

rectangular hyperbola. Theoretically, the value of h_s is constant for a constant land configuration; in practice the values obtained from the discontinuity in the force traces varied slightly, as may be seen from Fig.6.4. It is suggested that this is due to the manufacturing tolerance required for the production of the tools. The value of h_s used for each land configuration was the mean of the values obtained for the four tools used in each series.

As mentioned in Section 6.1. at high cutting speeds the maximum chip stream angle is always less than 45° , the actual magnitude being a function of cutting speed, workpiece material and land length. From previous observations of quick stop specimens obtained at various speeds, feeds and land configurations the maximum chip stream angle was estimated to be 30° and as the land length was only varied from 0.35 to 0.20 mm this was assumed to be the same for all tests. Using this value R_{min} was calculated for each groove width from

$$R_{min} = W/(2 \sin \gamma_u) \quad (6.1.)$$

Fig.6.10a,b,c,d and Fig.6.11a,b,c,d show the relationships obtained for each land configuration. It was thought more meaningful to present the results in this way and then transfer the results to the straight line form of Fig.6.12. from the mean curve representing the experimental results, since when $1/(R_o - R_{min})$ is used directly, a small error in R_o as R_o approaches R_{min} can introduce a considerable error in $1/(R_o - R_{min})$.

A number of factors emerge from analysis of these experimental relationships. In general the relationship for tools of constant land configuration but different groove widths was the same as can be seen from Figure 6. 12, the biggest variation being with the tool having the largest groove width, being used at the smallest undeformed chip thickness values. It is suggested that this is caused by the elastic recovery being greater with the chips having a large chip curl radius. The curves in Fig.6.10 and 6.11. become asymptotic to a line parallel to

the $h - h_s$ axis slightly above zero but allowing for some elastic recovery, this indicates that the maximum chip stream angle was approximately constant at 30° , for grooves of different width.

The slopes of the relationships shown in Fig.6.12 are found to be linearly related to land length passing through the origin as is shown in Fig.6.13. This indicates that the relationships developed in Section 4.9. illustrating the effect of land length on chip curl radius at slow cutting speeds may also be applied to high speed machining.

As a further check on the maximum chip stream angle, an estimate was obtained by performing tests with tools as shown in Fig.6.4., that is, with inlet angles of 35, 30, 25 and 20 degrees. Each tool was used over a range of high feed values and the relationship between the undeformed chip thickness and the chip curl radius was obtained in order to determine the inlet angle at which the groove interfered with the chip. With each tool the chip curl radius was found to become constant at feeds in excess of a particular value and the groove profile scored with the exception of the tool with 35° inlet angle. This was hardly scored at the bottom of the groove and at feeds up to 0.5 mm did not produce chips of constant radius. This seems to verify that the maximum chip stream angle was between 30 and 35 degrees.

The effectiveness of the chip breaking was observed to be inconsistent on some occasions. The visual evidence supports the view held by Spaans (17) that the chip formation is sometimes influenced by the manner in which the first chip forms, whilst the feed is increasing from zero to its steady state value, and this is not always predictable.

6.5. TOOL WEAR

In general, with common tool and workpiece materials, the tool is worn on either or both the clearance face, flank wear, or the rake face, cratering. In some cases, however, failure is caused by cutting edge

chipping and there is evidence to suggest that tools with negative primary lands will provide longer tool lives than plane face tools under conditions where cutting edge chipping is the mode of failure (88). In cases where flank wear is predominant it has been found (51) that tool life increases with controlled contact length tools but reduces as the primary rake angle is made more negative. It might be expected that:

- (a) the special built-up-edge protects the rake face, or
- (b) tool wear is accelerated due to a less efficient cutting action causing higher temperatures at the chip-tool interface.

It is the author's view, that when cutting common workpiece materials, the main application of tools with negative lands is likely to be on tools with chip forming grooves, the groove providing a much greater effective rake angle. When considering the application of negative primary lands to plane tools, it is useful to have some information on the tool life of such tools compared with tools without lands. Mayer et al (88) conducted tests at much higher cutting speeds than the authors previously quoted (51). It was concluded that tool life for non interrupted cutting when using chamfered tools decreases as the chamfer angle is made more negative and also as the land length is increased, presumably up to the point at which the land length equals the natural contact length.

Tool life tests were performed on an En 16T workpiece material using P 30 plane $+7^\circ$ rake inserts. The cutting edge angle was 75° , the depth of cut 2.5 mm and the feed constant at 0.25 mm/rev. The relationship between tool wear and cutting time was obtained at four cutting speeds from 100 - 240 m/min. Values of tool life at failure, using a failure criterion of an average flank wear of 0.3 mm, were obtained.

The relationship was found to be closely represented by the Taylor tool life equation $VT^{-1/k} = C$ and from the graph of $\log T$ versus $\log V$ the tool life constants C and K were obtained. The above procedure was repeated for tools with a -30° primary rake angle with land lengths of

0.25 and 0.75 mm respectively.

Tool life tests were also conducted with grooved tools. For all the tool life tests the feeds selected were in excess of that required to provide a length of the sticking friction zone to equal the land length. A single tool life test was also conducted using an obstruction type former.

There is little published work on the wear performance of groove type chip formers but it has been suggested (39) that the chip breaking performance of a groove type chip former improves with tool wear. This is obviously due to the length of the land being reduced, causing a decrease in chip curl radius. It is considered more meaningful to present the tool life relationships graphically rather than just present values of the tool life constants C and K.

6.5.1. Manifestation of Wear

Tool wear with the plane tools was on the flank. With the tools having a negative land and plane secondary face there was both flank wear and cratering of the secondary face, the flank wear dominating. With the grooved tools there was wear at the groove entrance in addition to flank wear. There was also slight wear at the groove exit.

6.5.2. Analysis of Tool Life Test Results

It may be seen from Fig.6.14. that the tool lives with the 0.25 mm and 0.75 mm land length tools were almost identical. Fig.6.14. also shows that the chamfered tools have a poorer wear performance particularly at high cutting speeds. Using an obstruction, the tool life was better at low cutting speeds but as the speed was increased the performance became approximately the same as that of the plane tool.

Of the two grooved tools it can be seen that the tool life was longer with the more positive primary rake angle, the -30° P.R.A. tool having the poorest wear performance of all the tools. The $+7^{\circ}$ P.R.A. grooved tool had the best performance up to a cutting speed of approximately

200 m/min but was worse than the plane tool, with and without an obstruction, at higher speeds.

The range of land configurations was not comprehensive as it was only considered necessary to determine the general trend, and this must be taken into account when formulating conclusions. However, it does appear that the effect of edge rounding of the special built-up-edge due to temperature, and causing in turn a general temperature increase, is the most likely explanation of the more rapid increase in tool wear with cutting speed, when using grooved tools. The increase in wear at the groove inlet compared with the exit is likely to be because of the higher temperature in this region.

6.6. DESIGN OF CHIP GROOVES

The basic groove parameters determining the chip curl radius are:

- (a) The configuration of the primary land, that is, land length and primary rake angle, and
- (b) groove configuration. It has already been shown that groove width is of prime importance; groove depth and contour, for example radius, are also considered.

6.6.1. The Configuration of the Primary Land

The land configuration determines the feed range over which the groove will operate, because at feeds below that which causes the length of the zone of sticking friction to equal the land length the tool behaves as a plane tool. At the same time it has been shown that the magnitude of this feed is related to the size of the primary rake angle. As the primary rake angle is made more negative, if the mode of tool failure is by flank wear, then tool life is reduced. However the value of feed at which the groove begins to operate is lower.

Another advantage of cutting with negative primary rake angles is that tool life may be increased in cases where cutting edge chipping is the mode of tool failure. As the primary rake angle is increased

positively, cutting edge strength is reduced (89,90). The problem then is to select the land length and P.R.A. compatible with tool strength and chip breaking range for a particular workpiece - tool combination.

Another aspect is the quality of the machined surface; it has been shown that for a particular workpiece material the surface profile is affected by the primary rake angle. For an En 8 steel there was an increase in the sidespread of material for primary rake angles more negative than -23° either from the dead metal zone ahead of the tool or by an extrusion of the "spanzipfel" by the minor flank, resulting in an increase in size of the cusp and a corresponding increase in surface roughness. The depth of the plastically deformed layer on the workpiece surface is similarly affected by changes in primary rake angle.

It is therefore concluded that the primary rake angle should be at the most convenient maximum value for cases where cutting edge chipping is not the mode of tool failure. That is, for example, the value of the clearance angle for a throw away tip type tool.

6.6.2. The Groove Configuration

It has been shown previously that provided the groove does not interfere with the chip it is the position of point A shown in Fig.4.19., that is, the outlet point of the groove that determines the chip curl radius. For a given U.C.T., chip curl radius reduces with groove width. Using a tool of given groove width the chip curl radius reduces with increase in undeformed chip thickness according to the relationships obtained in Section 4.9.

For a particular workpiece material there is a relationship between the chip curl radius and chip thickness for effective breaking, see Appendix B. Therefore a value of W can be determined to cause chip breaking at the smallest value of chip thickness and therefore feed. For maximum strength the contour of the groove should be such that the chip is just clear of the groove at the smallest chip curl radius or, if the

groove is of circular contour, the groove radius should be the minimum radius required. If the groove is designed with a smaller inlet angle, then at U.C.T. values in excess of that which causes the chip stream angle to equal the inlet angle, the chip will be in contact with the groove and wear of the groove will occur; allowance must also be made for elastic recovery.

It has been shown by Nakayama that the direction of chip flow can determine the chip breaking mode, as shown in Fig.3.3. In turning operations this is influenced by the cutting edge angle, the cutting edge inclination and tool corner radius. The workpiece diameter and depth of cut are also contributing factors which may determine whether the chip is obstructed by the workpiece shoulder. It is also possible to influence the chip flow direction by providing a tapered land as described in Section 4.1.2. However, this is in general undesirable as the chip flow direction changes with undeformed chip thickness and causes the chip thickness to vary across the section, which makes the chip breaking less predictable.

With very small chip thickness values, small feeds, the chip is usually very flexible and is less likely to effectively anchor at the flank; it also requires a large increase in radius to cause fracture. Under these circumstances it is possible to stiffen the chip by providing a groove of varying width. This causes the chip to be curved in two planes, thus there is less likelihood of deflection or slipping at the tool flank. The increased resistance to bending will also cause fracture to occur at a smaller expanded radius.

A method of determining the operating range of a groove type chip former is outlined in Appendix G. and an algorithm is presented indicating the detailed determination of the significant parameters.

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

7.1. CONCLUSIONS

1. A mechanism for the operation of the groove type chip former at high cutting speeds, is proposed. It is suggested that this is similar to the mechanism proposed for slow speed machining but is affected as described, by the changes in the built-up-edge configuration which occur at high cutting temperatures.
2. The value of feed at which a groove type chip former begins to operate can be readily determined from the discontinuity in the cutting force curve. It can also be accurately predicted by Abuladse's equation.
3. The relationship between the ratio Z_0 and the primary rake angle was found to be linear over a wide range of primary rake angle for the workpiece materials tested.
4. When cutting steels under conditions that cause continuous chip formation, the chip stream angle adopts a value of 45° at low cutting speeds irrespective of the value of primary rake; provided that the sticking feed is exceeded and the chip is unobstructed.
5. When cutting under conditions that cause the special built-up-edge to form its configuration is affected by increase in cutting temperature. That is, the built-up-edge angle reduces and the edge rounding of the built-up-edge increases. However, it does not disappear as does a conventional built-up-edge.
6. The chip curl radius induced when using chip forming grooves of various configurations can be predicted for a particular workpiece material from the results of a single test.
7. It has been shown how the primary land and groove dimensions for effective chip breaking may be determined for a given minimum value of feed.
8. For a given groove and land configuration the chip breaking feed range can be predicted.

9. When cutting with double rake angle tools the surface finish of the machined surface is adversely affected by sideflow as primary rake angle is decreased below a particular value. This value is determined by the cutting temperature and properties of the workpiece material. At more positive primary rake angles the surface profile of the machined surface may be smoother than the geometrically ideal profile.
10. For the materials tested the depth of the hardened layer on the workpiece surface is increased by the increase in ploughing caused by the edge rounding of the special built-up-edge. The principal causes of this are increase in cutting speed and decrease in primary rake angle.
11. In some cases the special built-up-edge is unstable in the X-Y plane and is manifest as a transverse chip. In particular this is when cutting at high temperatures with large negative rake angles.

7.2. FURTHER WORK

7.2.1. General

- (a) The physical model with resulting hodograph proposed in Section 4.6. utilised a number of straight surfaces to represent the modified form of the special built-up-edge. This model should be refined to represent more accurately the deformation patterns obtained from specimens of the quickly stopped cutting action when cutting at high speeds.
- (b) Further measurements should be made of the acceleration and separation time of the quick stop device. The device may need to be developed to improve its performance.

7.2.2. Tool Life

- (a) Cutting edge strength

Preliminary tests have been performed cutting intermittently with brittle tool materials using double rake angle tools. The results indicate considerable variation in tool life with variation in the configuration of the primary land. Further work should be performed to determine optimum tool configurations for given cutting conditions.

(b) Tool wear

The standard procedure for determining the wear performance of cutting tools is both expensive in terms of the amount of workpiece material used, and is time consuming. Tests comparing the relative performance of different tools obtained from conventional tests with average chip-tool interface temperature measured using a workpiece tool thermo-couple have proved inconclusive. However, this work should be pursued by, for example, measuring temperatures in a particular region, or using a stress-temperature technique as proposed by Barrow (91).

7.2.3. Chip Control

(a) The Anchoring of the Chip

It has been shown that the chip breaking action relies upon the effective anchoring of the chip at the point where it contacts the major flank. A method of making this more positive should be determined.

(b) The mechanical properties of the chip

In order to accurately predict the chip breaking range of a chip former the value of Young's modulus of elasticity and the ultimate tensile strength of the chip material must be known.

When cutting with chip forming grooves it is likely that the mechanical properties of the chip will be different to chips produced with conventional tools. This may be due to such factors as the variation in the subsurface deformation of the chip. The mechanical properties of chips produced with different workpiece materials and tool configurations should therefore be determined.

(c) Chip breaking at small feeds

The problem of chip breaking becomes more difficult as the feed and therefore the chip thickness reduces, as may be realised from the relationships obtained in Appendices B and C. The radius to which the chip must be formed may, however, be increased if the chip strength is increased. This may result from producing a chip that is additionally curved in a

plane normal to the conventional plane of curvature. Investigations should be undertaken into the chip breaking performance of tools with grooves of varying width, which should induce the curvature described above.

7.2.4. Surface Integrity

(a) Surface roughness

The work concerning sideflow of the workpiece and transverse chip formation should be elaborated in order to provide a more complete understanding of how these phenomena affect surface roughness. Examination of surfaces using the scanning electron microscope and light sectioning microscope has been found useful but a more comprehensive study, using these techniques, is required. Further metallurgical examination of the surface would be facilitated using a fine grained workpiece material.

(b) Surface stresses

The assessment of the stress condition of the workpiece surface has been of a qualitative nature. As the surface deformation of the machined surface may be quite considerable when using double rake angle tools, quantitative information must be obtained with tools of various configurations. X-ray diffraction techniques seem the most appropriate methods to use.

APPENDIX A

HENRIKSENS ANALYSIS RELATING THE CHIP BREAKING FEED TO THE CHIP FLOW CIRCLE RADIUS

From Figure A1 the bending moment at k

$$M = P.R. (1 - \cos \theta)$$

$$\delta_s = R.\delta\theta$$

where δ_s is the length of the beam, measured along the neutral axis, subtended by the angle $\delta\theta$.

Using Castigliano's strain energy theorem.

$$U = \int M^2 ds / 2 E.I.$$

where

U is the total strain energy

$$\begin{aligned} &= \int P^2 R^2 (1 - \cos \theta)^2 R d\theta / 2 E.I. \\ &= P^2 R^2 / 2 E.I. \int_0^{2\pi} 1 - 2 \cos \theta + \cos^2 \theta d\theta \\ &= P^2 R^2 / 2 E.I. [\theta - 2 \sin \theta + (\sin 2\theta + 2\theta)/4]_0^{2\pi} \\ &= 3\pi. P^2 R^3 / 2 E.I. \end{aligned}$$

the deflection at the opening, δ , is given by:

$$\delta = \partial U / \partial P = 3\pi P.R^3 / E.I.$$

The following assumptions then appear to have been made:

1. The above expression for the opening δ is valid when δ is small and changes in R are neglected.
2. The average radius R_1 of a deformed ring having initial radius R_0 is such that:

$$\delta = 2\pi (R_1 - R_0)$$

3. If the ring is in equilibrium under forces P and has an average radius R_1 , let the forces be given a very small increase ΔP which causes a small change in deflection $\Delta\delta$, and a small change in average radius ΔR_1 .

Assuming that the bending moment anywhere is given sufficiently accurately by:-

$$\Delta M = \Delta P \cdot R_1 (1 - \cos \theta)$$

$$\Delta \delta = 3\pi P \cdot R_1^3 / E \cdot I.$$

also $\Delta \delta = 2\pi [(R_1 + \Delta R_1) - R_1]$

$\therefore \Delta P = 2 E \cdot I \cdot \Delta R_1 / 3 R_1^3$

Then for a complete range of loading from $P = 0$ to $P = P$

$$\begin{aligned} P &= \int_0^P dP = \int_{R_0}^R (2 E \cdot I / 3 R_1^3) dR_1 \\ &= -1/3 [E \cdot I / R_1^2]_{R_0}^R \\ &= E \cdot I \cdot (1/R_0^2 - 1/R^2) / 3 \end{aligned} \quad \dots (A.1)$$

from bending theory

$$\sigma = M h_c / 2I$$

where σ is the direct stress

and h_c the chip thickness

the maximum bending moment

$$M = 2 P \cdot R. \quad \text{then } \sigma = P \cdot R \cdot h_c / I$$

and substituting for P from equation (A.1)

$$\begin{aligned} \sigma &= R \cdot E \cdot h_c [(1/R_0^2 - 1/R^2)] / 3 \\ &= E \cdot h_c (R^2 - R_0^2) / 3 R \cdot R_0^2 \end{aligned}$$

and if the degree of chip breaking is expressed by:

$$c = R/R_0$$

then $h_c = (3\sigma/E) (R \cdot R_0^2 / [R^2 - R_0^2])$

$$= 3\sigma \cdot R_0 \cdot R / E (R_0 \cdot c - R_0)$$

$$= 3\sigma \cdot c \cdot R_0 / E (c^2 - 1)$$

and if the feed is related to the chip thickness by the relationship:

$$h = K \cdot h_c$$

$$h = 3\sigma \cdot c \cdot R_0 / (K \cdot E (c^2 - 1))$$

Note Henriksen equated R_T to R_O ; for a full turn chip,

then $c = R/R_O = 2$

$$\therefore h = 2 \sigma R_O / E.$$

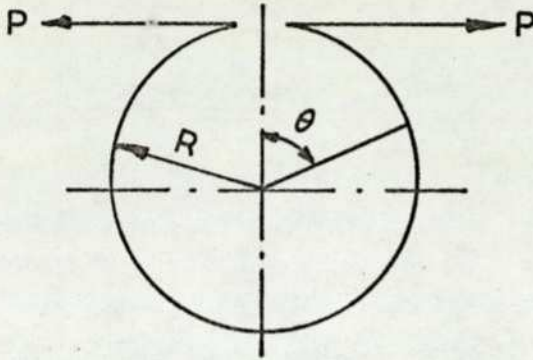


FIG. A.I.

APPENDIX B

ANALYSIS TO DETERMINE THE RELATIONSHIP BETWEEN CHIP CURL RADIUS FOR CHIP BREAKING AND CHIP THICKNESS TREATED AS BENDING OF A CURVED BEAM

From Figure B.1 it may be seen that the strain in the element PQ (y from the neutral axis)

$$\begin{aligned} &= (PQ^1 - PQ)/PQ \\ &= [(R_o + y)(\theta + \delta\theta) - (R + y)\theta]/((R + y)\theta) \\ &= [R_o(\theta + \delta\theta) - R.\theta + y\delta\theta]/((R + y)\theta) \end{aligned}$$

From the figure it may be seen that $R_o(\theta + \delta\theta)$ and $R\theta$ are both equal to the length along the neutral axis.

$$\therefore \text{strain} = y\delta\theta/(R + y)\theta \quad \dots (B.1)$$

if y is assumed to be small compared with R_o

$$\text{from } R_o(\theta + \delta\theta) = R.\theta.$$

$$\delta\theta = (R - R_o)\theta/R_o \quad \dots (B.2)$$

$$\begin{aligned} \text{then strain} &= (y/R) [(R - R_o)/R_o] \\ &= y [(1/R_o) - (1/R)] \end{aligned}$$

Neglecting lateral stresses, normal stress

$$\begin{aligned} \sigma &= E. \text{ strain} \\ &= E.y ((1/R_o) - (1/R)) \end{aligned}$$

Total normal stress (algebraically) = 0

$$\text{i.e. } \int \sigma.dA. = E [(1/R_o) - (1/R)] \int y.dA = 0$$

The moment of resistance $M = \int \sigma.y.dA$

$$\begin{aligned} &= E [(1/R_o) - (1/R)] \int y^2 dA \\ &= E.I [(1/R_o) - (1/R)] \\ &= E.I. (R - R_o)/R.R_o. \end{aligned}$$

and if $R = 2R_o$ i.e. for a full turn

and $M = 2\sigma \cdot I / h_c$

then $\sigma = E \cdot h_c (2R_o - R_o) / 2 \cdot 2 \cdot R_o^2$

i.e. $h_c = 4\sigma \cdot R_o / E$... (B.3)

In some cases the chip thickness may not be regarded as small when compared to the chip curl radius, in such cases.

From equation (B.1)

$$\epsilon = y \cdot \delta\theta / (R + y) \theta$$

and equation (B.2)

$$\delta\theta = (R - R_o) \theta / R_o$$

$$\therefore \epsilon = y \cdot (R - R_o) \theta / R_o (R + y) \theta$$

and $\sigma = E \cdot \epsilon$

$$= E \cdot y \cdot (R - R_o) / R_o (R + y)$$

$$\int \sigma dA = E (R - R_o) / (R + y) R_o \int y dA = 0$$

$$M = \int \sigma \cdot y \cdot dA.$$

$$= E(R - R_o) / [R_o (R + y)] \int y^2 \cdot dA.$$

$$= E \cdot I \cdot (R - R_o) / [R_o (R + y)]$$

and if $R = 2R_o$ i.e. for a full turn

and $M = 2\sigma \cdot I / h_c$

then $\sigma = E \cdot I \cdot R_o \cdot h_c / [R_o (2R_o + h_c/2) 2I.]$

$\therefore h_c = 4\sigma \cdot R_o / (E - \sigma)$... (B.4)

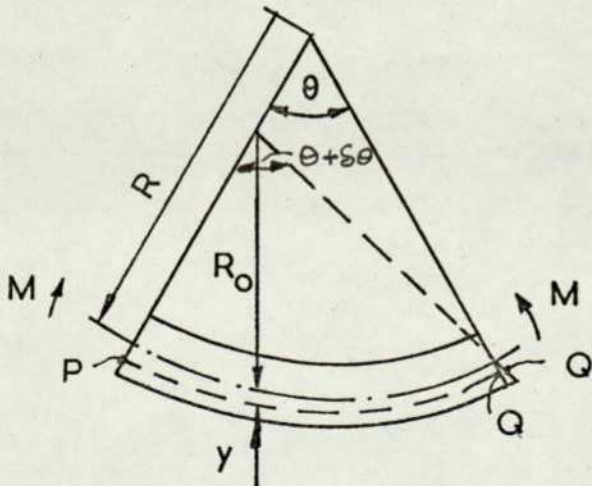


FIG. B.I.

APPENDIX C

ANALYSIS TO RELATE CHIP BREAKER CONFIGURATION TO CHIP THICKNESS AT FRACTURE

Assumptions

1. That the chip is form curled by the obstruction - or groove.

The radius of chip curl may be calculated from:

$$R_T = (w - h_c) \cot (\beta/2) \quad \dots (C.1)$$

where w is the distance from the cutting edge to the bottom of the chip breaker step.

h_c is the chip thickness = contact length

θ is the angle between the face and the obstruction.

2. On leaving the obstruction the chip recovers elastically to radius R_o where:

$$R_o = R_T \cdot E \cdot h_c / (E \cdot h_c - 2 R_T \cdot \sigma) \quad \dots (C.2)$$

from $\epsilon = \pm y (1/R_o - 1/R)$

where E is Young's Modulus of elasticity

and σ is initial yield stress.

3. On encountering the tool flank the tool expands until fracture occurs, according to:

$$h_c = 4\sigma \cdot R_o / E \quad \dots (C.3)$$

substituting equation (C.1) into equation (C.2) yields

$$R_o = (w - h_c) \cot (\theta/2) E \cdot h_c / [E \cdot h_c - 2 (w - h_c) \cot (\theta/2) \sigma]$$

and substituting for R_o in equation (C.3) yields:

$$\begin{aligned} E \cdot h_c^2 - 2 w \cdot \sigma \cdot h_c \cdot \cot (\theta/2) + 2 h_c^2 \cdot \sigma \cdot \cot (\theta/2) &= 4 w \cdot \sigma \cdot h_c \cot (\theta/2) \\ &\quad - 4 h_c^2 \cdot \sigma \cdot \cot (\theta/2) \end{aligned}$$

$$\therefore E \cdot h_c^2 - 6 w \cdot \sigma \cdot h_c \cot (\theta/2) + 6 h_c^2 \sigma \cdot \cot (\theta/2) = 0$$

$$\therefore h_c = 6 w \cdot \sigma \cdot \cot (\theta/2) / [E + 6 \cdot \sigma \cdot \cot (\theta/2)]$$

i.e. a linear relationship between the groove - or obstruction - geometry, and the chip thickness at fracture.

APPENDIX D

PATTERN OF TANGENTIAL VELOCITY DISCONTINUITIES

FOR CONTROLLED CONTACT LENGTH CUTTING

(a) Where cutting speed is low and the undeformed chip thickness is greater than that which causes the land length to equal the length of the sticking friction zone.

1) The case where the undeformed chip thickness equals the land length as shown in Figure 4.14

$$\dot{w} = k s V^* + k L V$$

or
$$\dot{w}/kH = \cos \gamma / (\sin \phi \cos (\phi - \gamma)) + \sin \phi / (\cos \gamma \cos (\phi - \gamma)).$$

If it is assumed that the chip flow direction is 45° to the direction of workpiece-tool relative motion, that is $\gamma = 45^\circ$.

$$\begin{aligned} \dot{w}/kH &= 1/\cos (\phi - \gamma) + 1/\cos (\phi - \gamma) \\ &= 2/\cos (\phi - \gamma) \end{aligned}$$

for $\dot{w}$ to be a minimum $\cos (\phi - 45^\circ)$ must be a maximum

$$\begin{aligned} d/d\phi \cos (\phi - 45^\circ) &= 0 \\ -\sin (\phi - 45^\circ) &= 0 \\ \phi &= 45^\circ \end{aligned}$$

$$\therefore h/h_c = 1/\sqrt{2} = 0.707$$

(b) If h is greater than the land length

$$\dot{w} = k s V^* + k L V$$

where s is the length of the shear plane

and L is the length of the dead metal zone

$$\therefore \dot{w}/k = h \cos \gamma / (\sin \gamma \cos (\phi - \gamma)) + L \sin \phi / (\cos \gamma \cos (\phi - \gamma))$$

if $\gamma = 45^\circ$

$$\dot{w}/k = h + L/\cos (\phi - \gamma)$$

for $\dot{w}$ to be a minimum $\cos (\phi - 45^\circ)$ must be a maximum therefore $\phi = 45^\circ$

and $h/h_c = 1/\sqrt{2} = 0.707$

APPENDIX E

ANALYSIS FOR THE REVISED MODEL OR TANGENTIAL VELOCITY

DISCONTINUITIES INCORPORATING ROUNDING OF DEAD METAL ZONE

For an upper bound estimate of the shear angle the rate of external work done $\geq$ the rate of internal energy dissipation.

therefore $dw/dt = \sum K S V^*$

From the physical diagram shown in Figure 4.15

$$AB = h/\sin \phi$$

$$BC = (h - 0.4 \sin 80^\circ \cos 80^\circ) / \sin \phi = (h - 0.068) / \sin \phi$$

$$CD = (h - x + q) / \sin \phi \\ = [h - 0.8 \cos 80^\circ \sin 80^\circ + (.068 \sin (100^\circ - \phi)) / (\sqrt{2} \sin (45^\circ + \phi))] / \sin \phi$$

$$BO = CO = \ell = 0.4 \cos 80^\circ = .068$$

$$DO = (0.6 - x) / \sin 45^\circ = (0.6 - 0.8 \cos 80^\circ \sin 80^\circ) / \sin 45^\circ = .655$$

From Hodograph

$$\bar{ab} = a_o(1) \sin 100^\circ / \sin (80^\circ - \phi) = \sin 80^\circ / \sin (80^\circ - \phi)$$

$$\bar{bc} = \bar{ab} - \bar{ac} = \sin 80^\circ / \sin (80^\circ - \phi) - \sin 80^\circ / \sin (100^\circ - \phi)$$

$$\bar{oc} = \sin \phi / \sin (100^\circ - \phi)$$

$$\bar{cd} = \sin 35^\circ \bar{oc} / \sin \phi = \sin 35^\circ / \sin (100^\circ - \phi)$$

$$\bar{bo} = \sin \phi / \sin (80^\circ - \phi)$$

$$\bar{do} = \sin \phi / \sin (135^\circ - \phi)$$

$$\therefore \frac{\dot{w}}{k} = AB \bar{ab} + BC \bar{bc} + CD \bar{cd} + BO \bar{bo} + CO \bar{co} + DO \bar{do} \\ = h \sin 80^\circ / [\sin \phi \sin (80^\circ - \phi)] + [(h - .068) / \sin \phi] [\sin 80^\circ / \sin (80^\circ - \phi) \\ - \sin 80^\circ / \sin (100^\circ - \phi)] \\ + [h - .137 + .068 \sin (100^\circ - \phi) / (\sqrt{2} \sin (45^\circ + \phi))] \sin 35^\circ / [\sin \phi \sin (100^\circ - \phi)] + .069 \sin \phi / \sin (80^\circ - \phi) \\ + .069 \sin \phi / \sin (100^\circ - \phi) + .655 \sin \phi / \sin (135^\circ - \phi)$$

Figure F.1 illustrates how the actual depth of cut, a , is a function of rake angle and the apparent depth of cut, a^1 . The resulting effect on the peak to valley height is obtained by assuming the limiting case where the peak to valley height is the actual depth of cut.

percentage variation = 0.04%.

APPENDIX G

DETERMINATION OF THE CHIP FORMER DIMENSIONS

AND THE OPERATING FEED RANGE

The following information must be available:

- (a) The minimum feed at which chip breaking is required - $s_{\min}$
- (b) The relationship between the ratio Z_o and rake angle γ_1 for the particular speed range. This may be obtained as described in section 4.4.1.
- (c) Knowledge of the wear performance and failure characteristics of the particular workpiece tool combination. This enables the primary rake angle to be selected as described in section 6.6.1.
- (d) E and σ for the chip material. Some data is available for steel workpieces (34).
- (e) The constant K , the maximum chip stream angle $\gamma_{\max}$ and the chip thickness ratio, c_h . These can be obtained from a single test to determine the $h - R_o$ relationship, using a grooved tool and the land configuration approximating to that obtained as described below. The value of K , $\gamma_{\max}$ and c_h can be determined as shown in sections 4.9 and 6.4.4. A value of W of $\approx 10b_{\gamma r}$ is usually appropriate for this test.
- (f) The cutting edge angle v_s .

Procedure:

1. Determine $h_{\min}$ from:

$$h_{\min} = s_{\min} \cos v_r$$

2. Obtain land length $b_{\gamma r}$ from the $Z_o - \gamma_1$ relationship for a value of

$$h_s = 1.2 h_{\min}$$

to account for the transition feed range. Note $Z_o = h_s / b_{\gamma r}$.

3. Using equation B.4 and c_h determine R_o

$$\begin{aligned} \text{i.e. } R_o &= h (E - \sigma) / (4\sigma c_h) \\ &= h K_1 \end{aligned} \quad \dots (G.1)$$

This equation assumes a full circle chip that is $R = 2 R_o$, this being the value of R_o at which acceptable chip breaking commences.

4. Select a value of h of $1.2 h_s$ so that $R < \text{infinity}$, calculate

R_{MIN} from equation 4.2 that is:

$$\begin{aligned} R_{MIN} &= R_o - K (h - h_s) \\ \therefore R_{MIN} &= R_o - K / (0.2 h_s) \end{aligned} \quad \dots (G.2)$$

and substituting into equation 6.1 determine W , that is

$$W = 2 R_{MIN} \sin \gamma_u$$

5. Knowing R_{MIN} and W , the groove radius can be calculated.

The chip former dimension are now known.

Determination of operating feed range:

As the minimum feed is known it is only necessary to establish the value of maximum feed before over breaking commences. It has been suggested (87) that this occurs at values of $R < R \approx 1.2 R_o$. Using this value equation B.3 becomes modified to:

$$\begin{aligned} R_o &= (0.2E - \sigma) h / (2.4 \sigma c_h) \\ \therefore R_o &= h K_2 \end{aligned} \quad \dots (G.3)$$

R_o calculated from equation (G.3) is obviously $<$ that obtained from equation (G.1) $\therefore h$ must be increased and R_o calculated from:

$$R_o = K / (h - h_s) + R_{MIN}$$

and compared with the new R_o computed from equation (G.3). Proceed using this iterative technique until R_o calculated from equation (G.3) exceeds R_o from equation (G.1). Read the values of h at which this occurs and calculate s_{max} - the maximum feed for acceptable chip breaking.

The above process is shown as an algorithm in Figure G.1 which provides a "guide" to the prediction of chip breaking performance as the following factors may cause inaccuracy:

- (a) In calculating the relationship between R_o and h_c for failure, the chip is assumed to be circular, in fact it is helical.
- (b) The mechanical properties of the chip may be inconsistent.
- (c) The anchoring action at the tool flank is not positive.
- (d) Account must also be taken of the possibility of the chip contacting the workpiece shoulder. This may be determined providing the workpiece diameter and depth of cut are known - using Stablers law, or modifications of it if the length of the primary cutting edge is small.

As a result of testing out the above procedure to determine how the predicted chip breaking range matched the results obtained in the chip breaking tests, the following observations are made:

When calculating R_o from equation G.1 a factor of safety of 2 should be used. It is suggested that this is due to the factors described in (a), (b) and (c) above.

The equation G.3 appears to underestimate the feed at which overbreaking commences for the cutting conditions used. This equation assumes overbreaking occurs when $R = 1.2 R_o$, using a value of $R = 1.1 R_o$ predicts more accurately the largest acceptable feed value.

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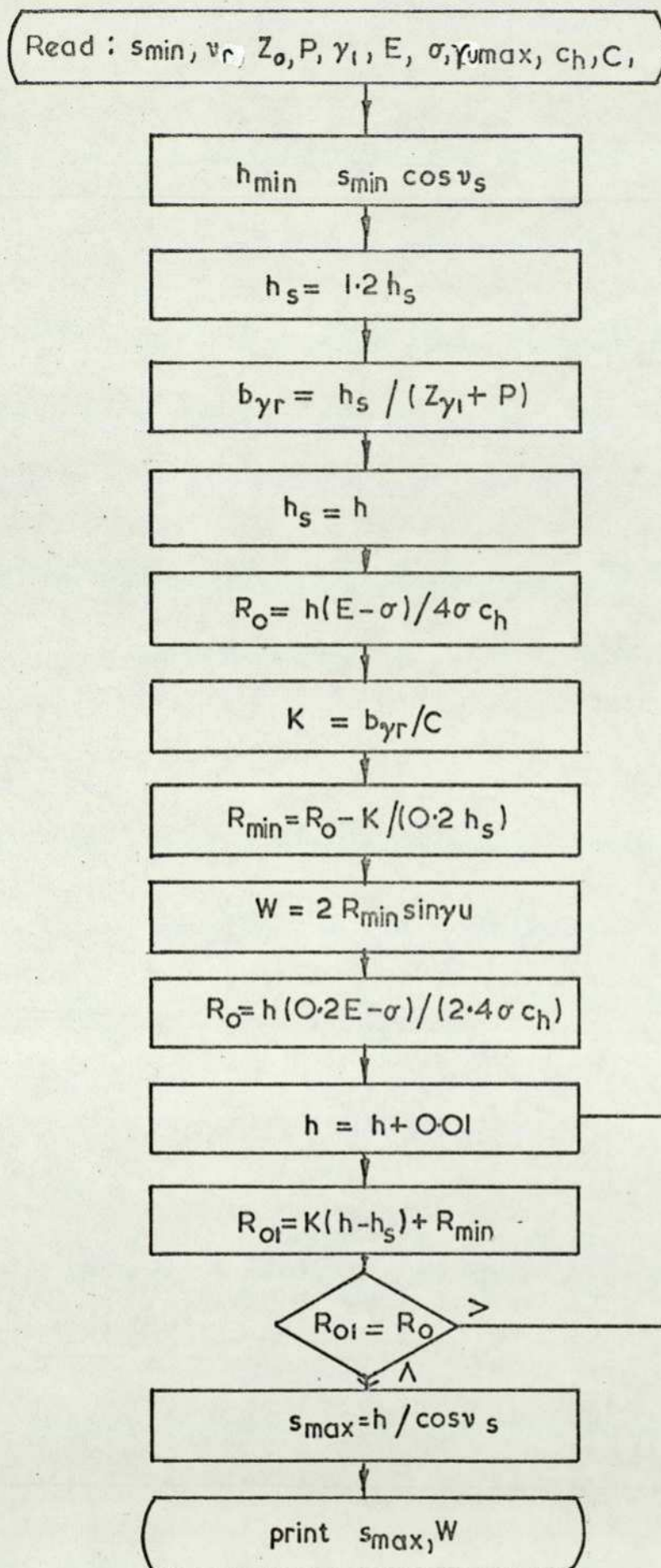
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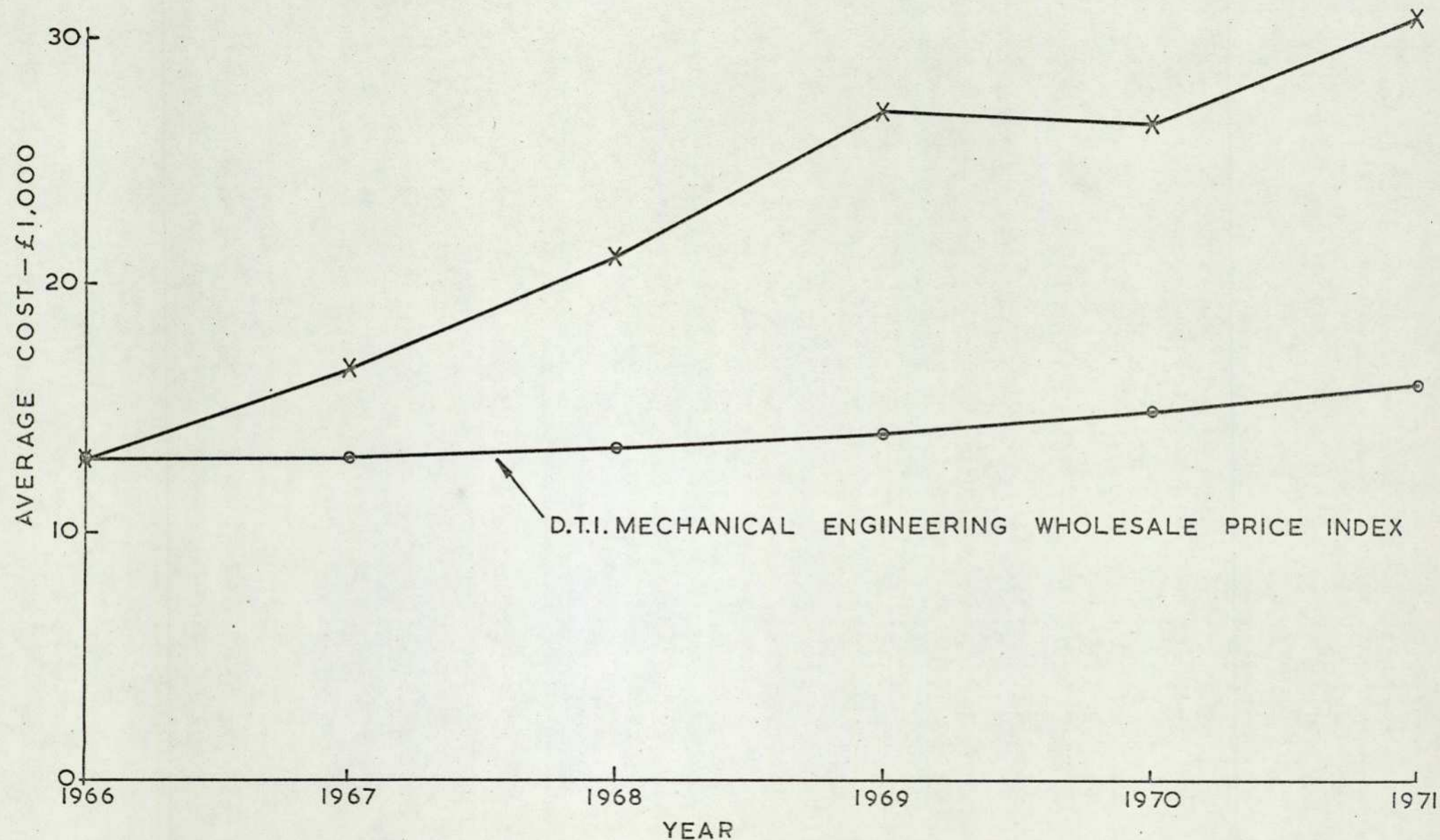
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- 5.3. Variation of arithmetic average roughness - C.L.A. μm versus cutting speed for plunge type cuts made at different values of feed - after Shaw et al.
- 5.4. a) Ideal surface profile when machined surface is generated by corner radius alone.
b) Groove wear on profiling cutting edge.
- 5.5. a) Effect of sideflow on surface roughness.
b) The Sokolowski effect.
- 5.6. Method of assessing the roughness of the primary surface.
- 5.7. Table showing details of edge retention techniques.
- 5.8.a,b,c. Effect of mounting and polishing on edge retention.
- 5.9. Examination of the plastically deformed layer.
- 5.10. Variation of cutting and feed forces with cutting speed when using tools of different rake face configuration.
- 5.11. Variation of surface roughness with cutting speed when orthogonally machining with tools of different primary rake angle.
- 5.12. The effect of primary rake angle and cutting speed on the depth of the work hardened zone when machining orthogonally.
- 5.13. The effect of primary rake angle on the shape of the special built-up-edge.
- 5.14.a,b. The effect of land length on the shape of the special built-up-edge.
- 5.15. Variation of surface roughness with cutting speed when machining obliquely at various feeds
a) plane tool b) controlled contact length tool.

Fig.No.

- 5.16. The effect of land length on surface roughness when obliquely machining with C.C.L. tools of differing primary rake angle.
- 5.17.a,b. The effect of primary rake angle on surface roughness when obliquely machining.
- 6.1. a) Effect of height of chip groove heel.
b) Bending moment on the chip.
- 6.2. Experimental relationship between U.C.T. and built-up-edge angle from results in Fig.6.10.d.
- 6.3. Experimental relationship between undeformed chip thickness and chip curl radius with different land lengths.
- 6.4. Tool dimensions for chip breaking tests.
- 6.5. Variation of cutting force with undeformed chip thickness for various primary rake angles.
- 6.6.a,b. Variation of chip form and colour of surface oxide with undeformed chip thickness.
- 6.7. Variation of feed force with undeformed chip thickness for various primary rake angles.
- 6.8. The effect of increase in ploughing force due to the rounding of the special built-up-edge caused by feed increase.
- 6.9. Photomicrograph of the cross section of a transverse chip.
- 6.10,a,b,c,d. Experimental relationship between $h-h_s$ and R_o-R_{min} for a range of primary rake angles.
- 6.11.a,b,c,d. Experimental relationship between $h-h_s$ and R_o-R_{min} for a range of primary rake angles.
- 6.12. Relationship from Fig.6.10. and 6.11. shown in straight line form.
- 6.13. The slopes of the experimental relationships obtained from Fig.6.12. versus land length.
- 6.14. Experimental relationship between tool life and cutting speed for various tool configurations.

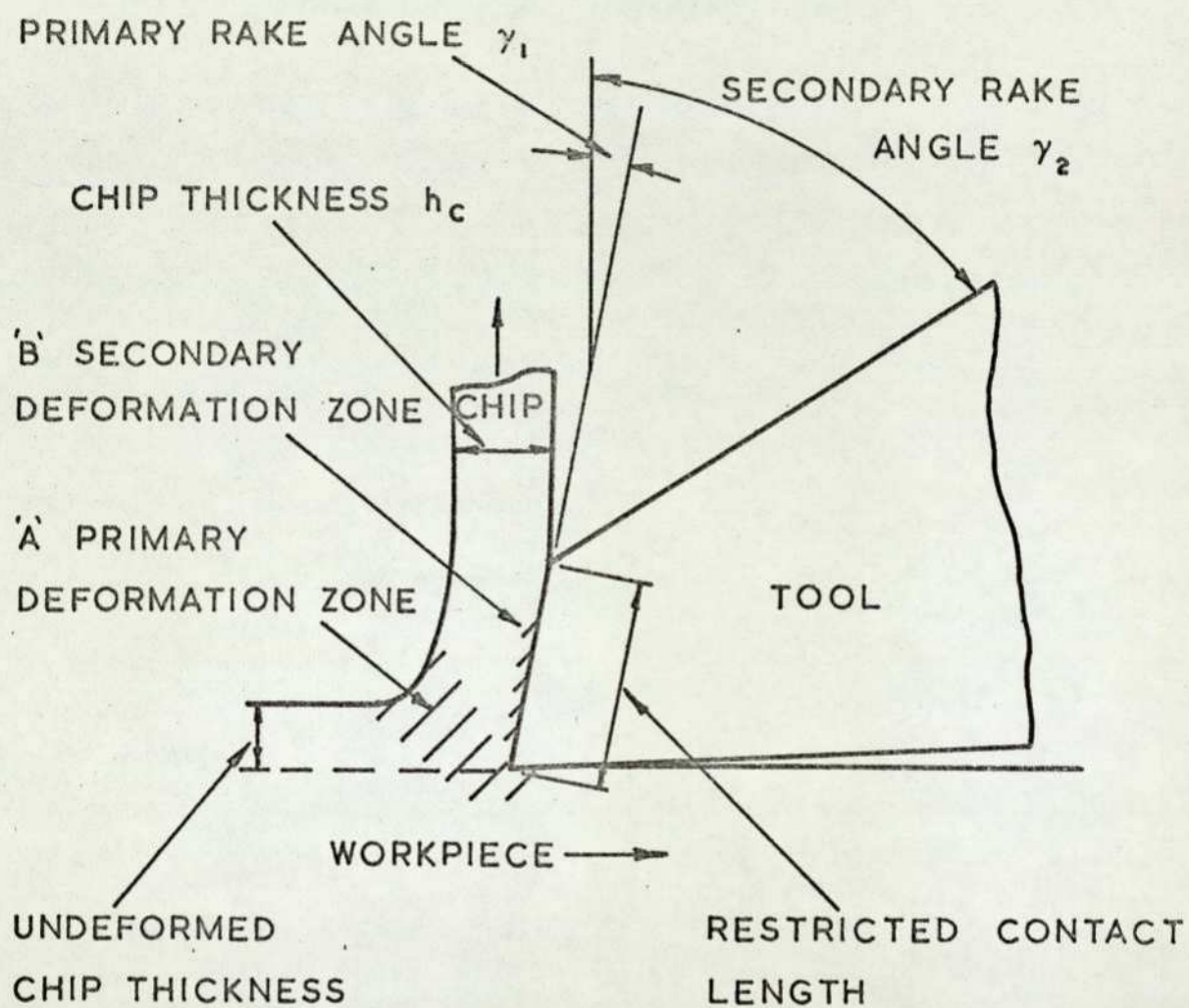


FLOW DIAGRAM REPRESENTING THE ALGORITHM FOR
DETERMINATION OF GROOVE WIDTH & FEED RANGE

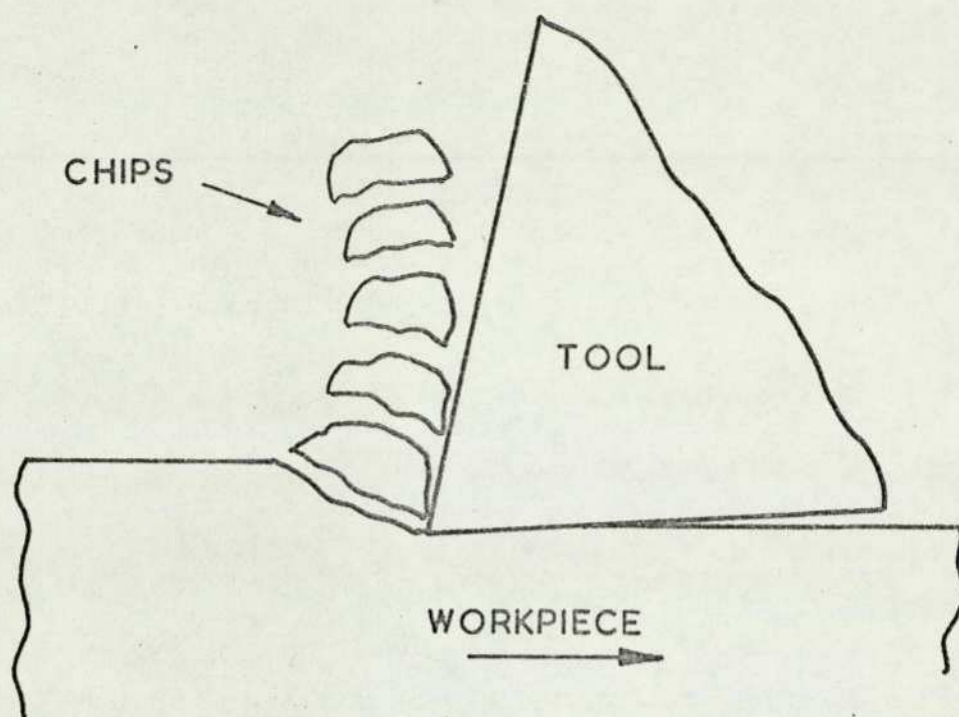


AVERAGE COST OF NUMERICALLY CONTROLLED MACHINE TOOLS 1966-71

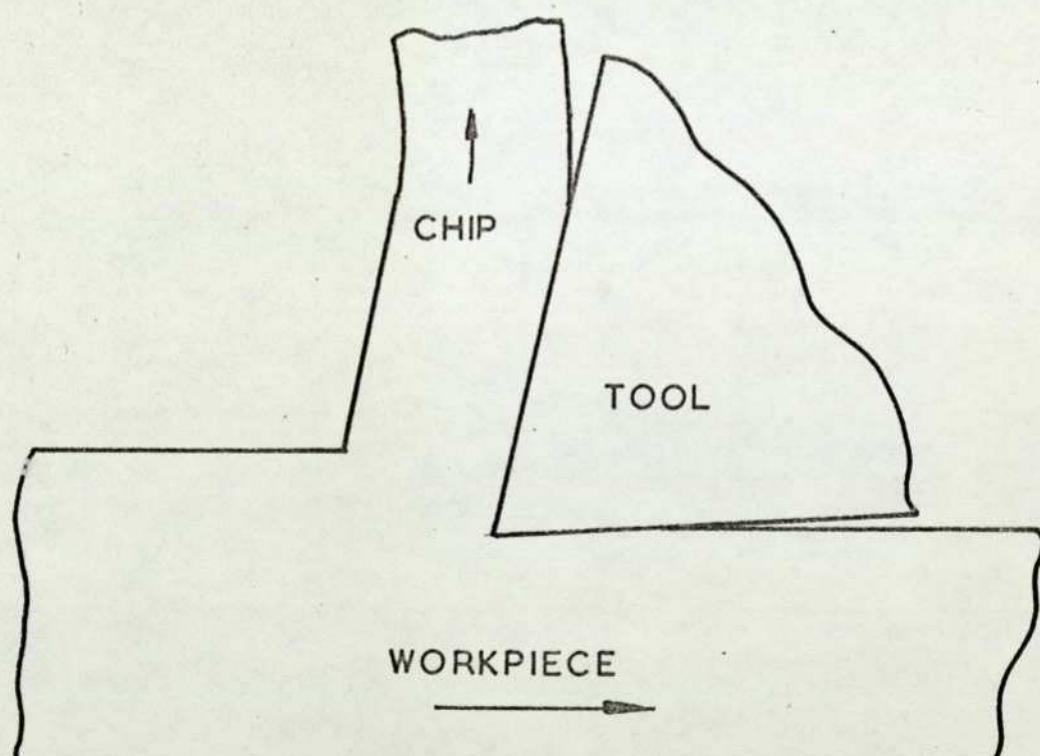
FIG. 1.1.



ORTHOGONAL CUTTING WITH A RESTRICTED
CONTACT LENGTH TOOL SHOWING ZONES
OF PLASTIC DEFORMATION



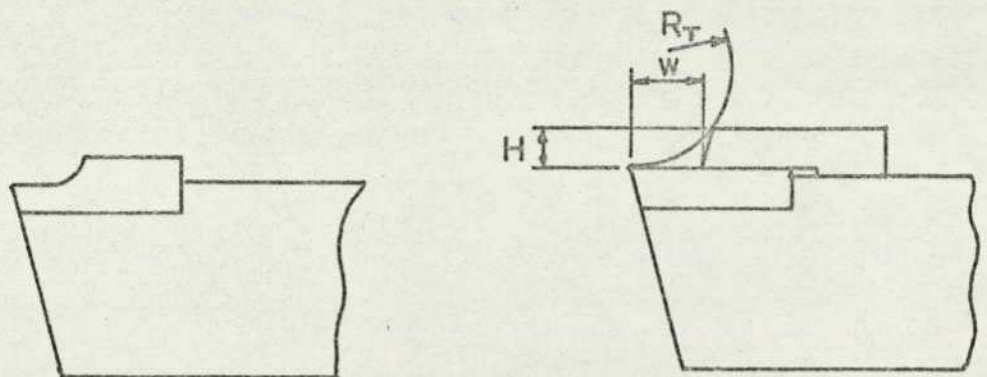
(a) DISCONTINUOUS CHIP



(b) CONTINUOUS CHIP

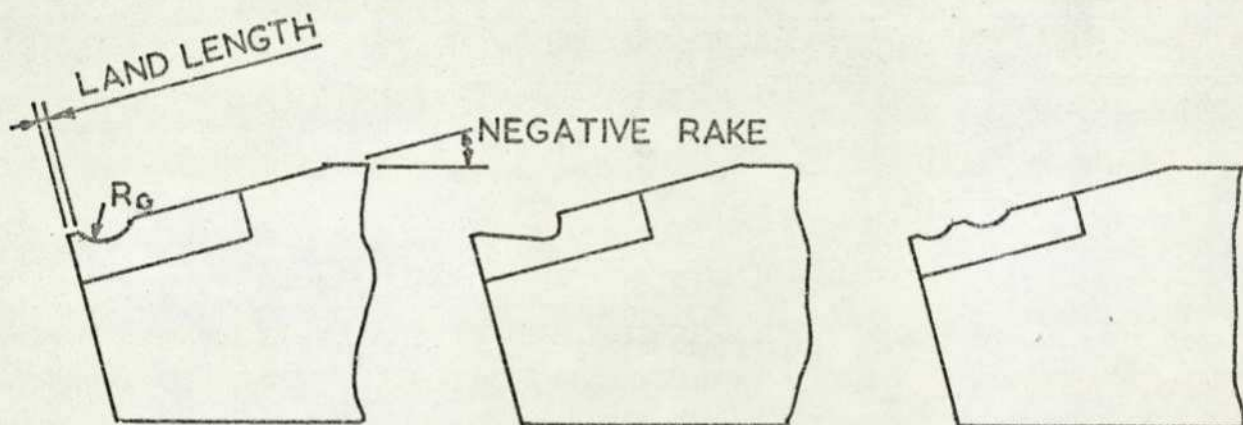
TYPES OF CHIP FORMATION

(a) OBSTRUCTION TYPE FORMERS



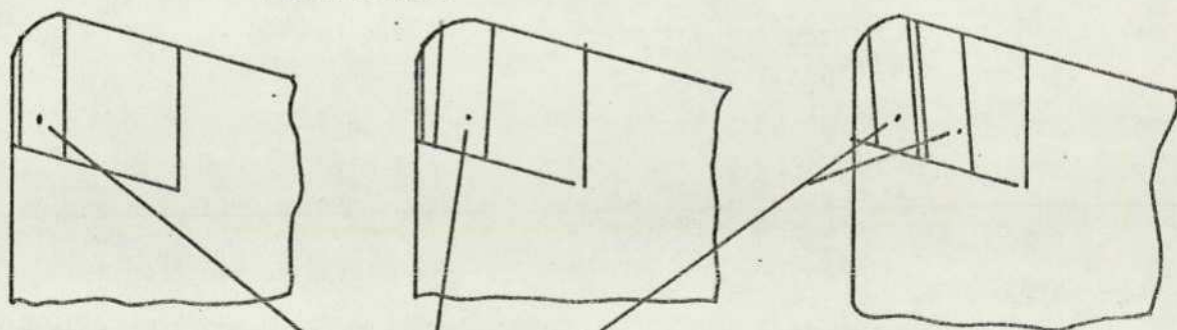
GROUND TYPE

CLAMPED TYPE



(b) GROOVE TYPE FORMERS

NOTE: BOTH TYPES CAN BE EITHER ANGULAR OR PARALLEL



PARALLEL

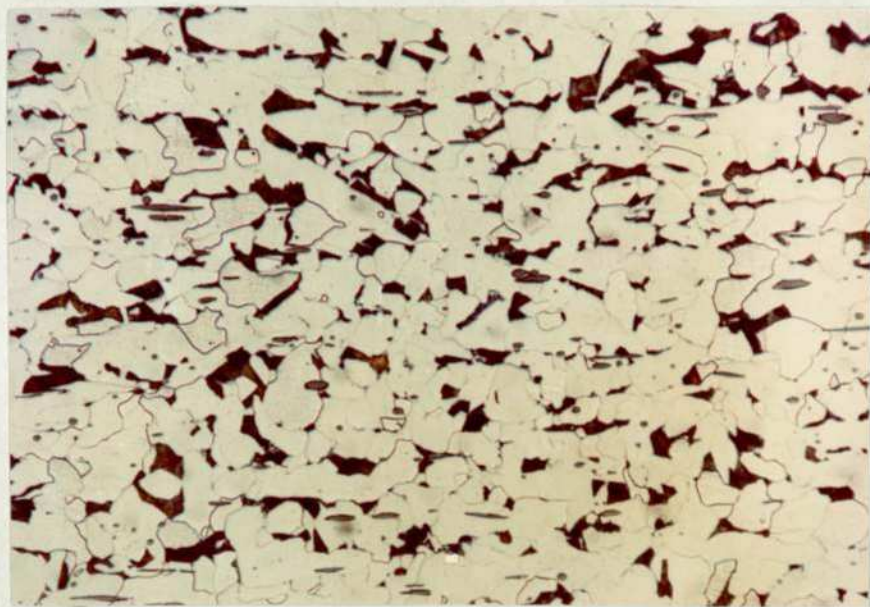
GROOVE
NEGATIVE OPEN
ANGLE

POSITIVE OPEN
ANGLE

VARIOUS TYPES OF CHIP FORMER

WORKPIECE SPECIFICATION	FORM	PERCENTAGE OF ADDITIONAL ELEMENTS					
		C.	Si.	Mn.	S.	P.	Mo.
En 1 A	4 in. sq. bar	0.11	0.02	1.4	>> 0.1	0.055	-
CDS 1	5 in. dia. tube	0.125	0.22	0.44	0.021	0.016	-
En 8	4 in. dia. bar	0.44	0.175	0.66	0.018	0.006	-
En 1 B	6 in. dia. bar	0.105	0.035	1.16	0.63	0.062	-
En 16 S	4 in. dia. bar	0.385	0.29	1.64	0.037	0.015	0.3

CHEMICAL COMPOSITION OF WORKPIECE MATERIALS



X 250

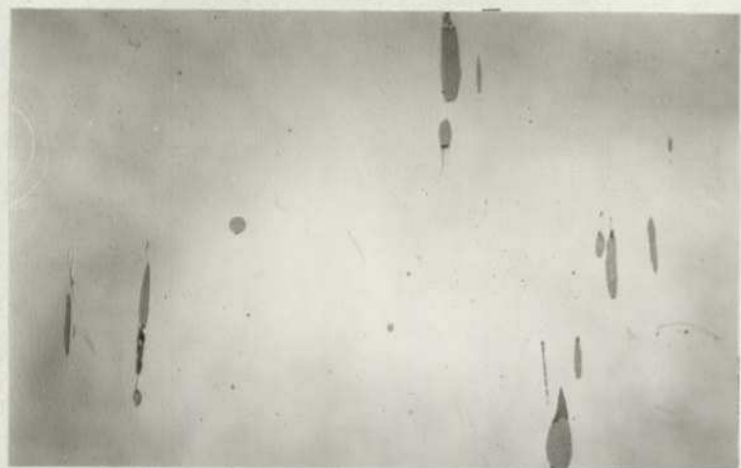
MICROSTRUCTURE OF En 1A 4in. SQUARE BAR.



1. 0.25 mm. FROM EDGE X 250



2. 12.5 mm. FROM EDGE X 250



3. 25 mm. FROM EDGE X 200



4. 37.5 mm. FROM EDGE X 200

PHOTOMICROGRAPHS OF UNETCHED En 1A WORKPIECE MATERIAL SHOWING
SEGREGATION OF MANGANESE SULPHIDE INCLUSIONS.



X 75

1.



X 75

2.

MICROSTRUCTURE OF WORKPIECE MATERIALS.

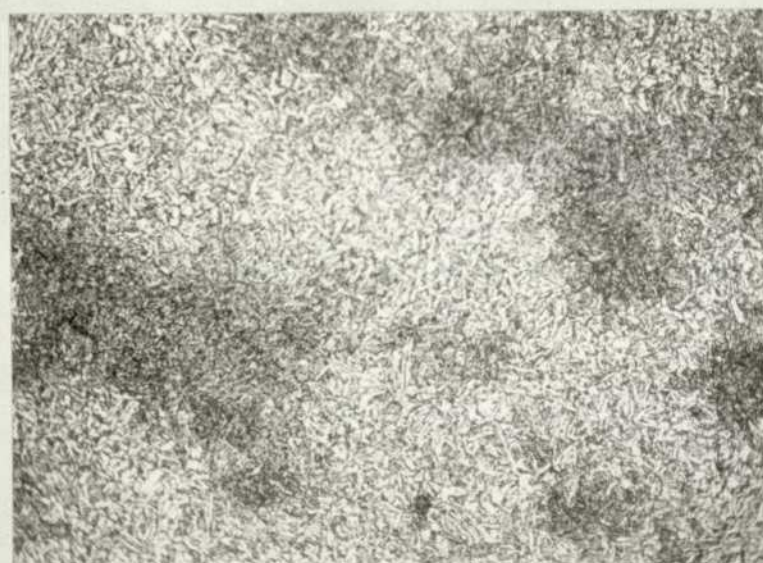
1. CDS-1 5 in. DIAMETER TUBE

2. EN 8 4 in. DIAMETER BAR



X 75

1.



X 250

2.

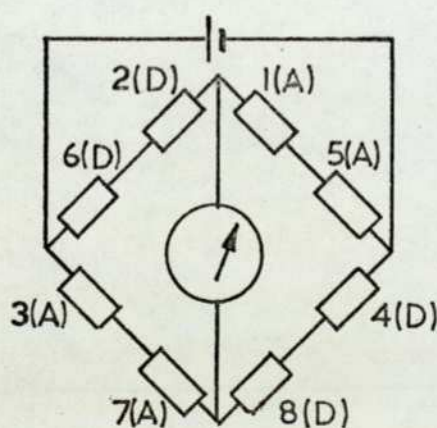
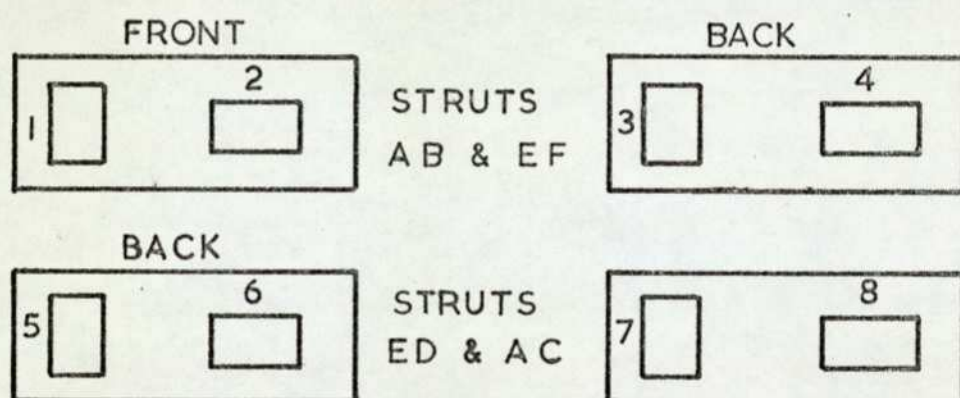
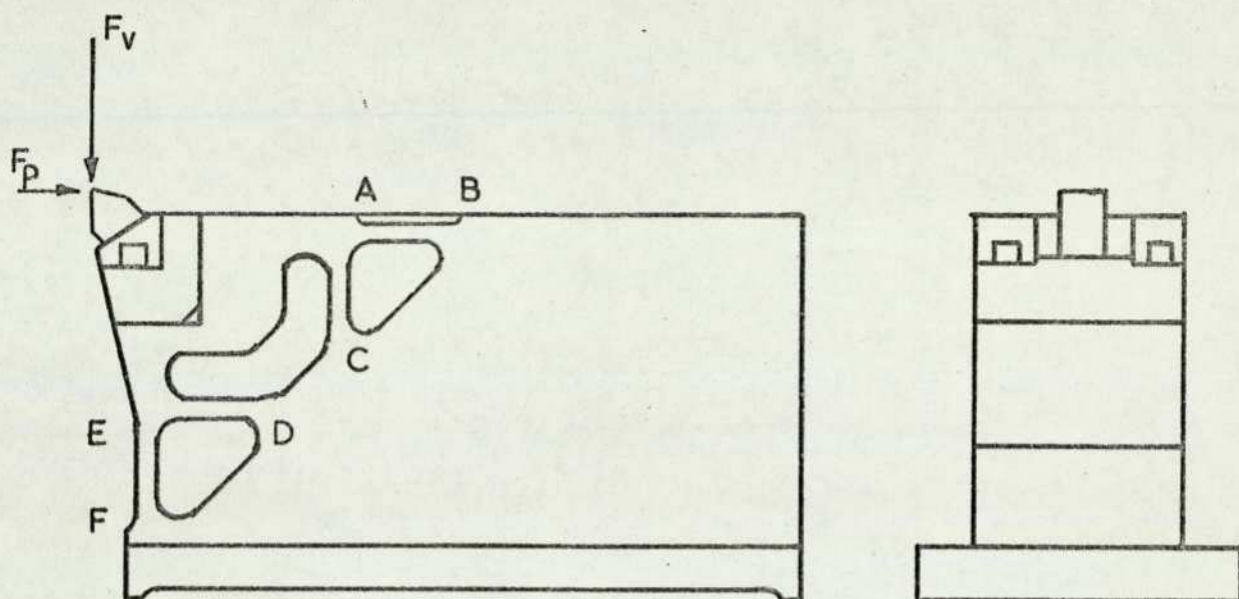
MICROSTRUCTURE OF WORKPIECE MATERIALS.

1. En 1B 6 in. DIAMETER BAR

2. En 16T 4 in. DIAMETER BAR



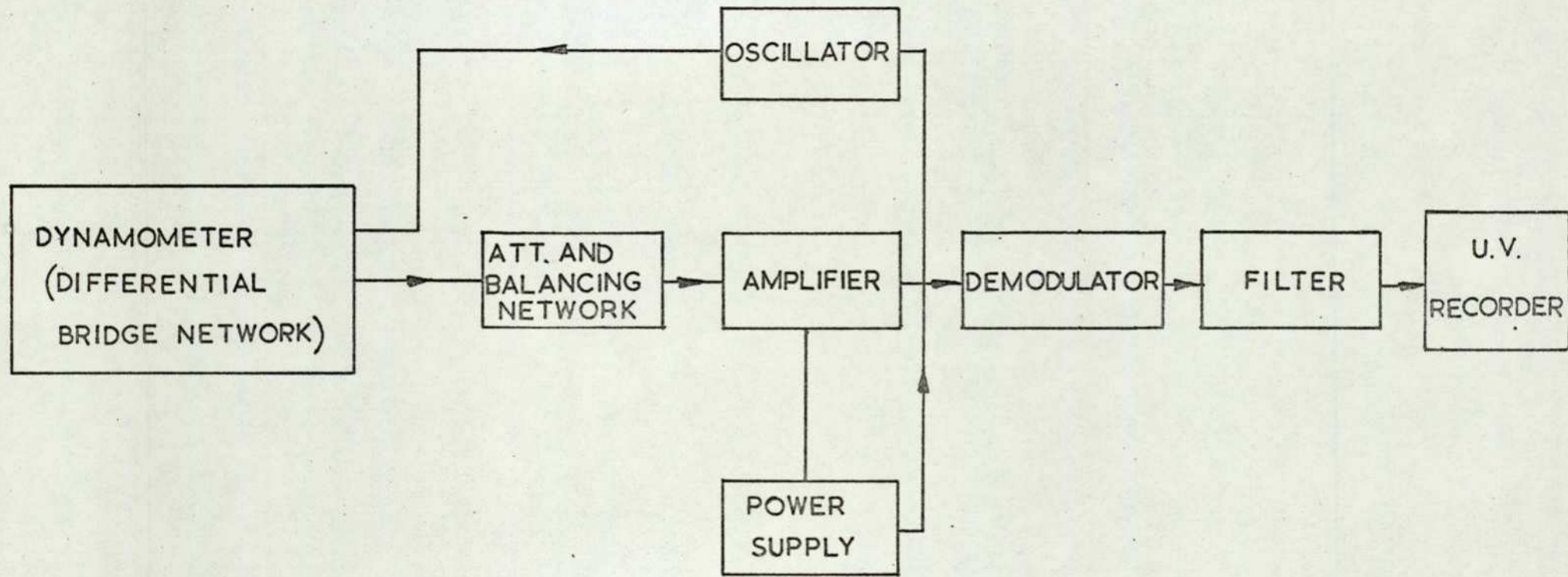
TWO COMPONENT DYNAMOMETER WITH
INSTRUMENTATION & RECORDING EQUIPMENT



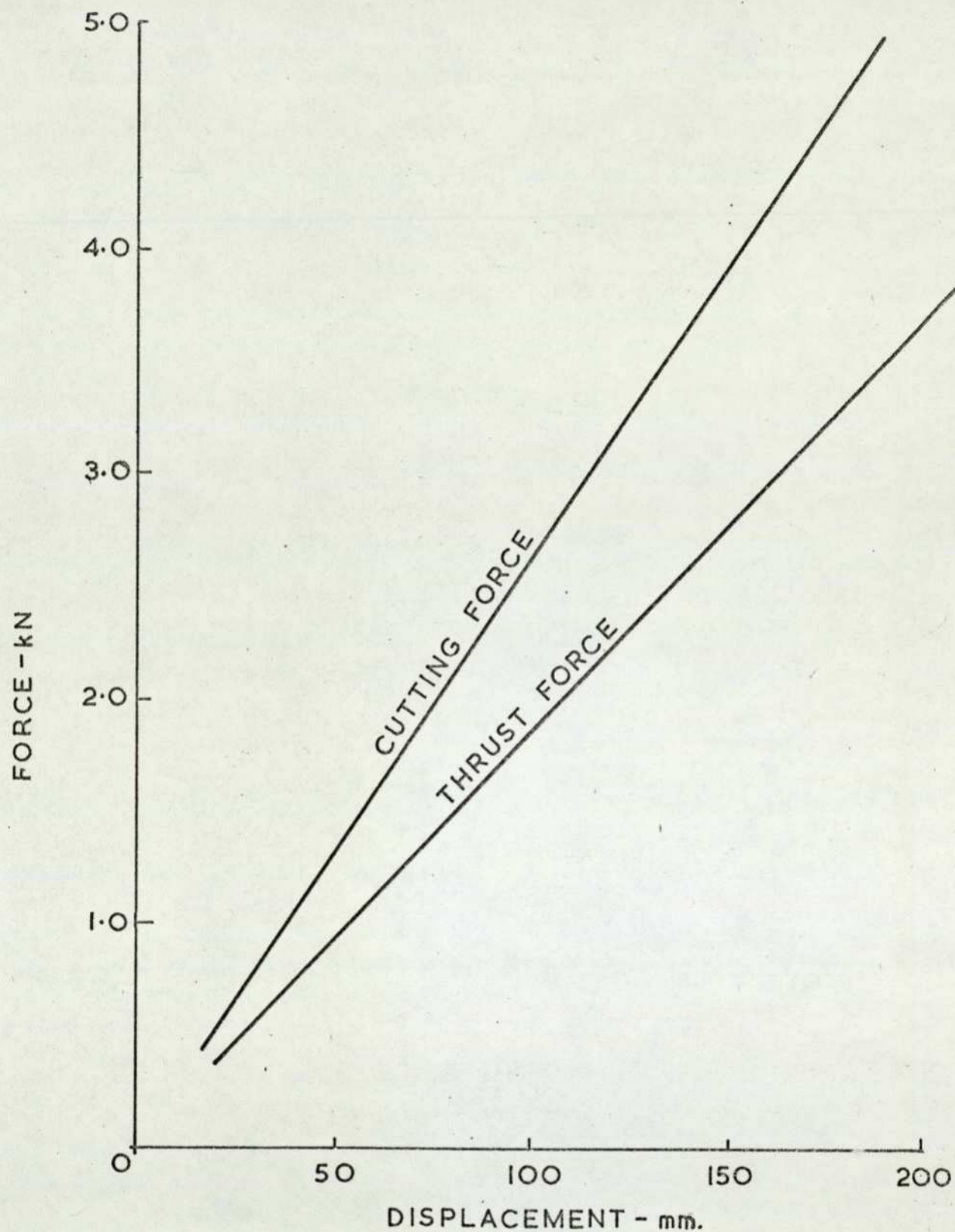
A - ACTIVE GAUGE

D - DUMMY GAUGE

POSITIONS OF STRAIN GAUGES



CARRIER AMPLIFIER SYSTEM BLOCK DIAGRAM-S E LABORATORIES



CALIBRATION CURVES FOR TWO COMPONENT
METAL CUTTING DYNAMOMETER

INSTRUMENTATION CONVERTER & CARRIER AMPLIFIER

ATTENUATION $F_v = 18 \text{ db}$ $F_p = 12 \text{ db}$

GALVANOMETER TYPE B 450 SENSITIVITY 0.048 ma/cm

NATURAL FREQUENCY 392 Hz

FIG. 2.9.

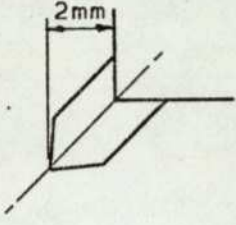
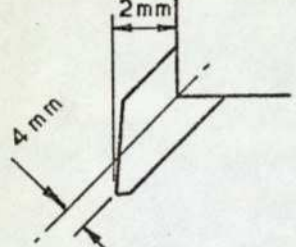
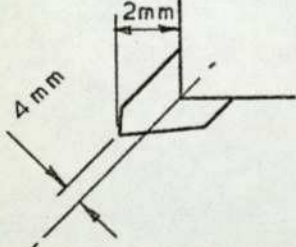
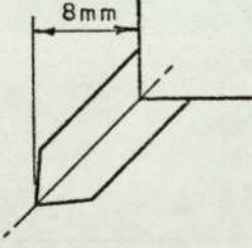
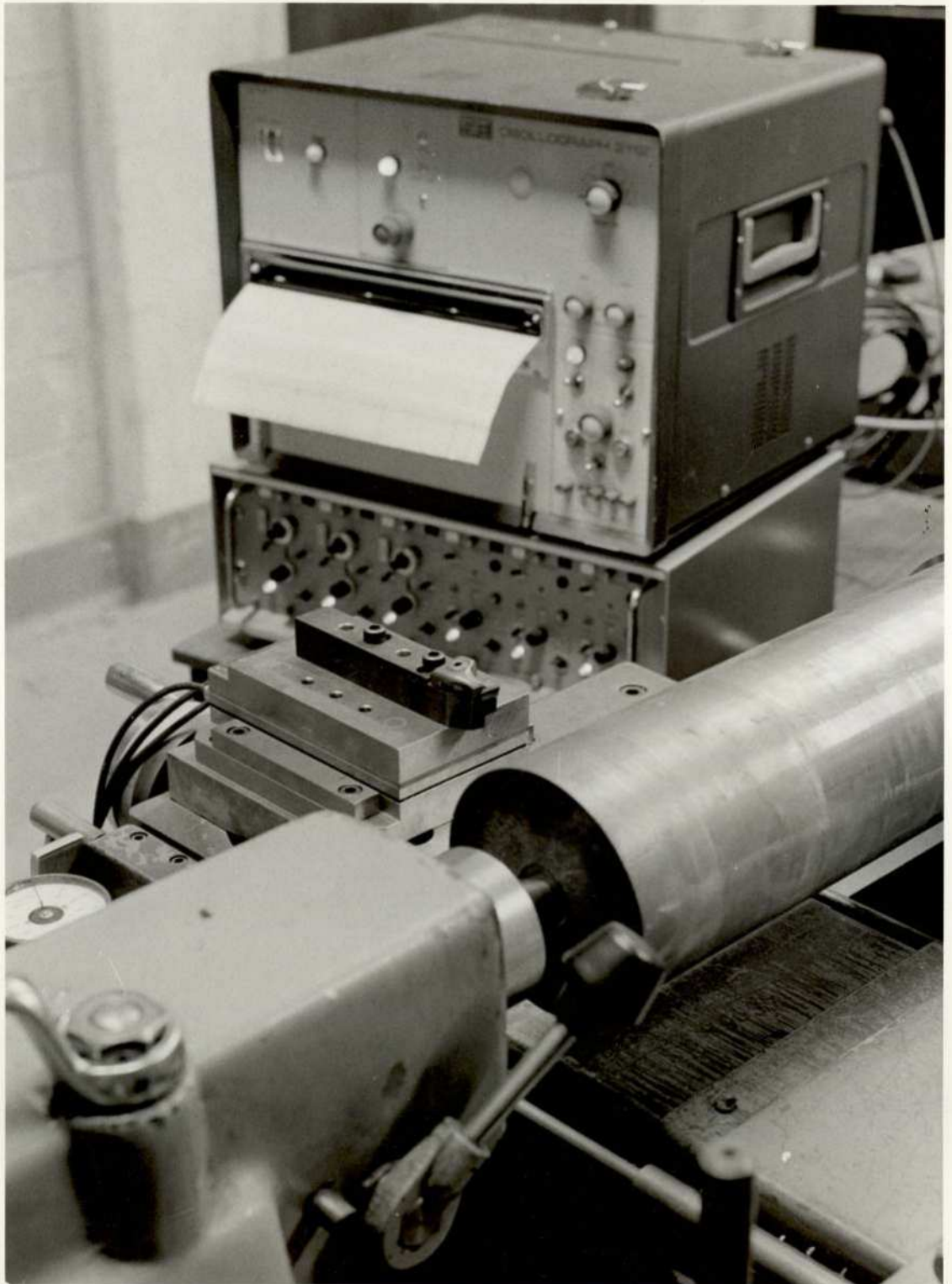
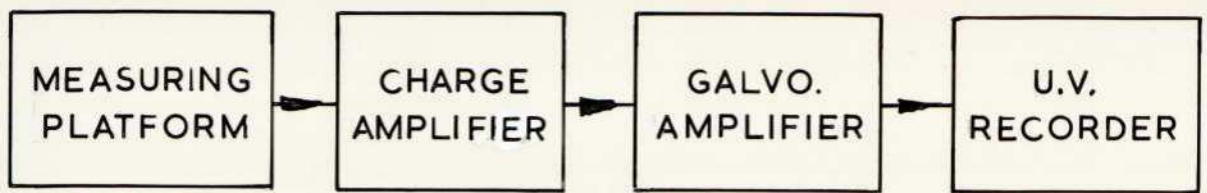
POSSIBLE ERRORS FOR VARIATION IN POSITION OF TOOL CUTTING EDGE				
TOOL POSITION	SLOPE KN/CM		% DIFFERENCE FROM POSITION I	
	F_p	F_v	F_p	F_v
1 	0.194	0.25	—	—
2 	0.189	0.24	2.5	4.0
3 	0.191	0.25	1.5	0
4 	0.193	0.257	0.5	2.5

FIG. 2.10



THE 'KISTLER' MEASURING PLATFORM & RECORDING EQUIPMENT

d_w - workpiece travel during separation time t_s

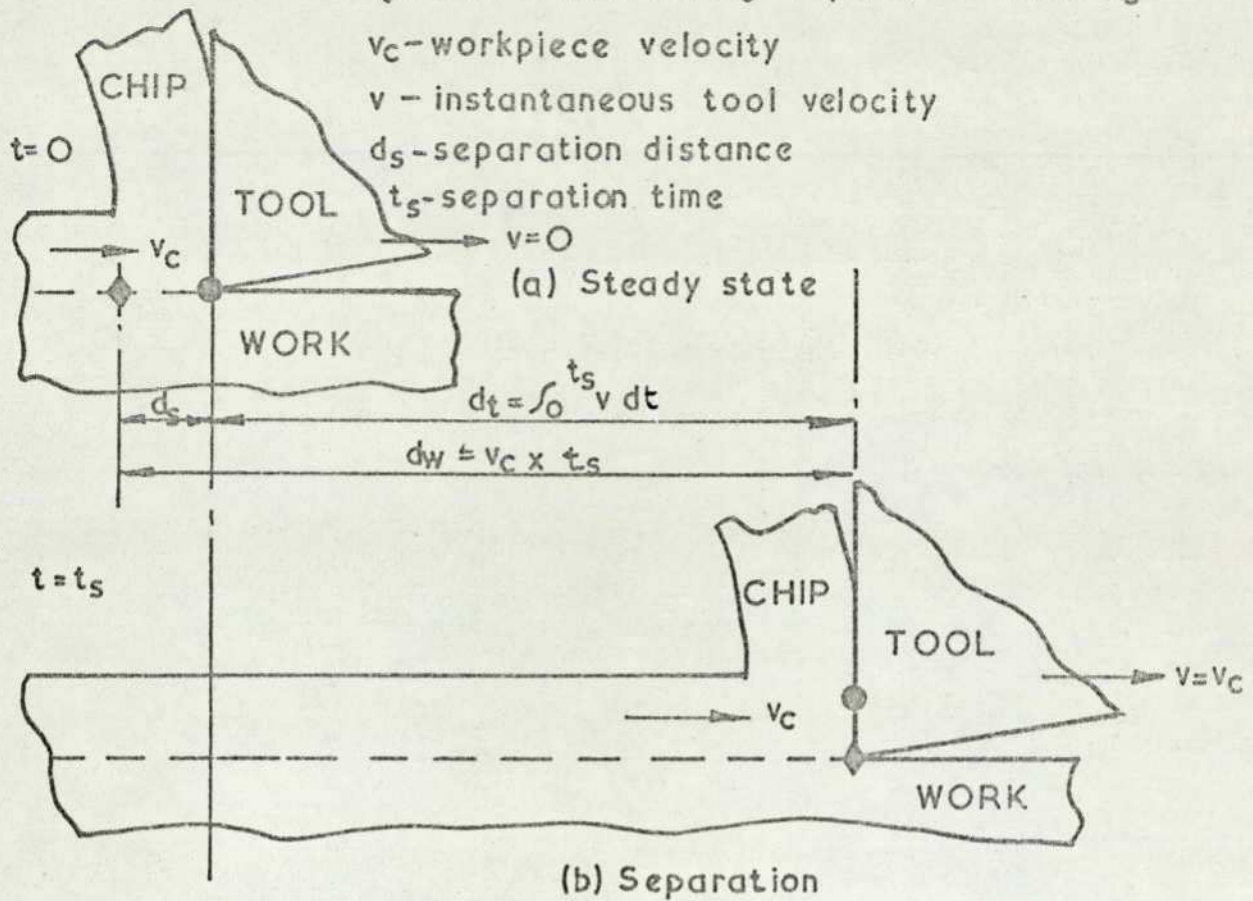
d_t - tool travel during separation time t_s

v_c - workpiece velocity

v - instantaneous tool velocity

d_s - separation distance

t_s - separation time

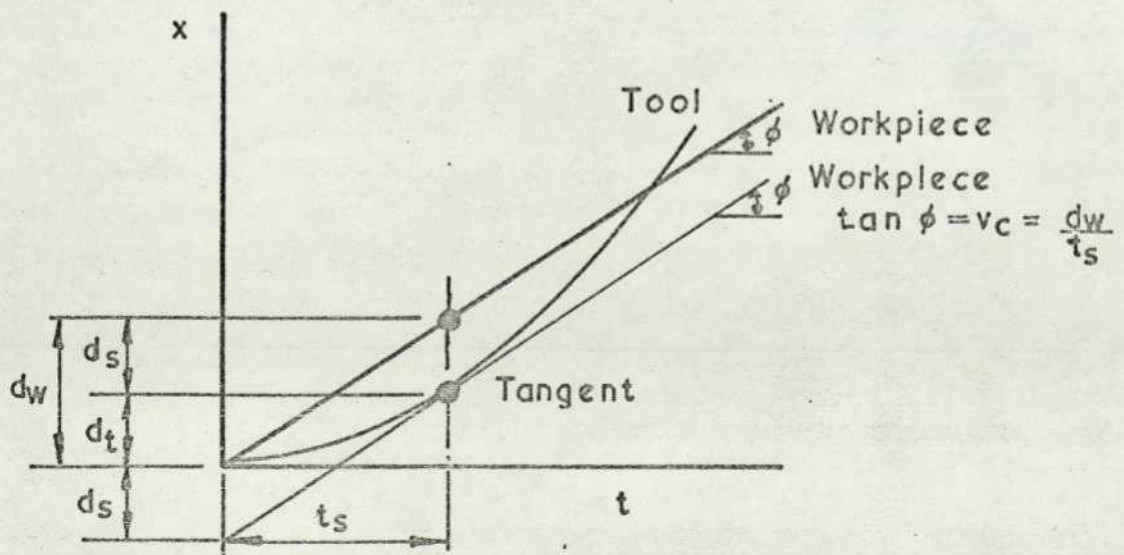


$$d_s = d_w - d_t = v_c t_s - \int_0^{t_s} v dt$$

assuming constant acceleration

$$\int_0^{t_s} v dt = v_c \frac{t_s}{2} \quad \text{and} \quad d_s = \frac{v_c t_s}{2}$$

$$\text{and} \quad a = \frac{v_c}{t_s} \quad \therefore \quad d_s = \frac{v_c^2}{2a}$$



CAPTIVE BOLT
PISTOL

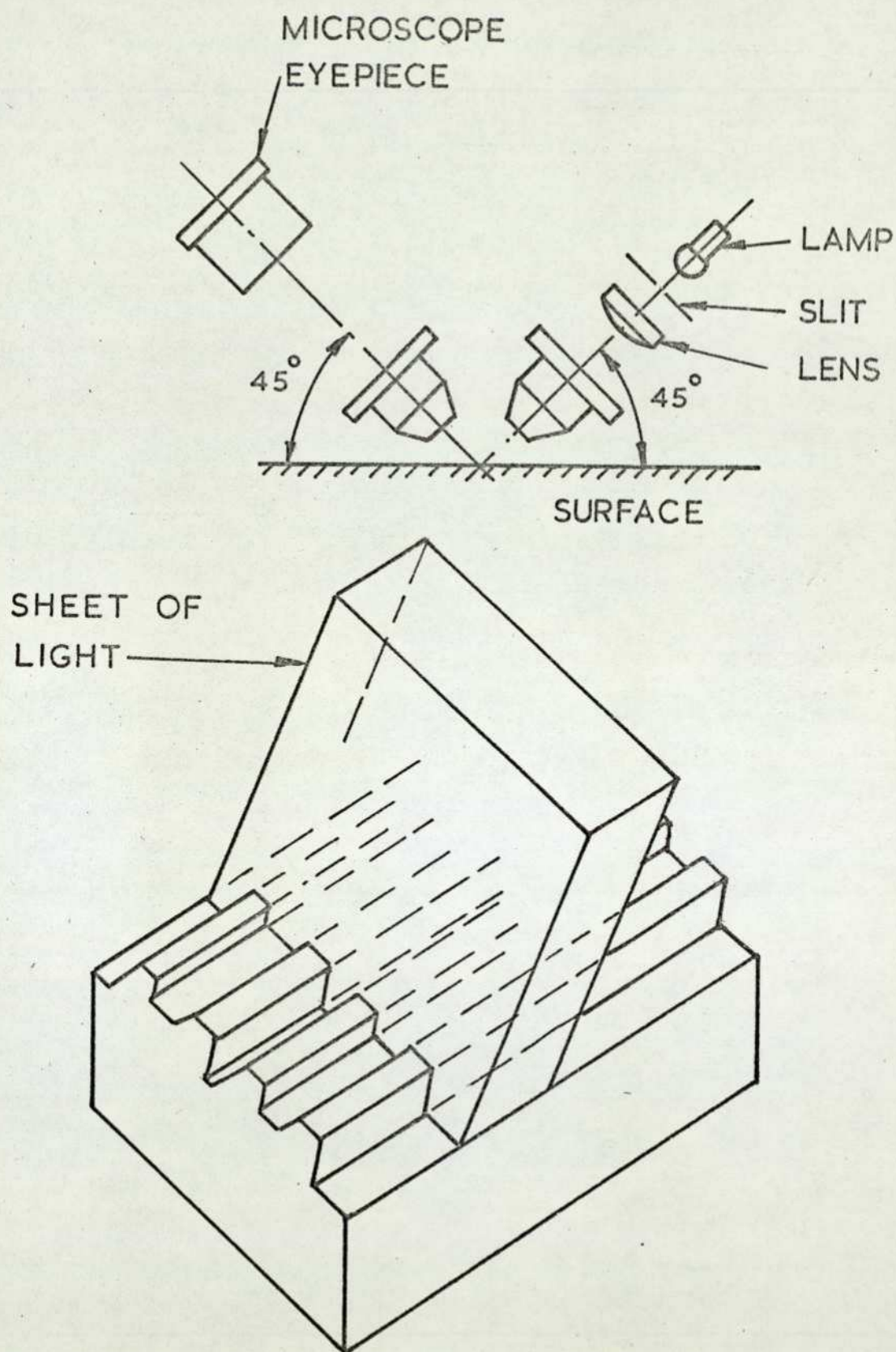
TOOL
HOLDER

HINGE
PIN

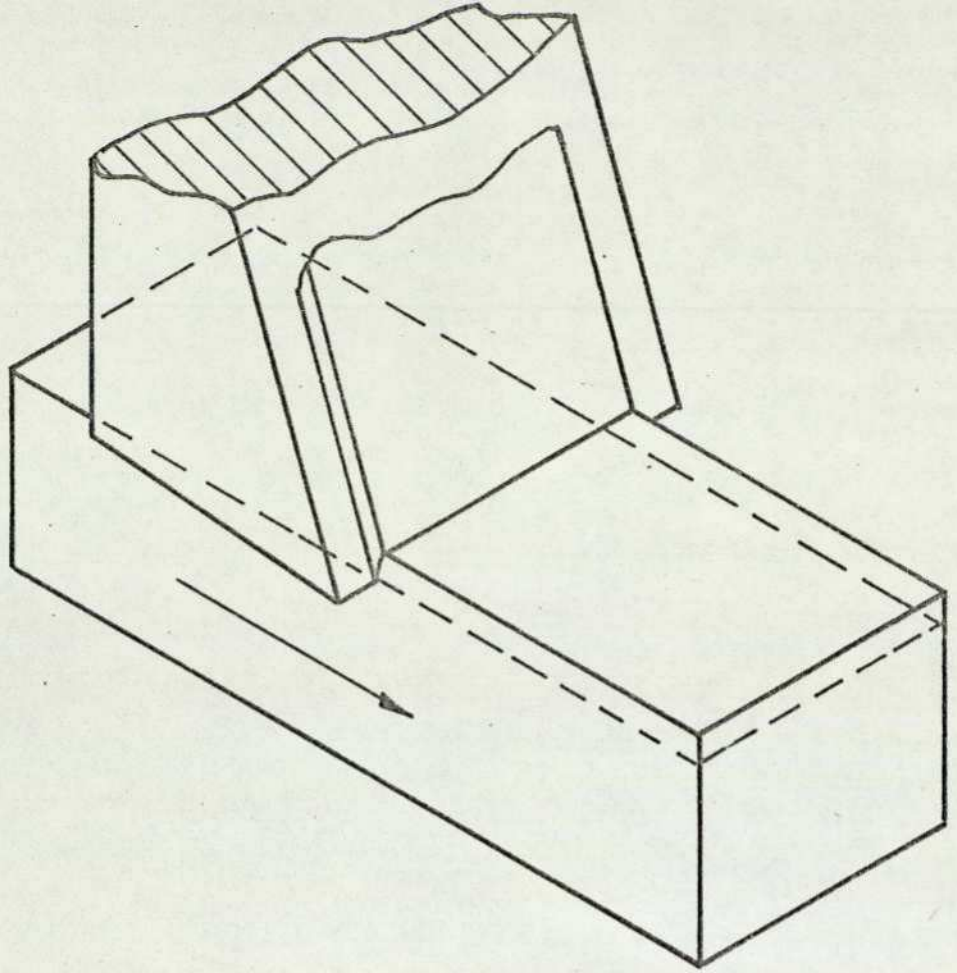
SHEAR PIN
BUSHES

QUICK STOP DEVICE

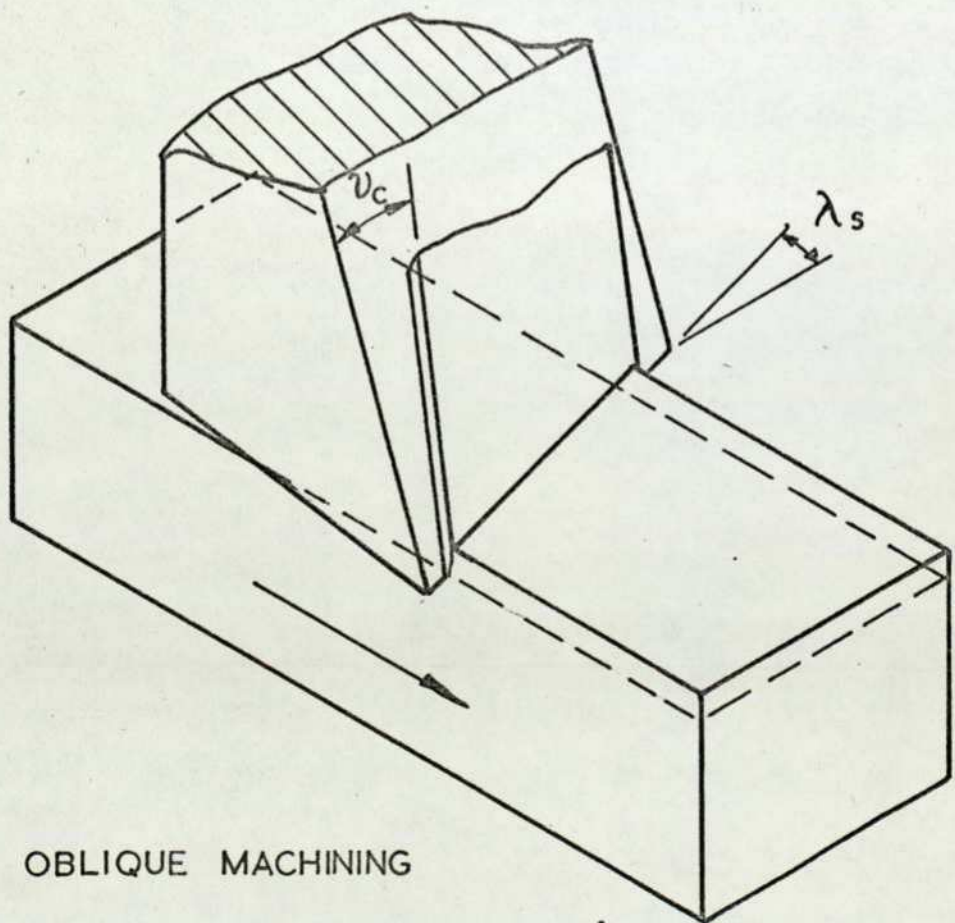
FIG. 2.13.



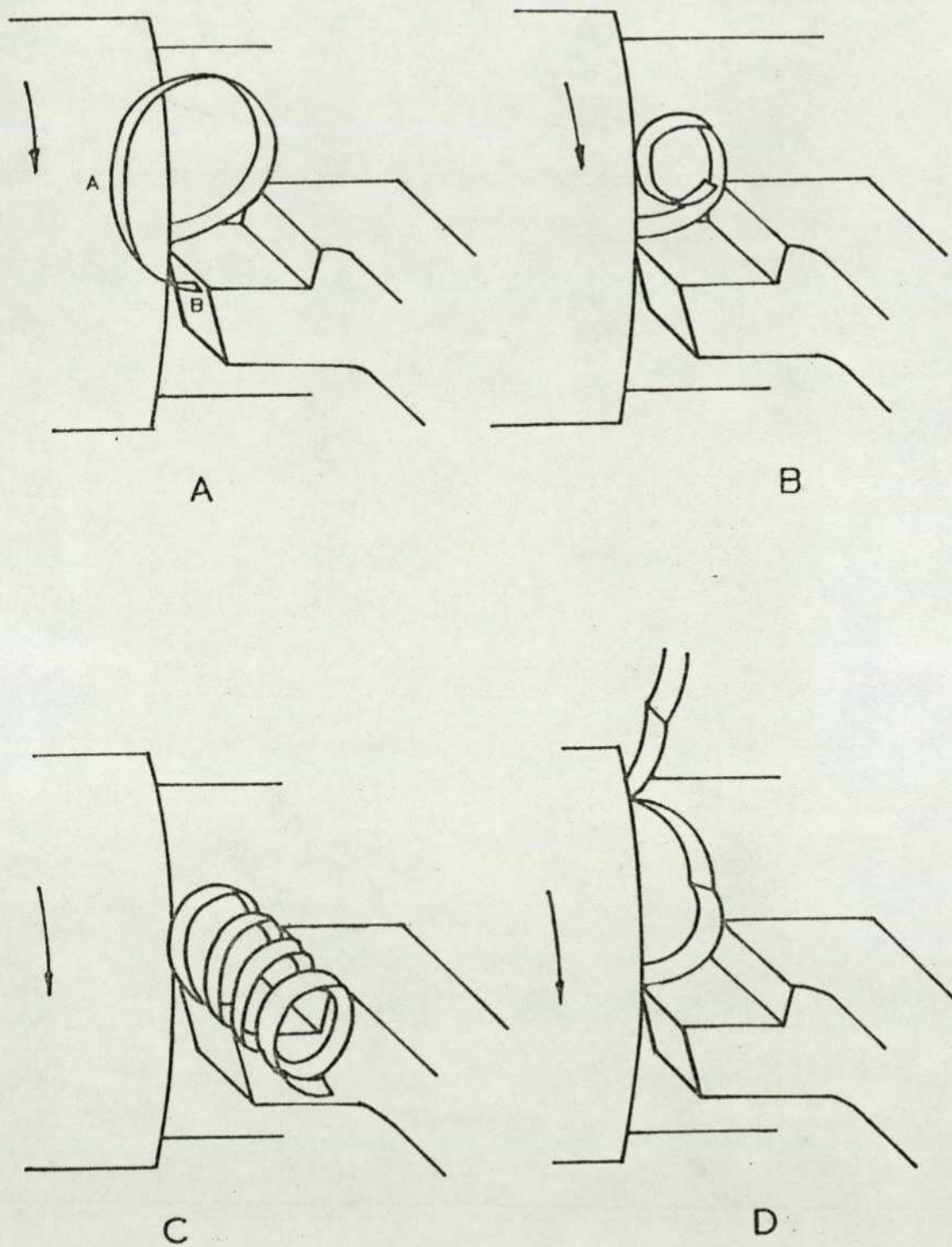
OPTICAL PRINCIPLE OF LIGHT SECTIONING MICROSCOPE



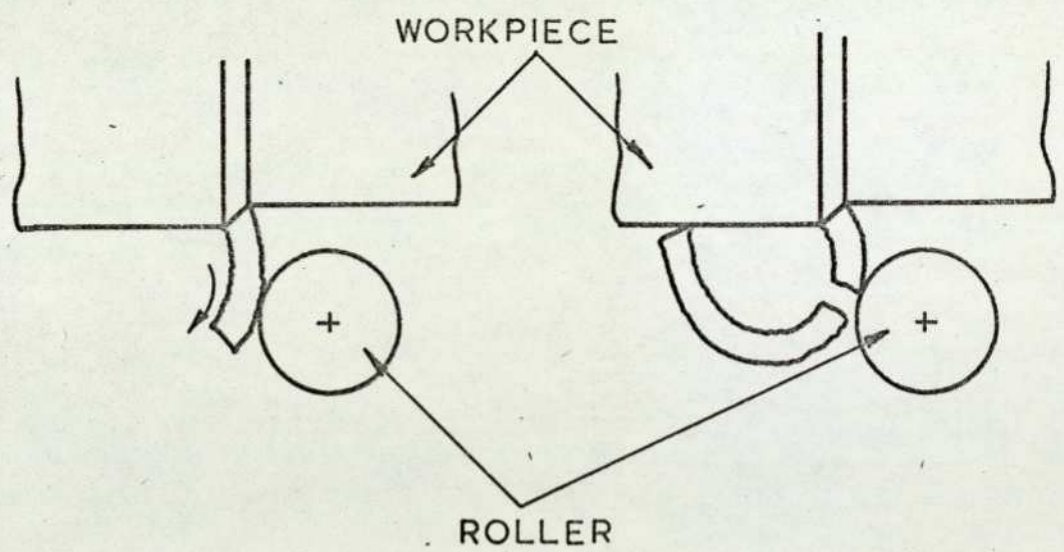
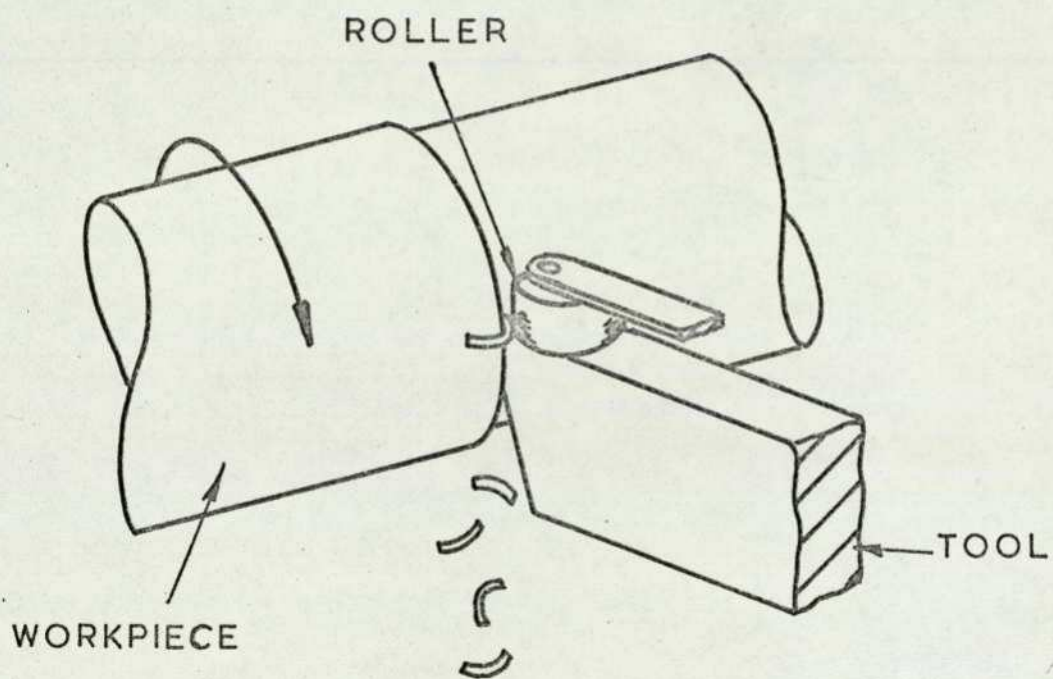
ORTHOGONAL MACHINING



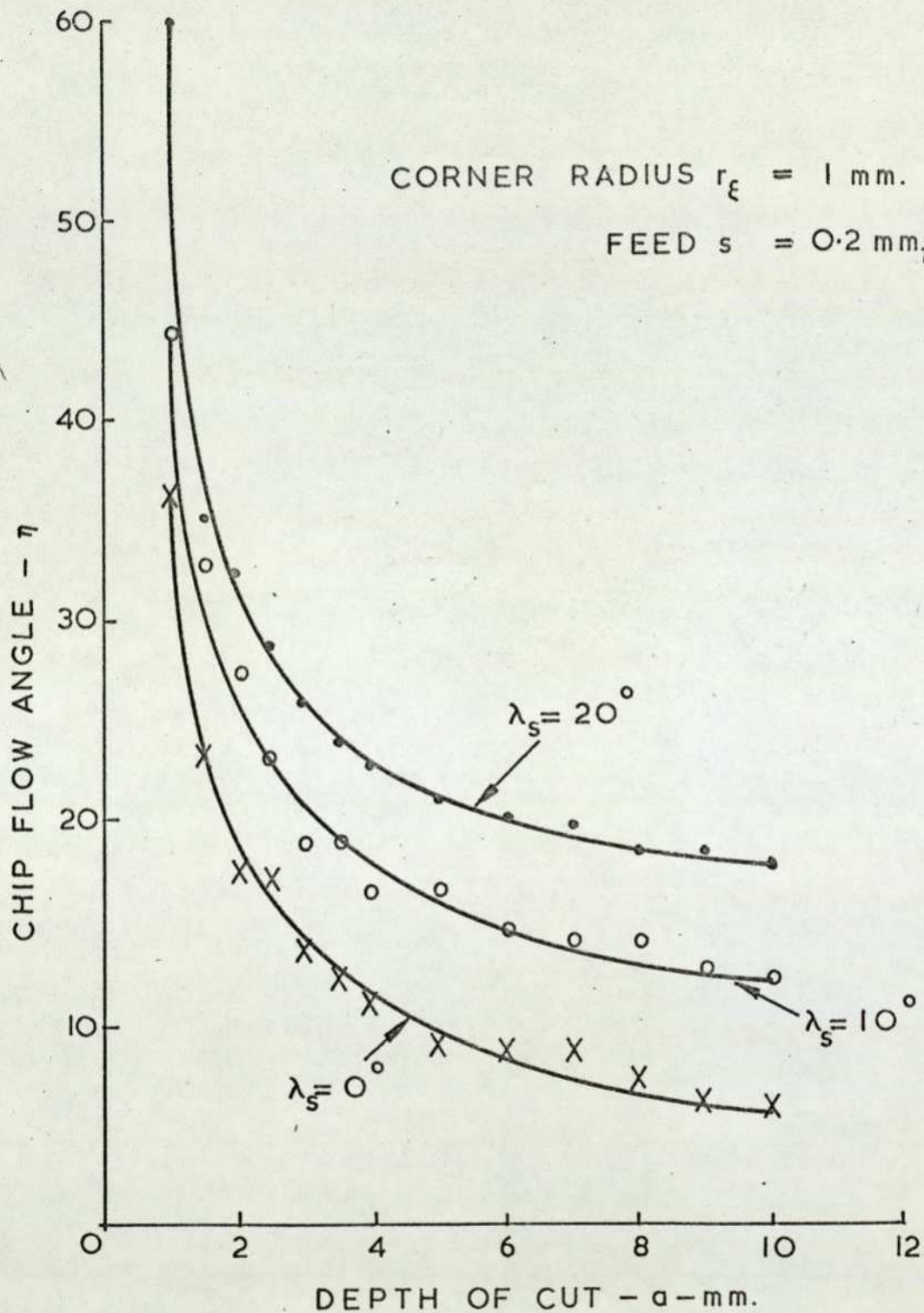
OBLIQUE MACHINING



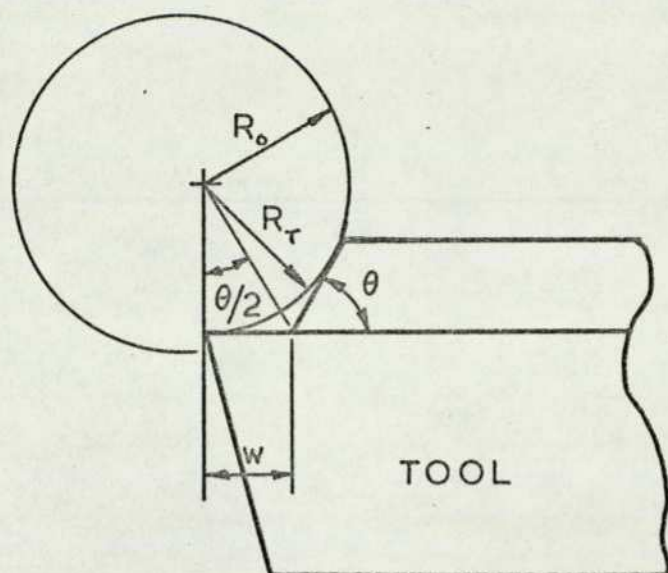
TYPES OF CHIP BREAKING ACTION - AFTER NAKAYAMA ⁽¹⁰⁾



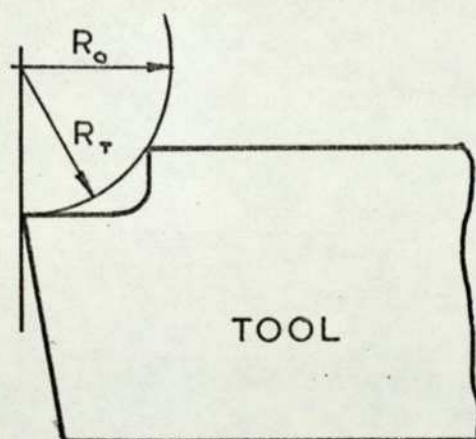
CHIP BREAKING ROLLER - AFTER IOFFE (21)



CHIP FLOW ANGLE VERSES DEPTH OF CUT
FOR VARIOUS INCLINATION ANGLES.
AFTER SPAANS ET-AL(17)

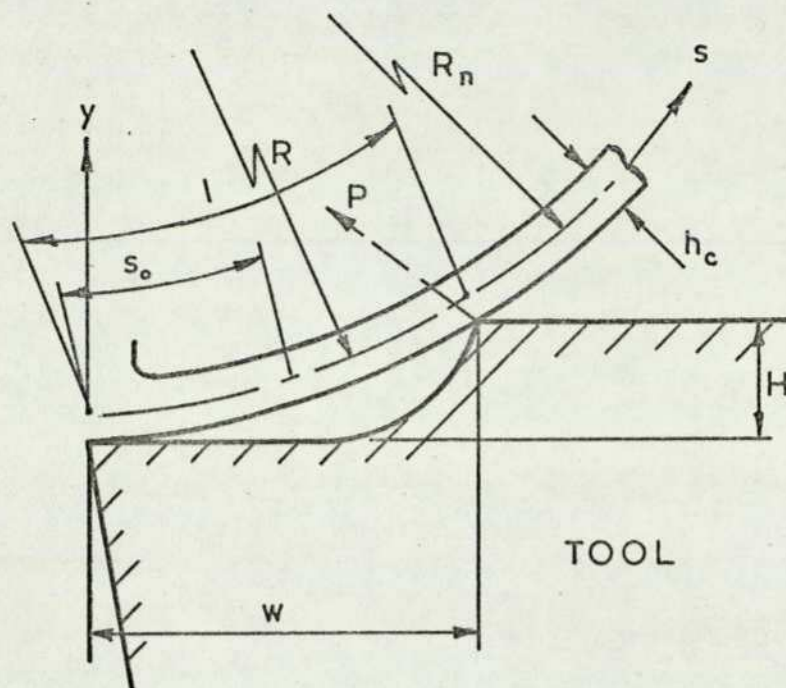


(a)

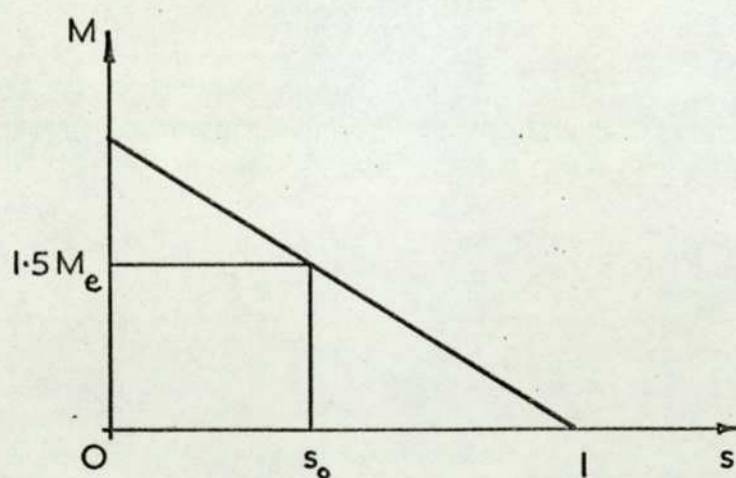


(b.)

CHIP FLOW CIRCLE WITH MODIFICATION
— AFTER HENRIKSEN (27)

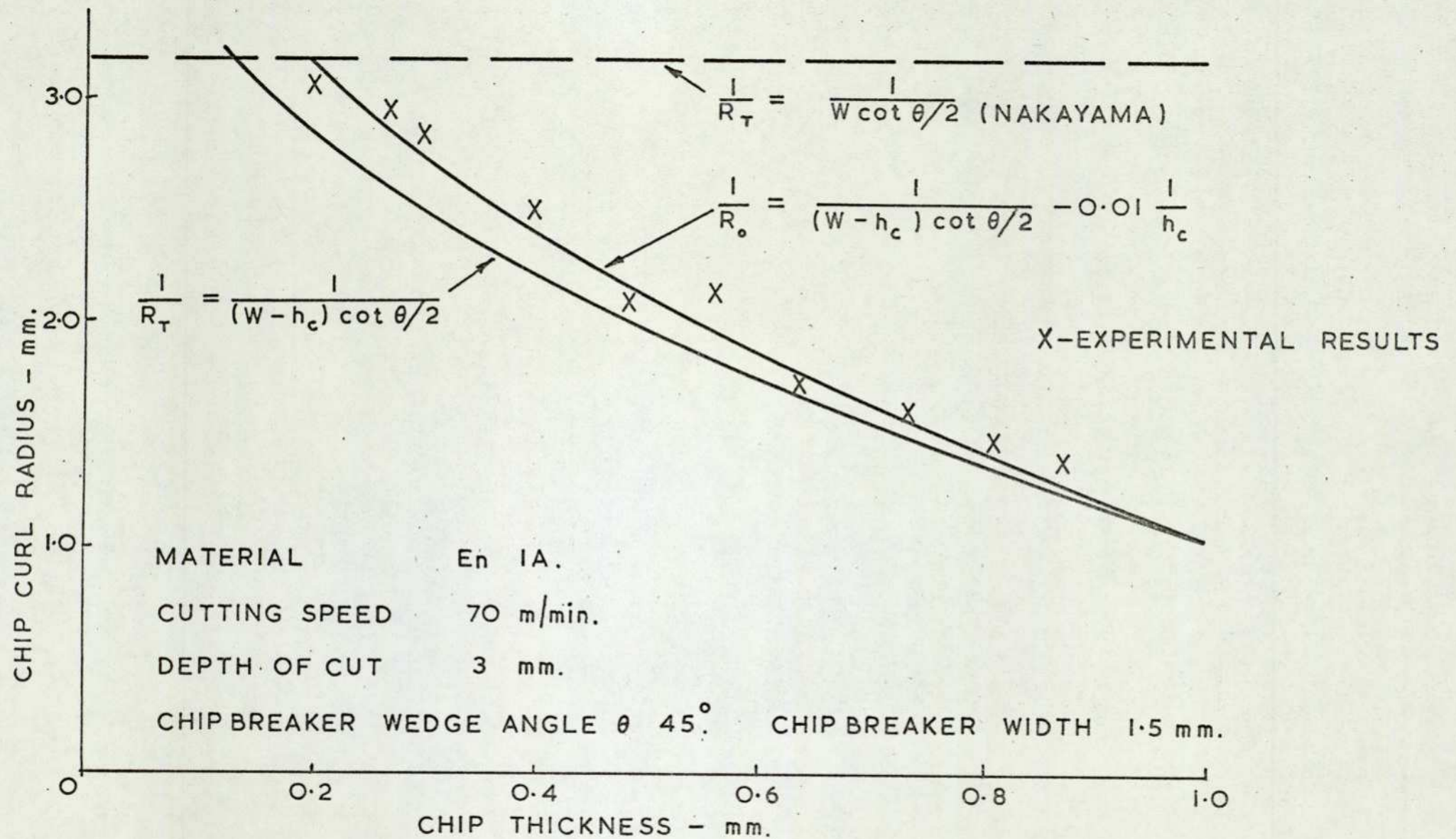


(a) ILLUSTRATION OF THE BENDING DEFORMATION OF THE CHIP



(b) DISTRIBUTION OF BENDING MOMENT

THE BENDING OF THE CHIP - AFTER OKUSHIMA(30)



COMPARISON BETWEEN THE EXPERIMENTAL (MEASURED) CHIP CURL RADIUS & THE THEORETICALLY CALCULATED -AFTER AL-MANDALAWI(32) FIG. 3.7.

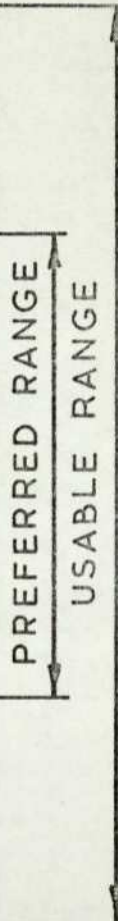
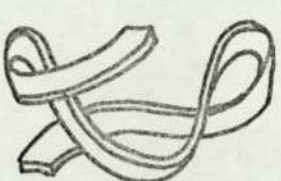
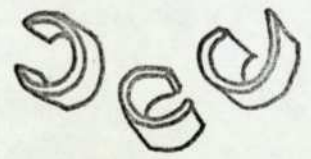
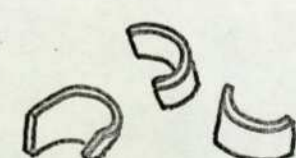
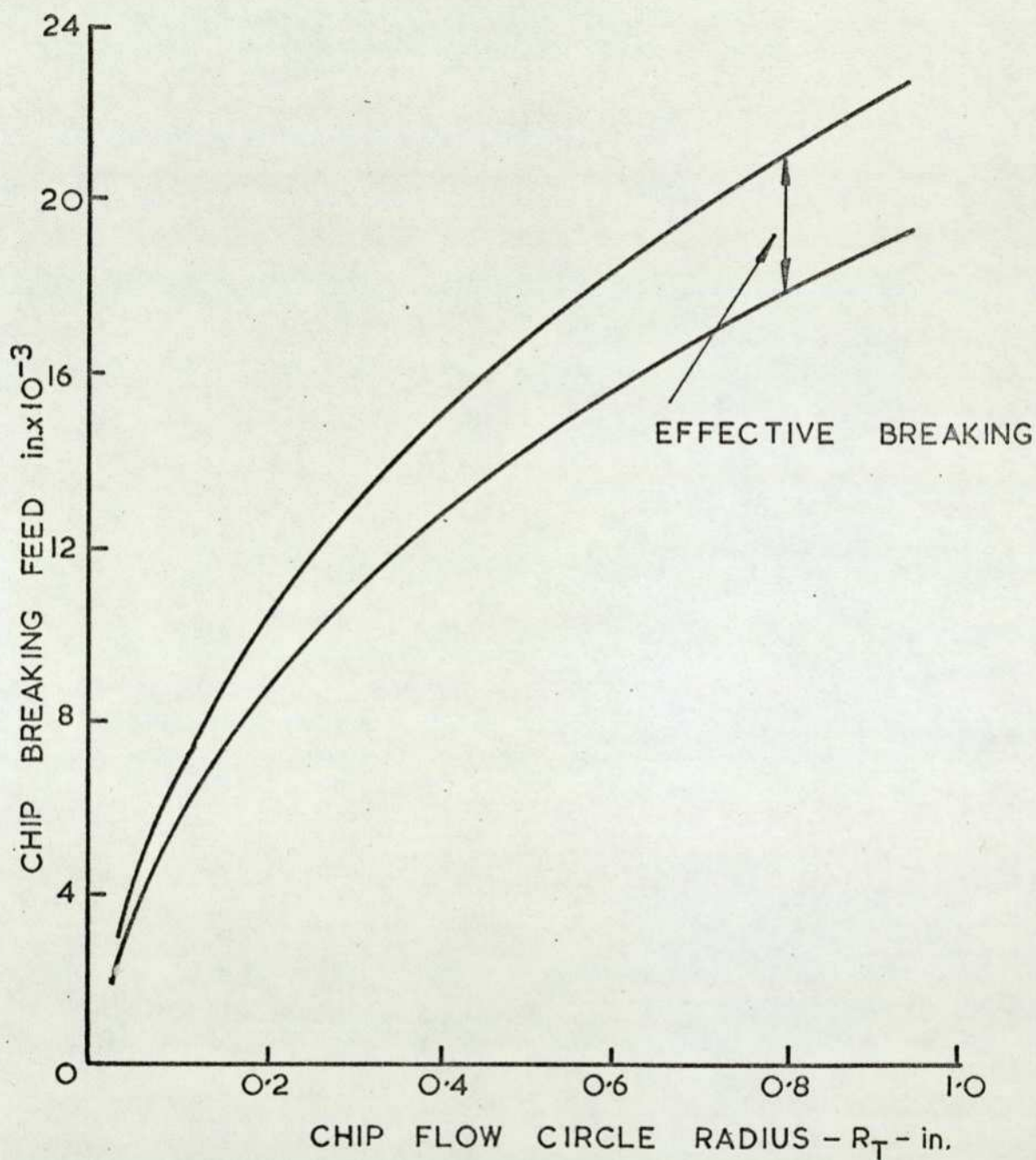
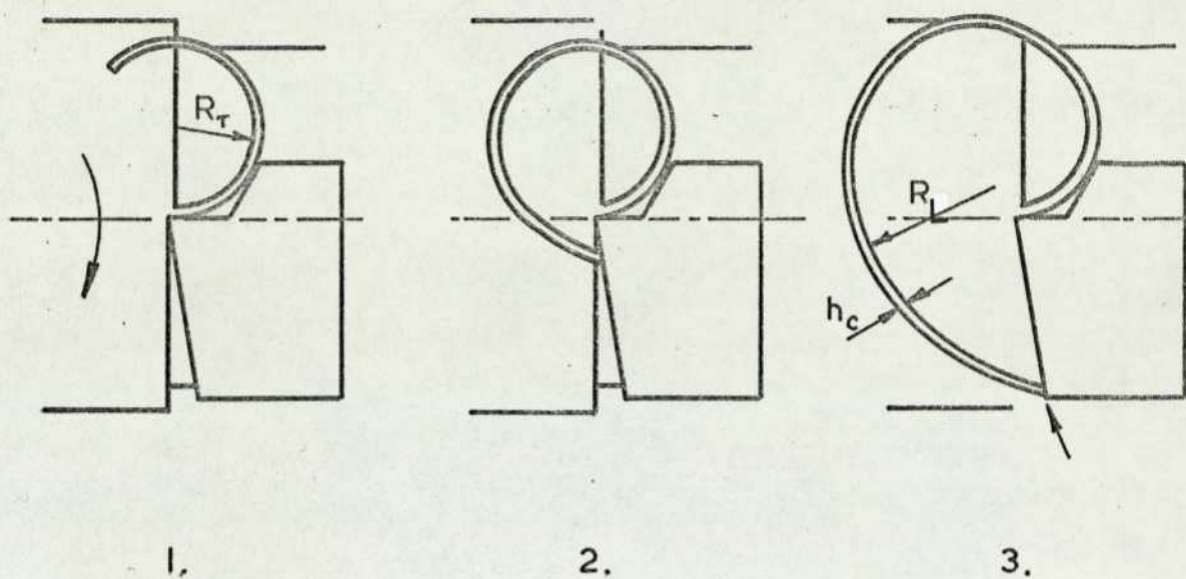
INCREASING FEED 	STRAIGHT CHIPS		 PREFERRED RANGE USABLE RANGE
	SNARLING CHIPS		
	INFINITE HELICES		
	REGULAR INTERMITTENTS		
	FULL TURNS		
	HALF TURNS		
	FRAGMENTS & SPLINTERS		

CHART FOR CHIP CLASSIFICATION

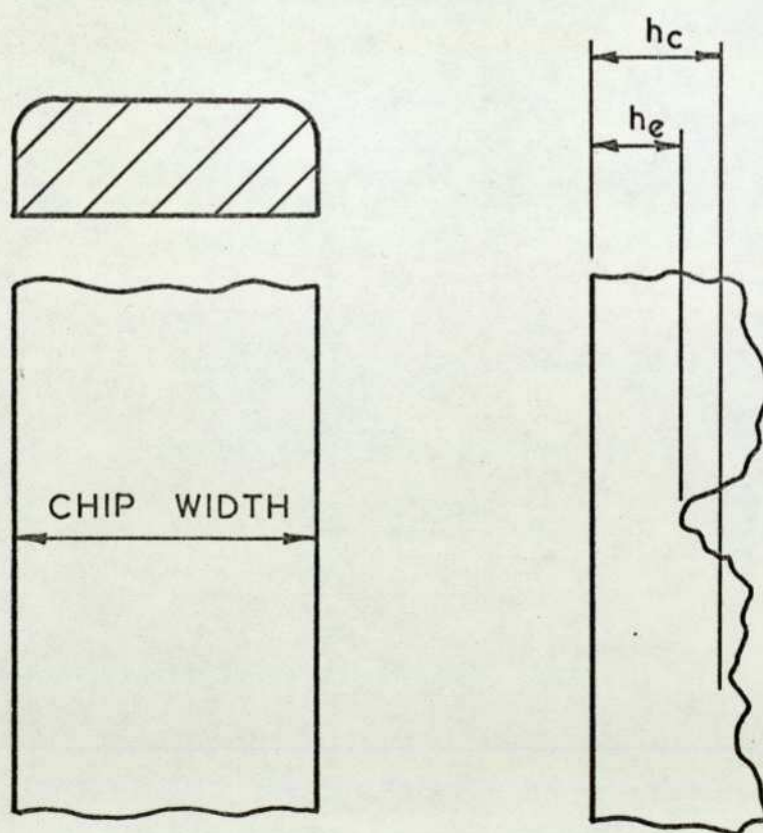
-AFTER HENRIKSEN (27)



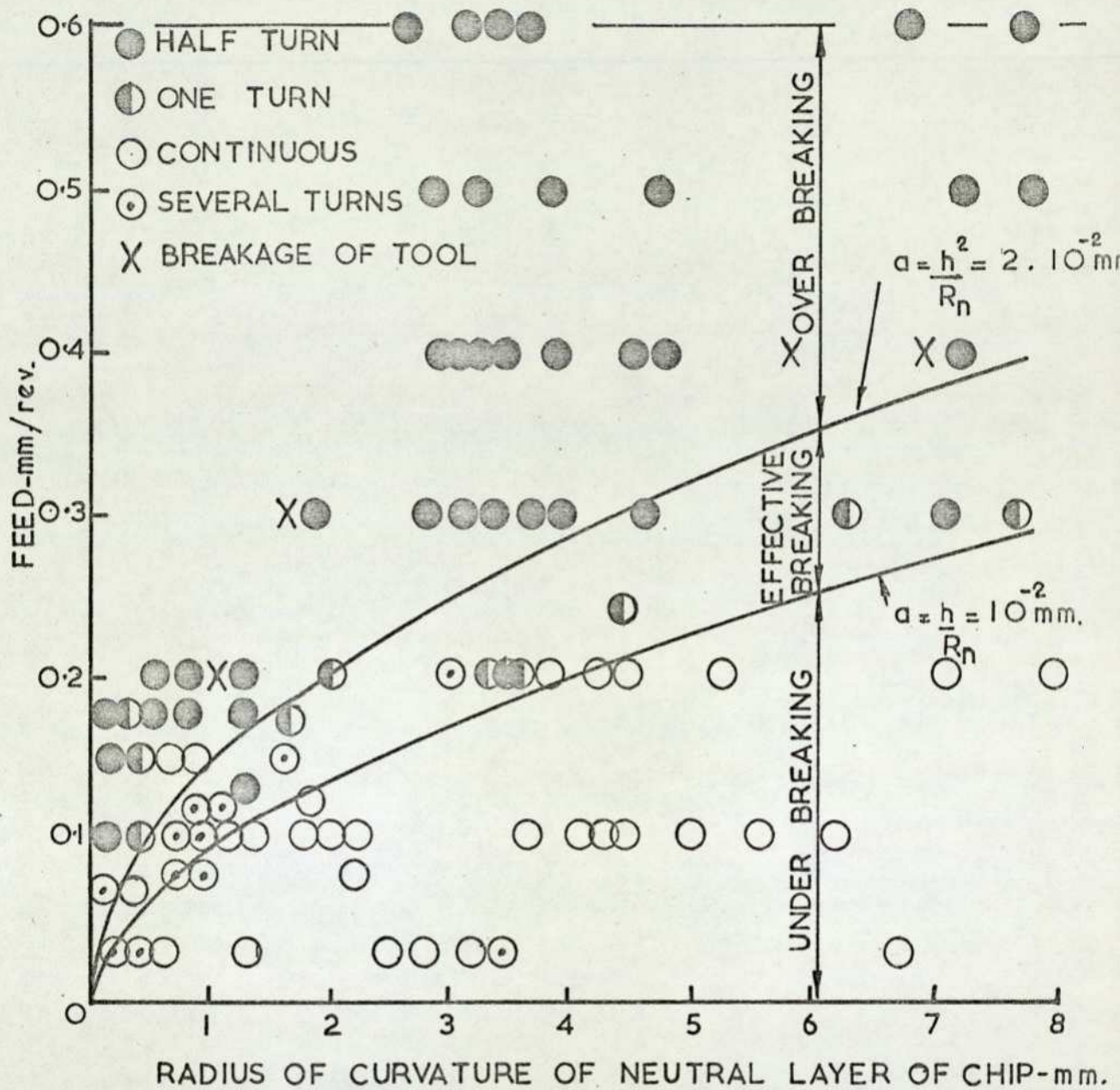
CHIP FLOW CIRCLE RADIUS VERSUS CHIP BREAKING
FEED FOR AN ANNEALED STEEL - AFTER HENRIKSEN(27)



(a) LIMITING CONDITION OF TYPE 'A' CHIP BREAKING



(b) EFFECT OF IRREGULARITY OF UPPERMOST OF CHIP
ON MECHANICAL PROPERTIES—AFTER NAKAYAMA (34)

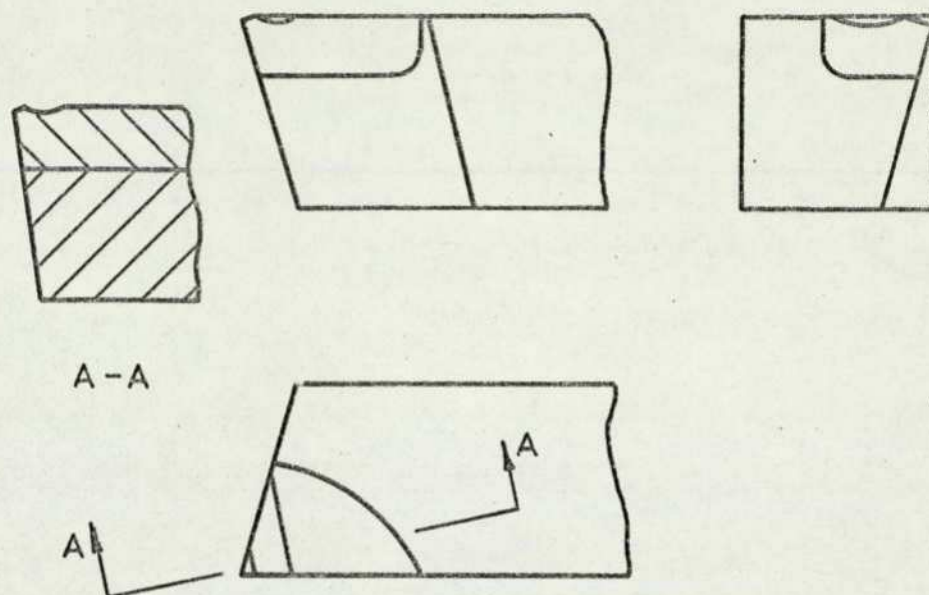


CALCULATED RADIUS OF CURVATURE VERSUS
FEED - AFTER OKUSHIMA ET AL(30)

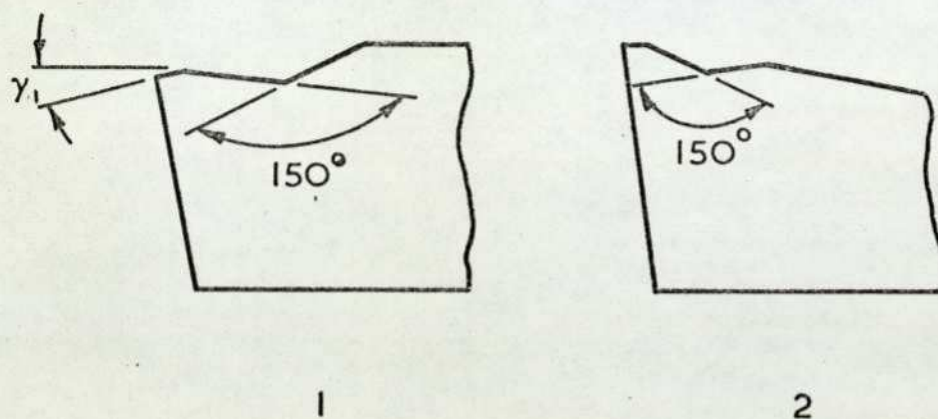
TOOL INCLINATION ANGLE λ_s	LAND RAKE γ_1	CUTTING EDGE ANGLE γ_r	ORTHOGONAL RAKE γ_0	GROOVE POSITION ON TOOL RAKE FACE	
FOR MACHINING COMPONENTS $\sigma_t \leq 80 \text{ kg/mm}^2$ & WITH A RIGID MACHINING SYSTEM	FOR COMPONENTS WITH DEFECTIVE SURFACE LAYER ALLOWANCE VARIATIONS & IMPACT LOADS	FOR ALL OTHER CASES	FOR MOST CASES	AT $s < 0.2 \text{ mm/rev}$ & $a < 1 \text{ mm}$. ALSO AT $r_\xi = 3 \text{ TO } 5 \text{ mm}$. & $a < 1.5 \text{ mm}$.	TYPE II GROOVE NORMAL TO CUTTING EDGE
	FOR MACHINING COMPONENTS WITH DEFECTIVE SURFACE LAYER	AT $s < 0.3 \text{ mm/rev}$ & $t > 1.0 \text{ mm}$.	WITH CHIPS OVER 100mm. IN LENGTH WHEN FURTHER REDUCTION IN LAND SIZE CAUSES CHATTER & CHIPPING OF LAND	AT $a > 1 \text{ mm}$. & $s > 0.2 \text{ mm/rev}$	TYPE I GROOVE PARALLEL TO CUTTING EDGE
FOR SEMI-FINISH & FINISH MACHINING OF COMPONENTS WITH $\sigma_t \leq 80 \text{ kg/mm}^2$ & INSUFFICIENT RIGIDITY OF MACHINING SYSTEM	FOR SEMI-FINISH & FINISH MACHINING				

NOTE: THE REMAINING FACTORS OF TOOL GEOMETRY ARE THE SAME AS IN CONVENTIONAL TOOLS

* AT $s \geq 0.8 \text{ mm}$. LAND ANGLE FROM 15° TO 20° IS MADE $0.4 - 0.6 \text{ mm}$. WIDE

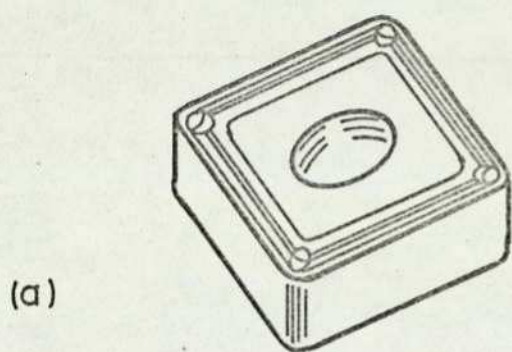


(a) TOOL WITH DIFFERENT ORIENTATION OF GROOVE
—AFTER SKURATOV (40)

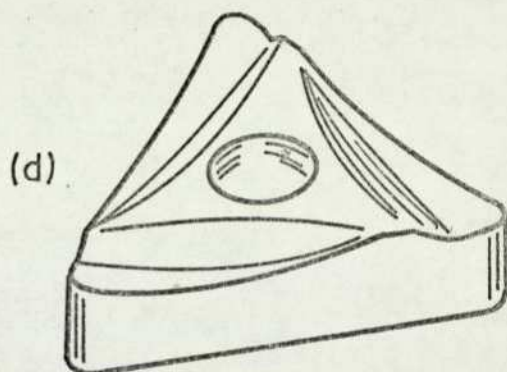


(b) TOOLS WITH VEE TYPE CHIP-CURLING GROOVES
—AFTER IGOSHIN (41)
1) SMALL ACTUAL RAKE ANGLE
2) LARGE ACTUAL RAKE ANGLE

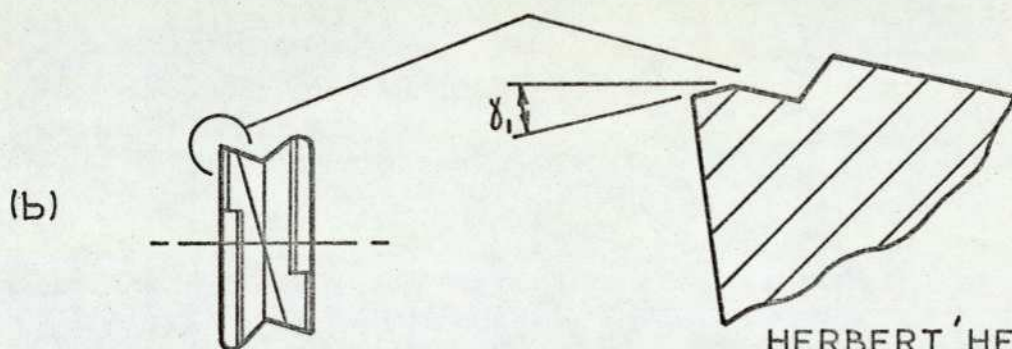
TOOLS WITH DIFFERENT GROOVE ORIENTATIONS
& VEE TYPE GROOVES



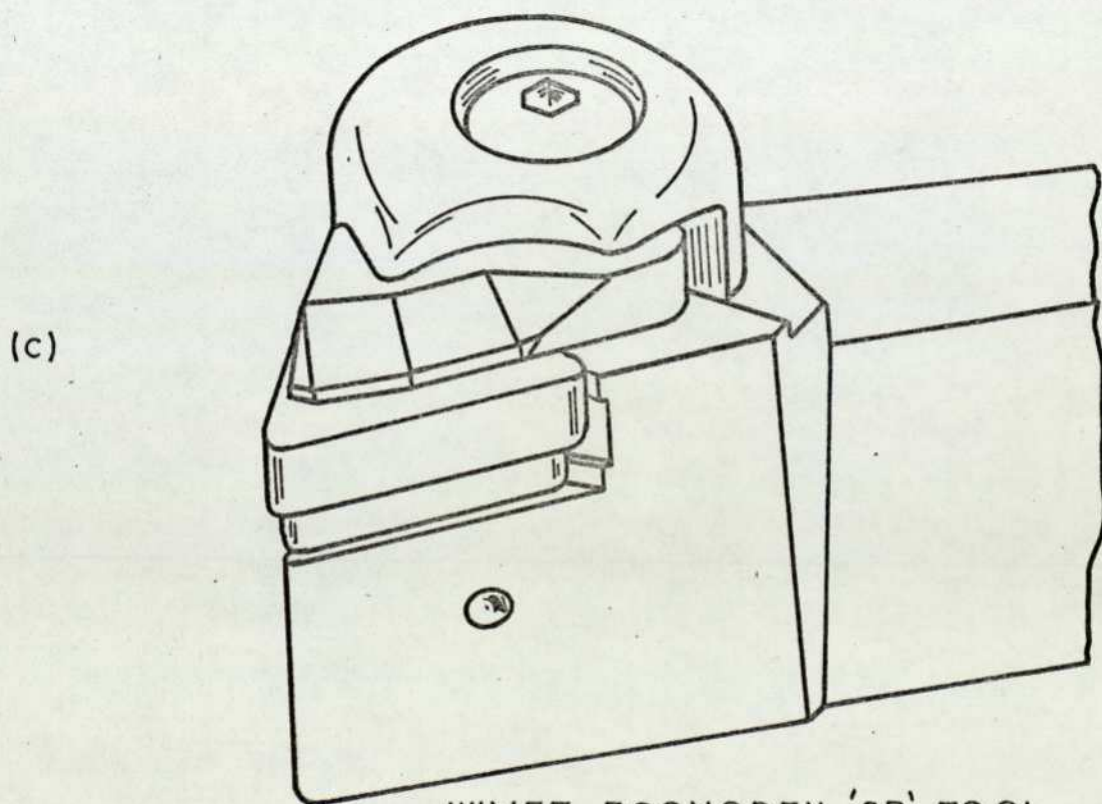
SANDVIK 'TRIPLE GROOVE'
TOOL



VALENITE -MODCO
POSITIVE -NEGATIVE
TOOL

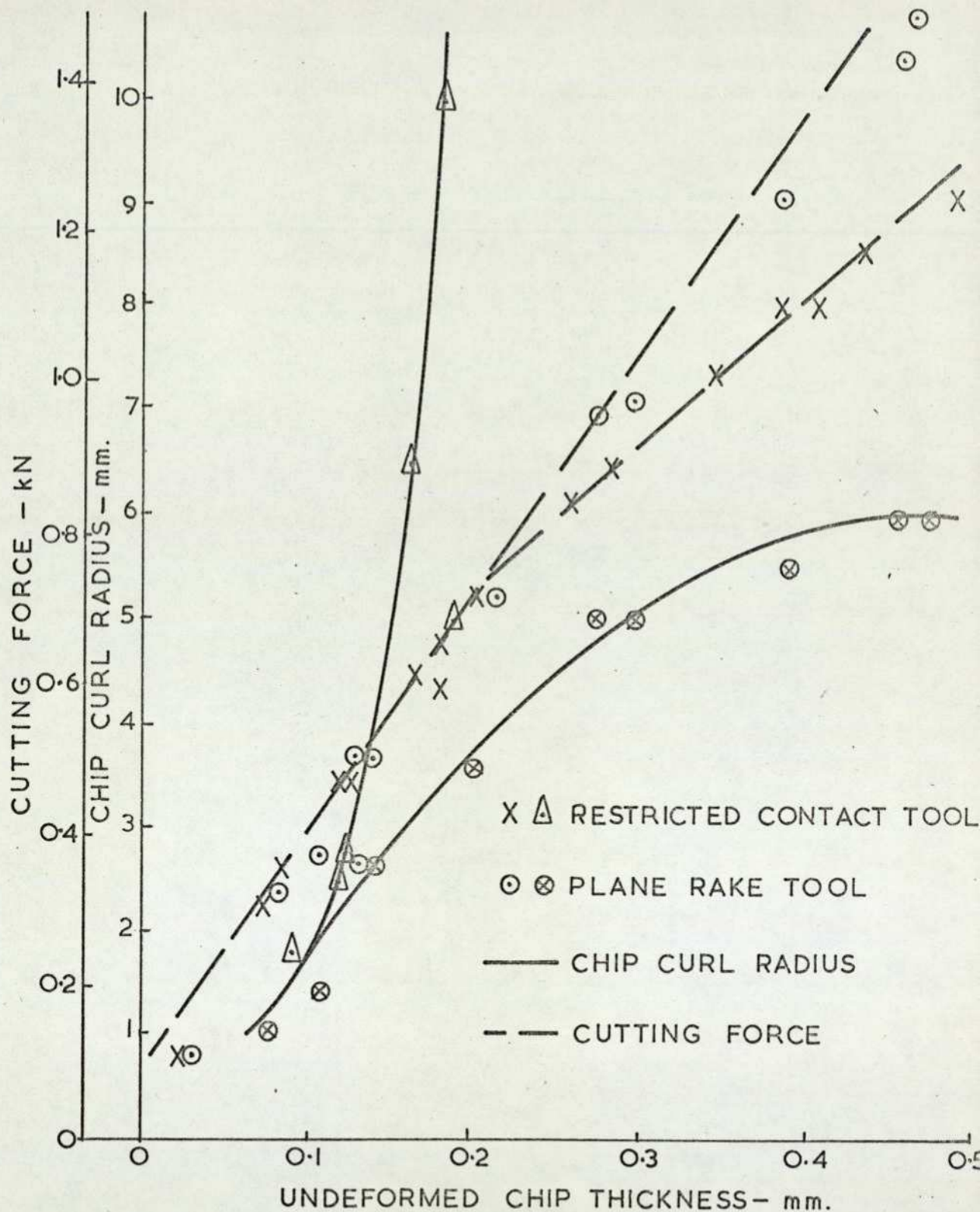


HERBERT 'HERTEL' TOOL



WIMET ECONODEX 'SP' TOOL

SOME COMMERCIAL CHIP BREAKERS



EXPERIMENTAL RELATIONSHIP BETWEEN

UNDEFORMED CHIP THICKNESS, & CUTTING

FORCE & CHIP CURL RADIUS FOR A PLANE RAKE

& A RESTRICTED CONTACT LENGTH TOOL

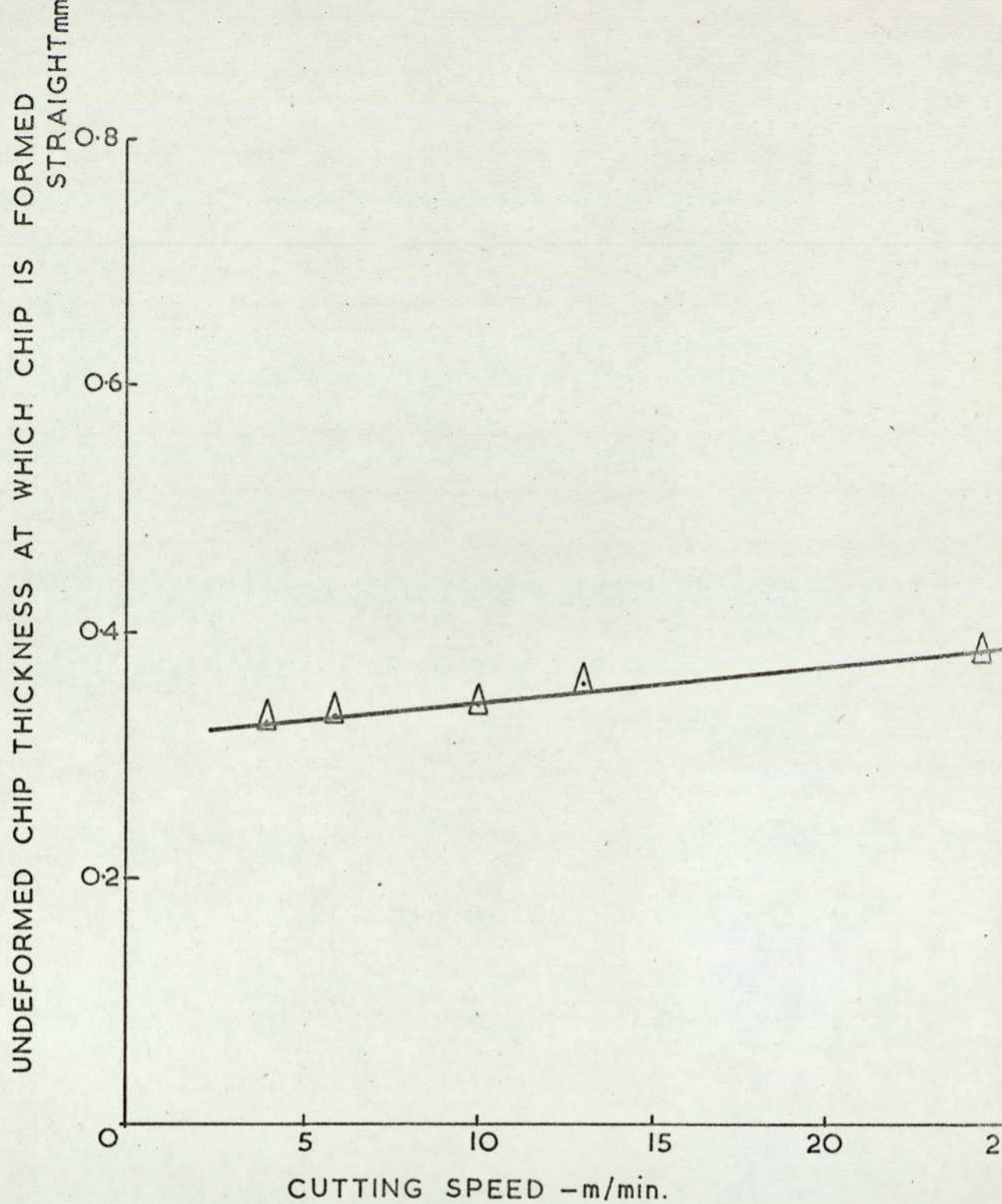
RESTRICTED CONTACT LENGTH 0.39 mm.

MATERIAL En 1A. PRIMARY RAKE ANGLE 20° .

SECONDARY RAKE ANGLE 60° .

CUTTING SPEED 2.5 m/min

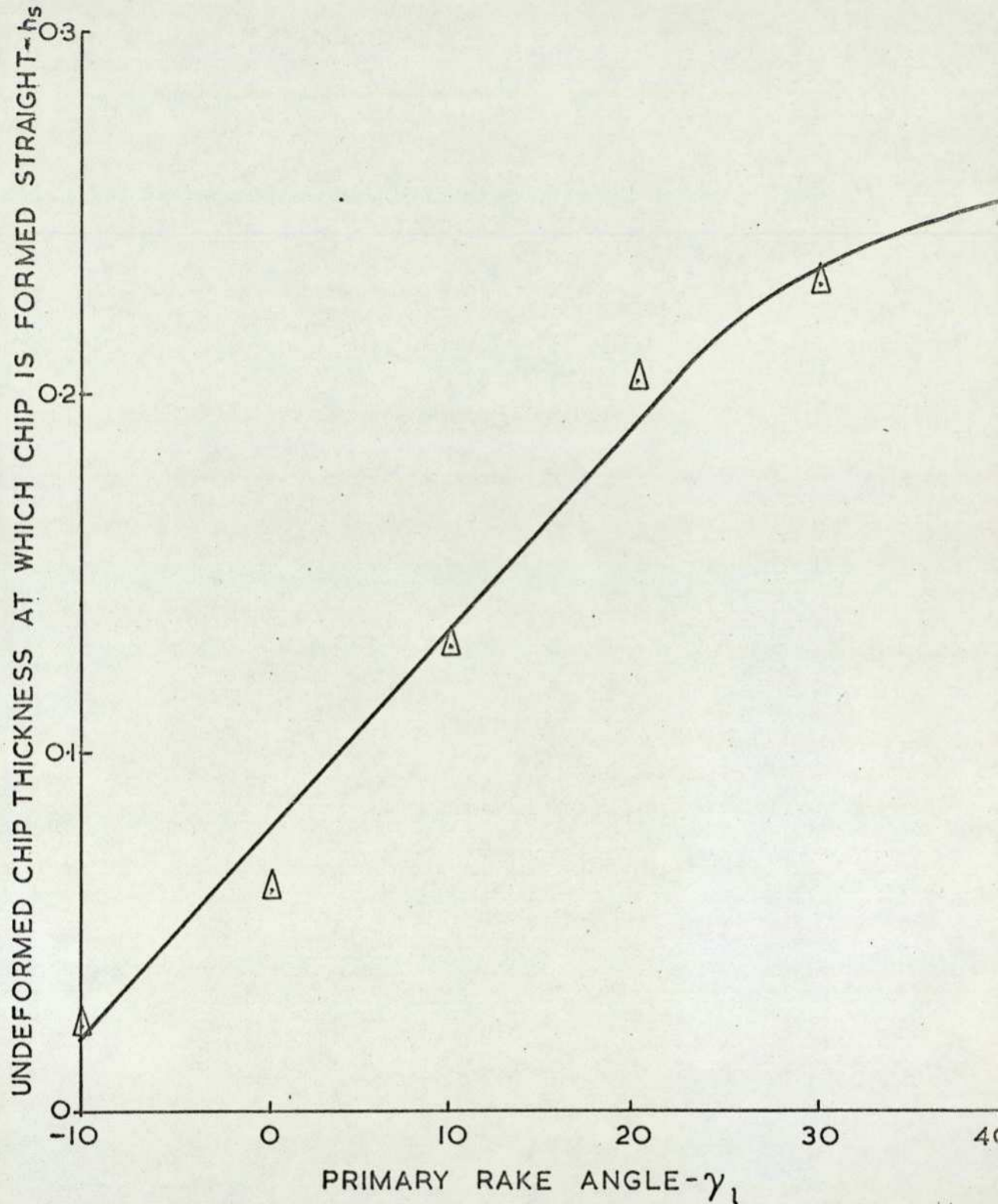
FIG. 4.1.



EXPERIMENTAL RESULTS SHOWING THE
RELATIONSHIP BETWEEN U.C.T. AT WHICH CHIP
IS FORMED STRAIGHT & CUTTING SPEED

MATERIAL En 8. $\gamma_1 = 20^\circ$. $\gamma_2 = 45^\circ$. $b_{\gamma r} = 1.0 \text{ mm}$.

FIG. 4.2.



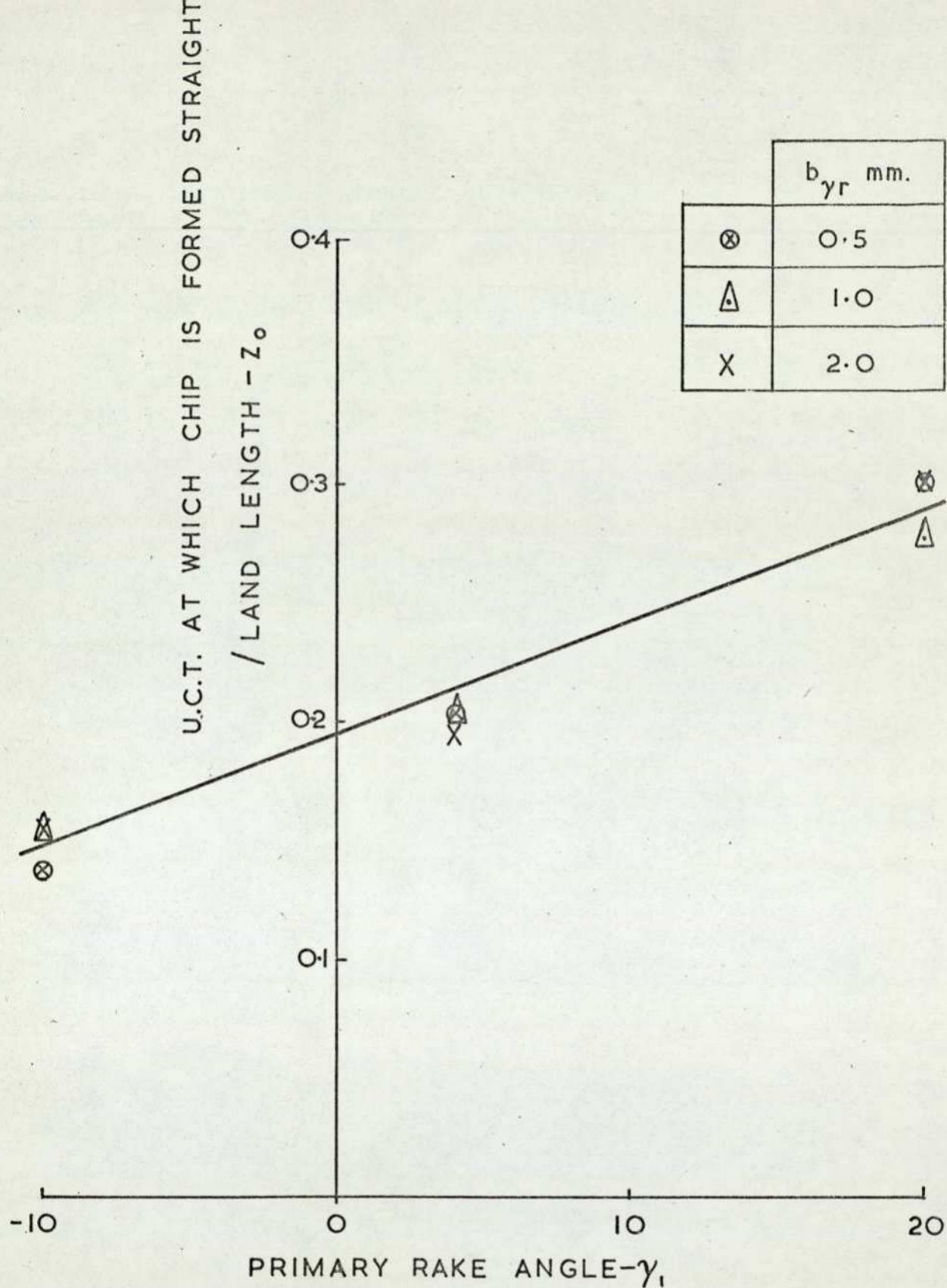
EXPERIMENTAL RESULTS SHOWING THE RELATIONSHIP
BETWEEN PRIMARY RAKE ANGLE & UNDEFORMED CHIP
THICKNESS AT WHICH THE CHIP IS FORMED
STRAIGHT

MATERIAL En 1A. PRIMARY LAND LENGTH 0.4 mm.

SECONDARY RAKE ANGLE 60° .

CUTTING SPEED 2.5 m/min.

FIG. 4.3.



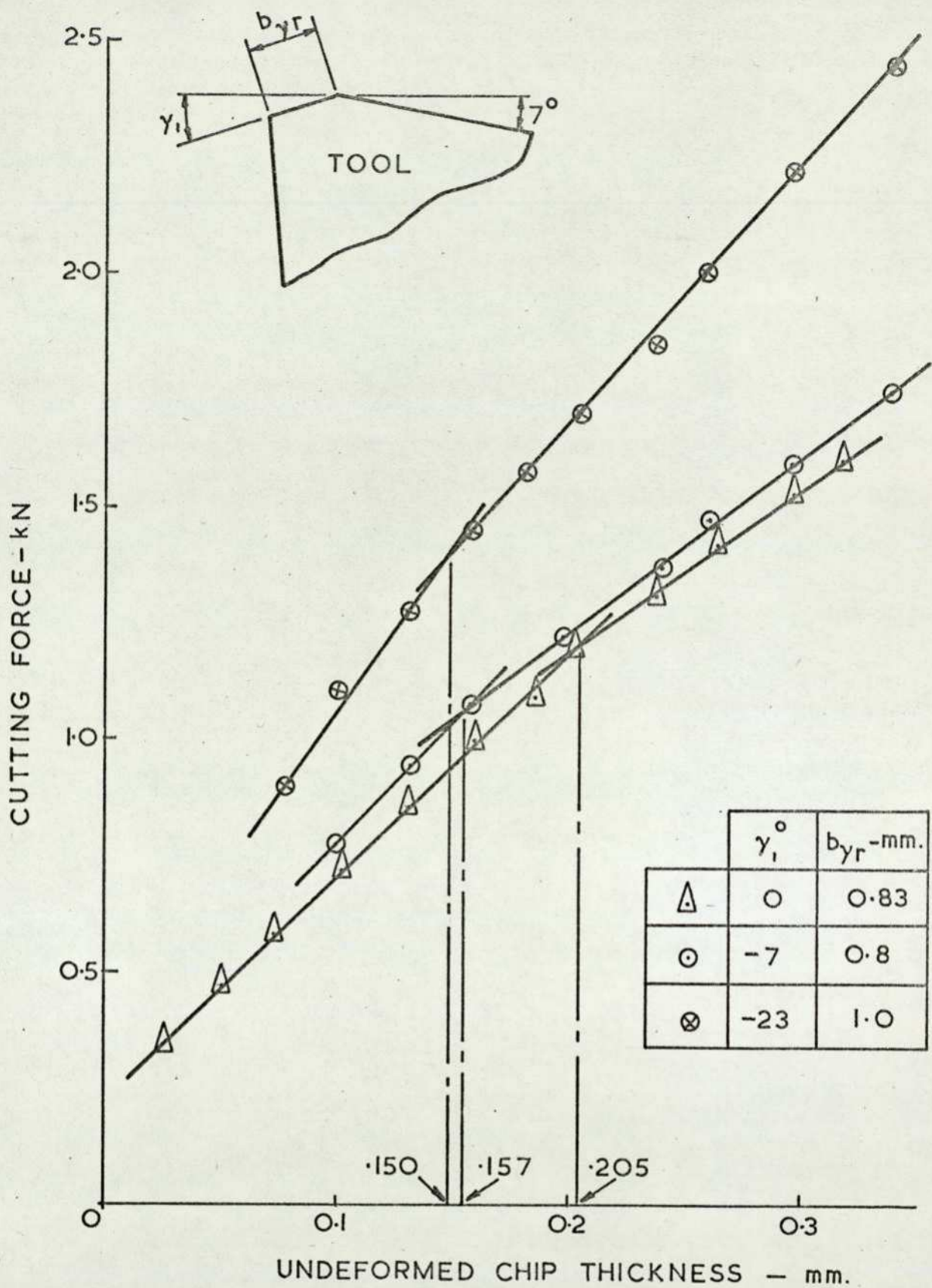
EXPERIMENTAL RESULTS SHOWING THE

RELATIONSHIP BETWEEN THE RATIO U.C.T. AT
WHICH CHIP IS FORMED STRAIGHT / LAND
LENGTH & THE PRIMARY RAKE ANGLE

MATERIAL En 8. CUTTING SPEED 10 m/min.

SECONDARY RAKE ANGLE $\gamma_2 = 45^\circ$

FIG. 4.4.



EXPERIMENTAL RESULTS SHOWING DISCONTINUITY
IN CURVE WHEN LENGTH OF ZONE OF STICKING
FRICTION EQUALS LAND LENGTH FOR TOOLS
OF DIFFERENT P.R.A.

MATERIAL CDS.1. CUTTING SPEED 120 m/min.

FIG.4.5.

WIDTH OF CUT 4 mm.

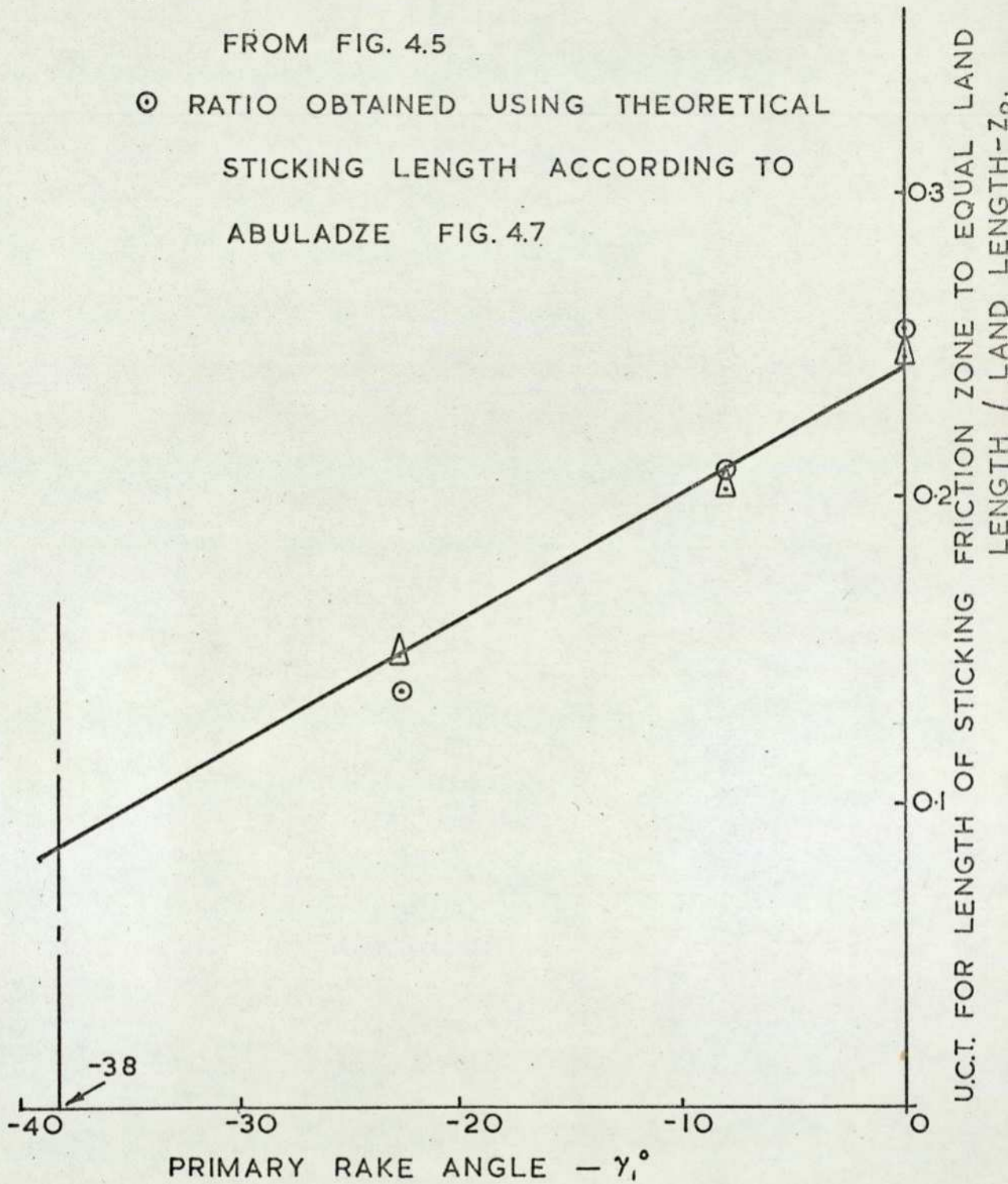
△ EXPERIMENTAL RATIO OBTAINED

FROM FIG. 4.5

⊙ RATIO OBTAINED USING THEORETICAL

STICKING LENGTH ACCORDING TO

ABULADZE FIG. 4.7

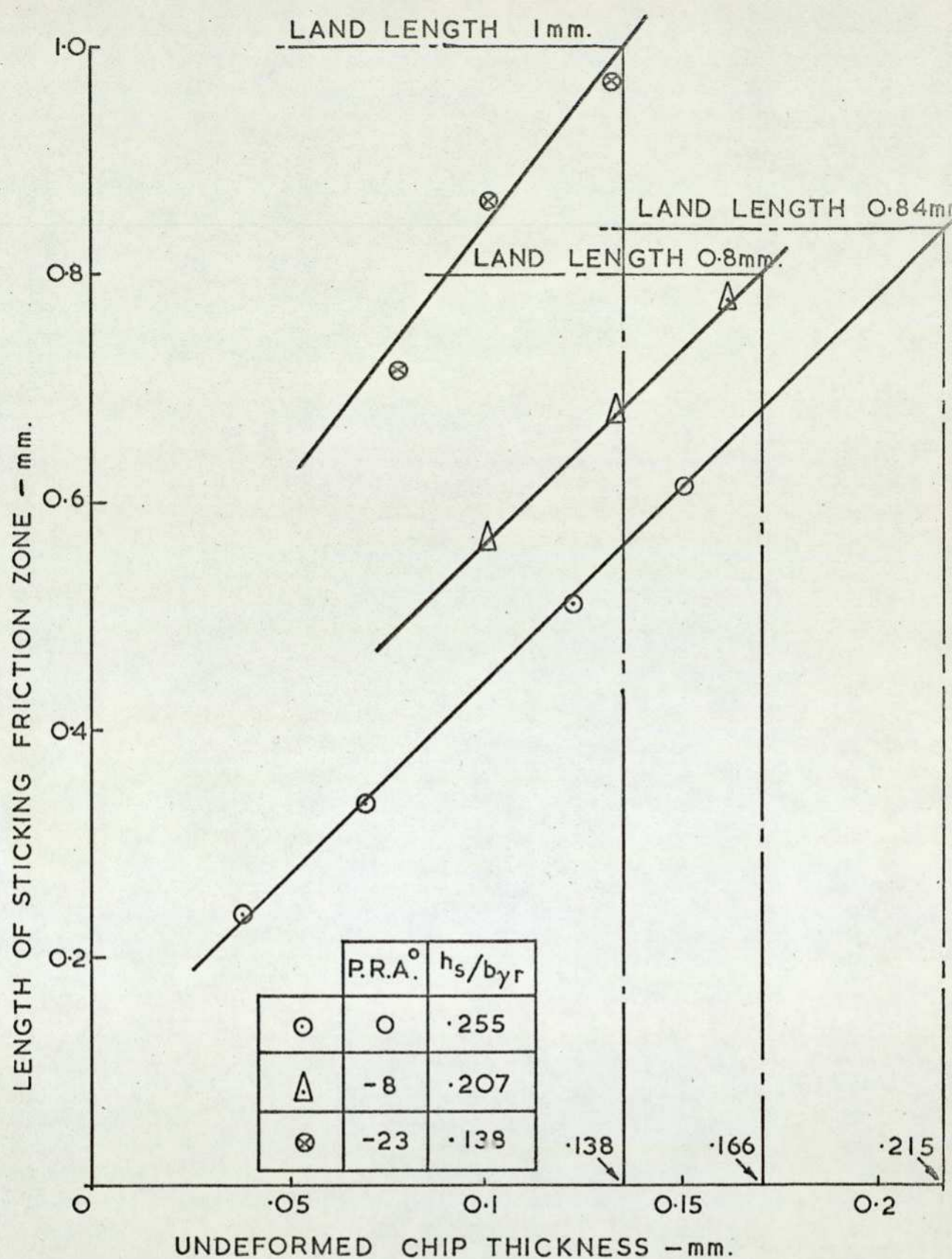


RELATIONSHIP BETWEEN PRIMARY RAKE ANGLE
& RATIO, LENGTH OF STICKING ZONE / LAND
LENGTH, Z_0 .

MATERIAL CDS I. CUTTING SPEED 120 m/min.

WIDTH OF CUT 4 mm.

FIG. 4.6.



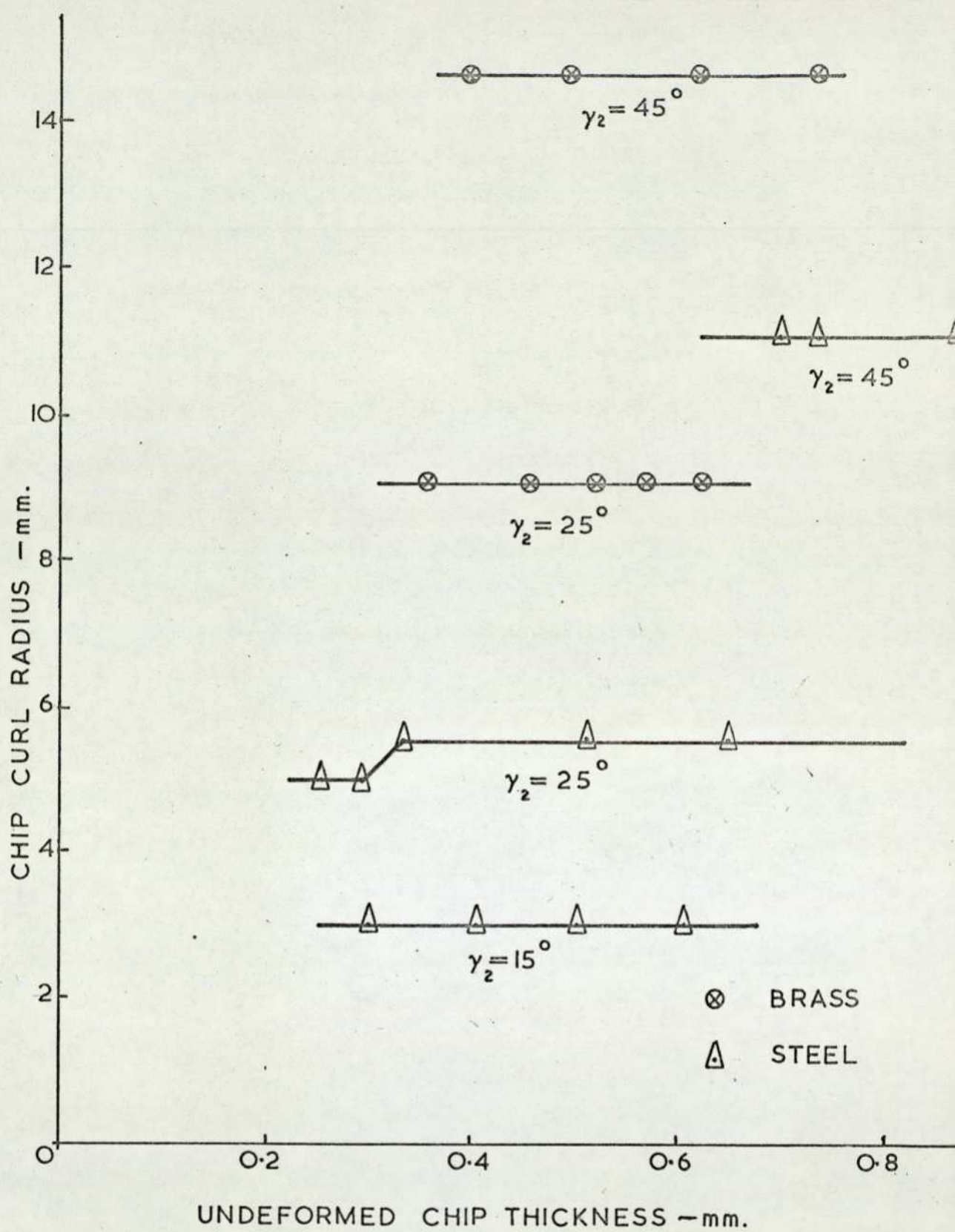
RELATIONSHIP BETWEEN LENGTH OF ZONE OF STICKING FRICTION ACCORDING TO ABULADZE'S EQUATION & UNDEFORMED CHIP THICKNESS, FOR TOOLS OF DIFFERENT P.R.A.

MATERIAL CDS1. CUTTING SPEED 120 m/min.

WIDTH OF CUT 4 mm.

SECONDARY RAKE ANGLE 7°.

FIG. 4.7.



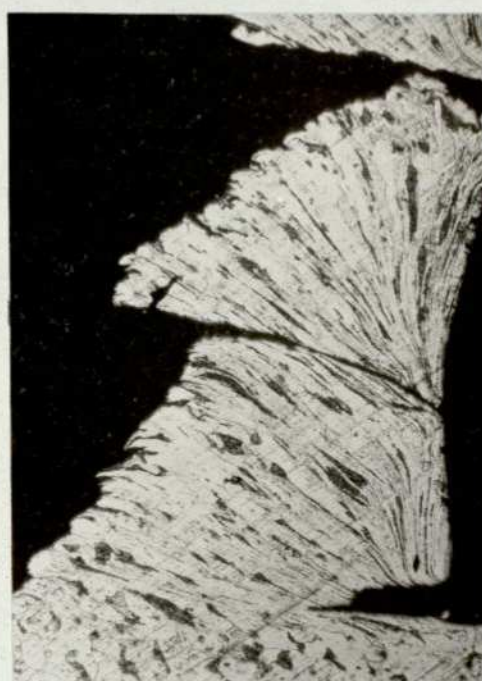
THE EFFECT OF SECONDARY RAKE ANGLE γ_2 &
 WORKPIECE MATERIAL ON CHIP CURL RADIUS
 FOR $h > h_s$

PRIMARY RAKE ANGLE 0° . LAND LENGTH 0.4 mm.

CUTTING SPEED 2.5 m/min.



X 70



X 70



X 70

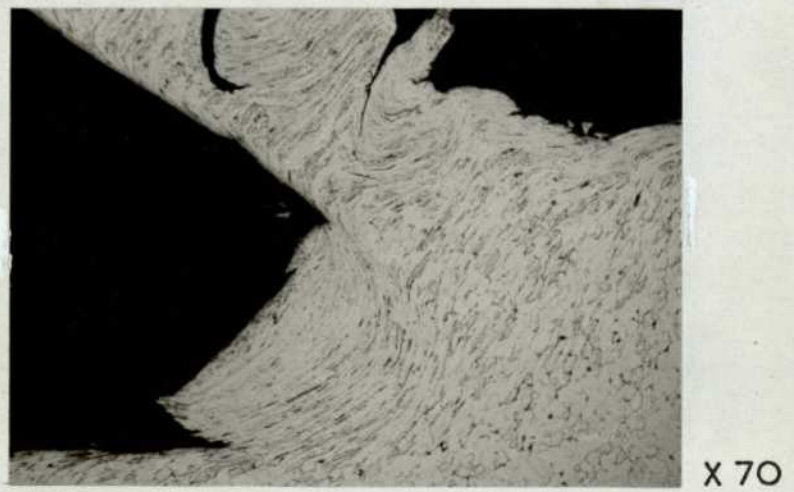
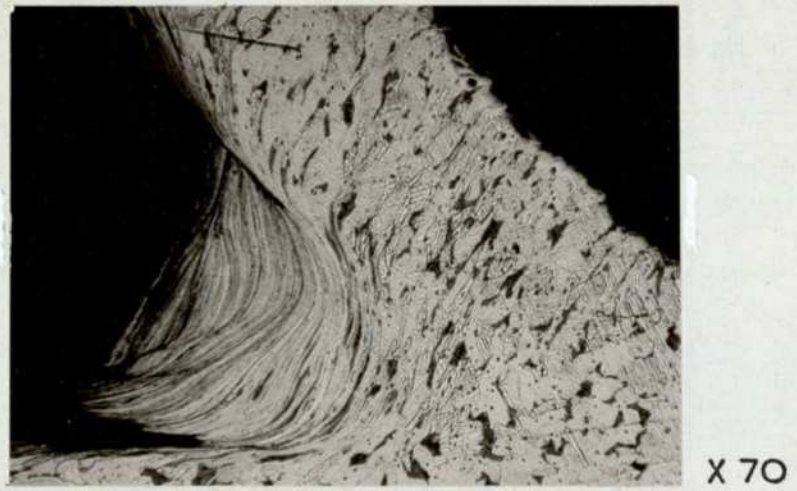
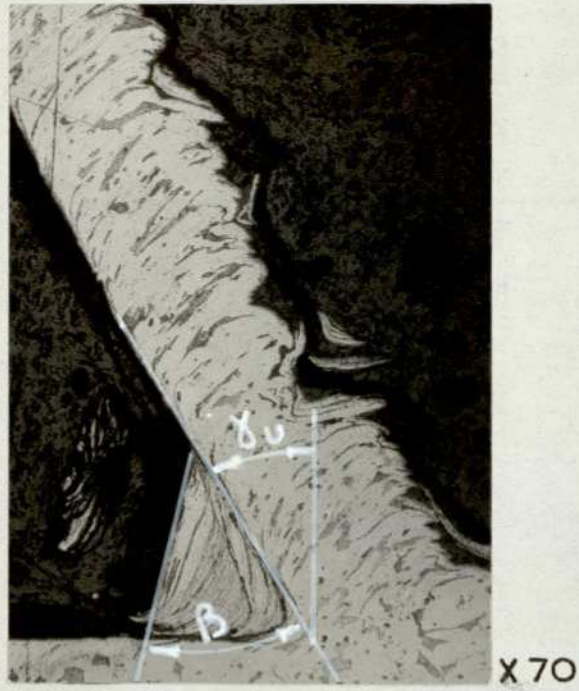
INCREASING FEED

a. THREE PHASES OF CHIP FORMATION
PHOTOMICROGRAPHS OF THE QUICKLY STOPPED
CUTTING ACTION

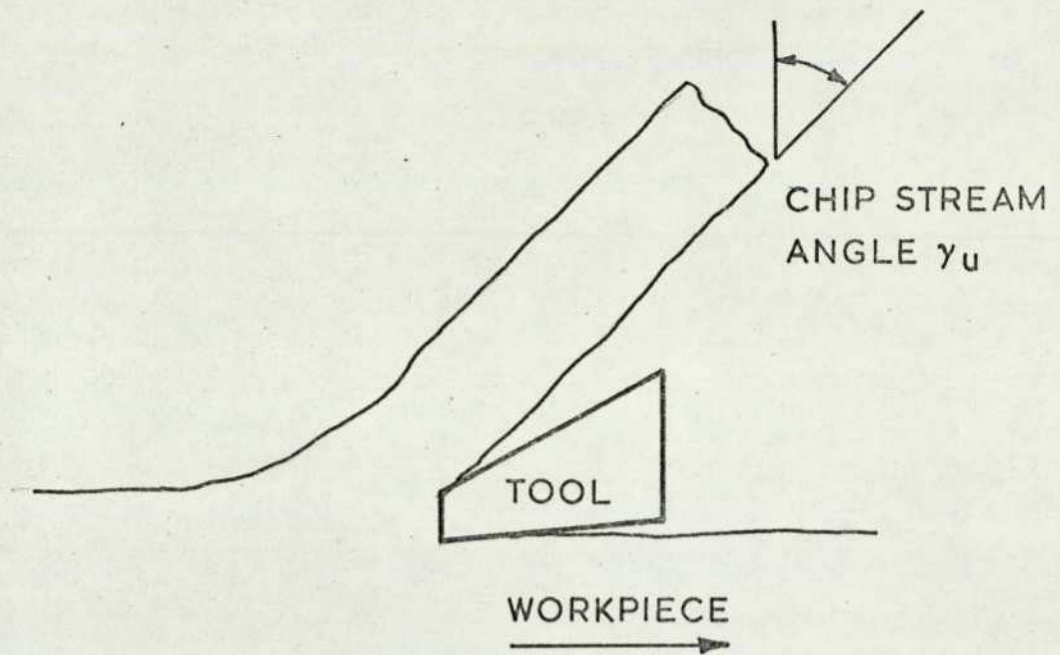
MATERIAL En 1A. CUTTING SPEED 2.5 m/min.

PRIMARY RAKE ANGLE 0° AND LENGTH 0.25 mm.

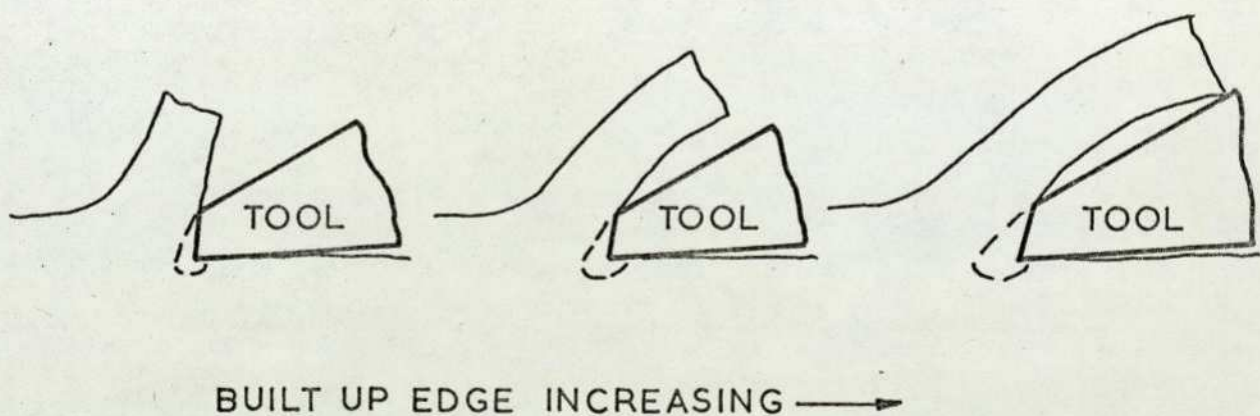
FIG.4.9 a.



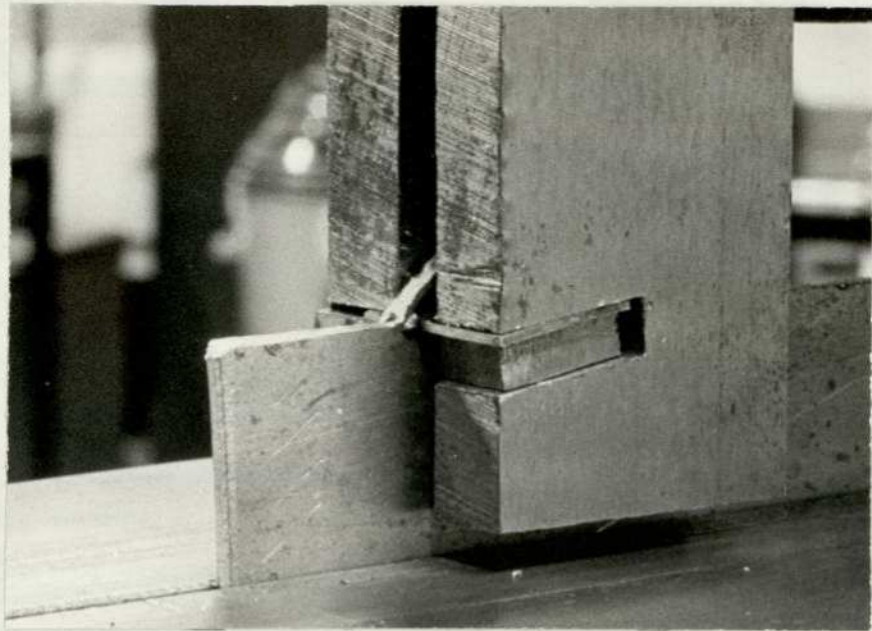
b. THE VARIATION IN SIZE OF THE B.U.E. WITH
DIFFERENT PRIMARY RAKE ANGLES



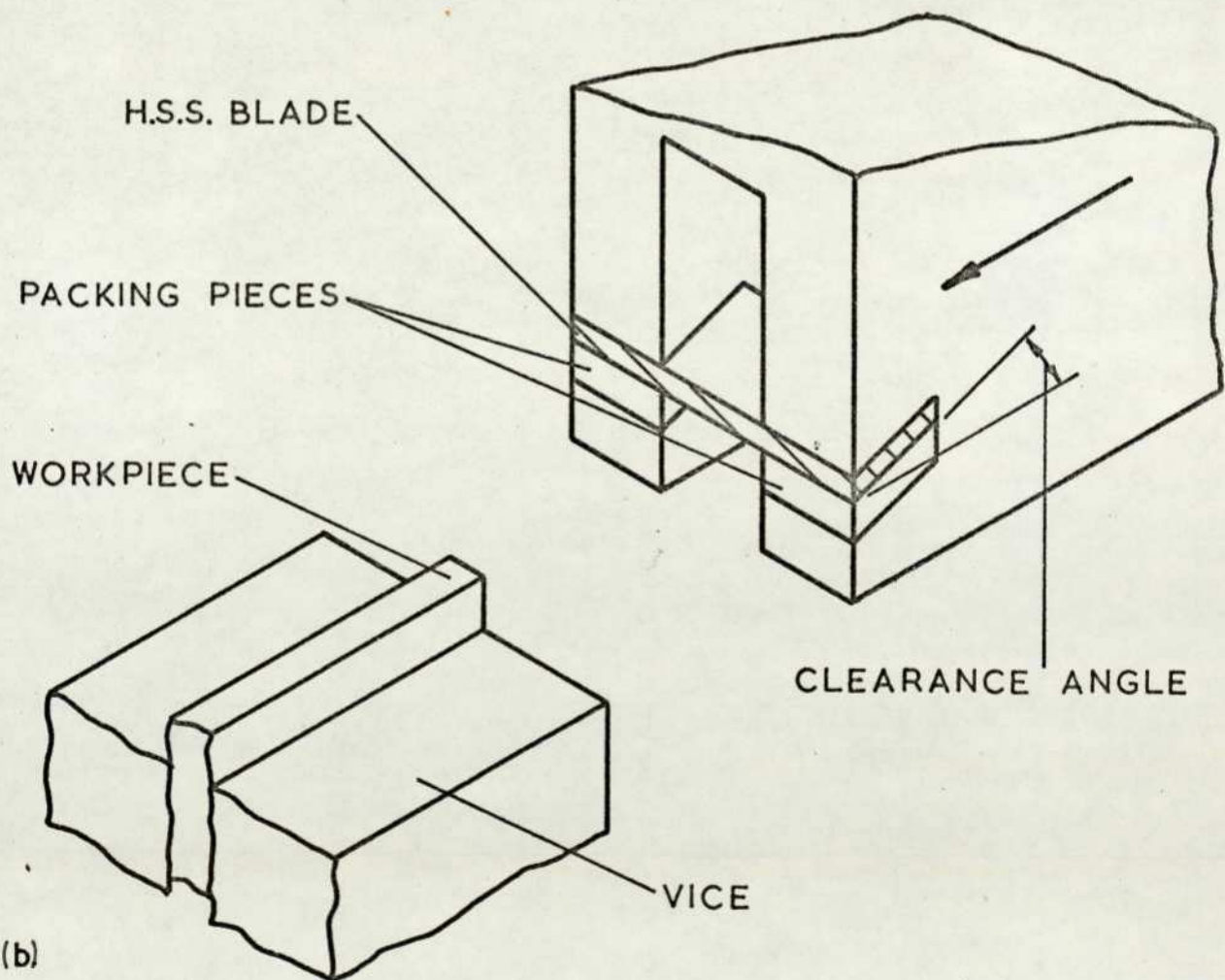
(a) CUTTING WITH A RESTRICTED CONTACT LENGTH
TOOL INDICATING THE CHIP STREAM ANGLE



(b) NEGATIVE CHIP CURL & HOW IT IS PRODUCED



(a)

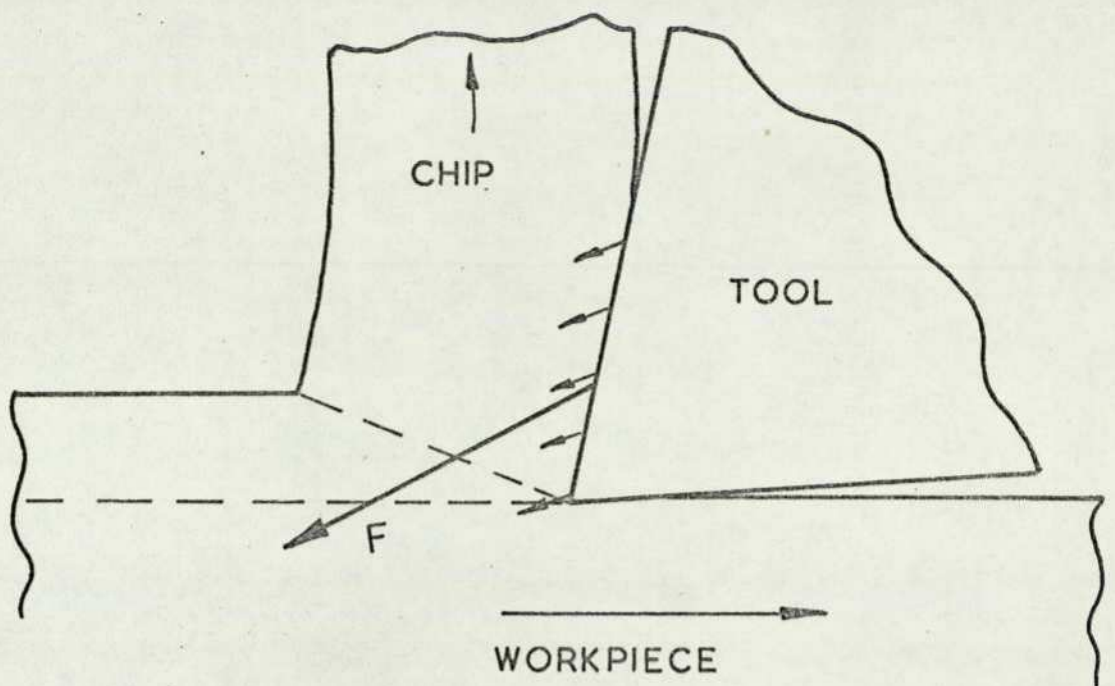


(b)

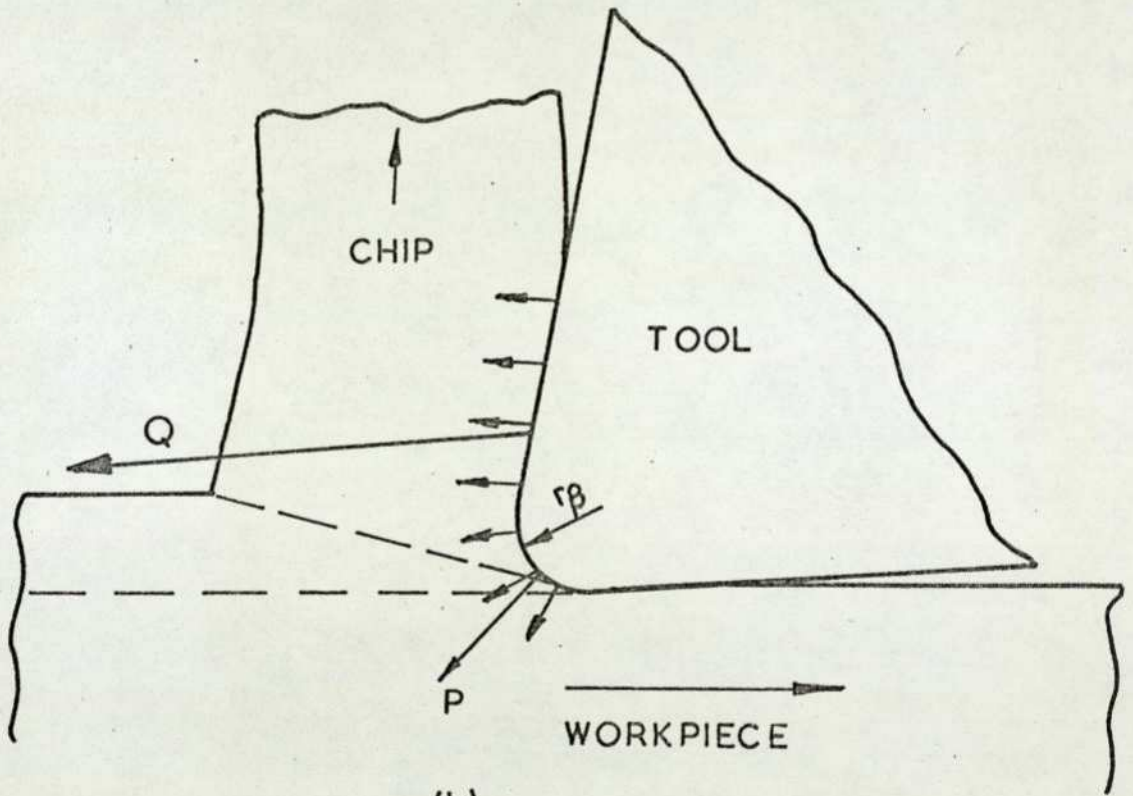
SPECIAL TOOL & PHOTOGRAPH OF THE CHIP

FLOW WHEN CUTTING WITH THIS TOOL

FIG.4.11a,b

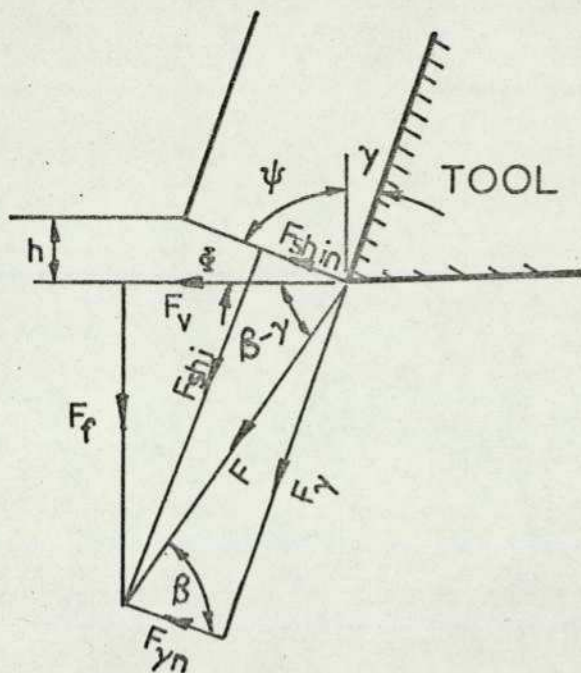


(a)

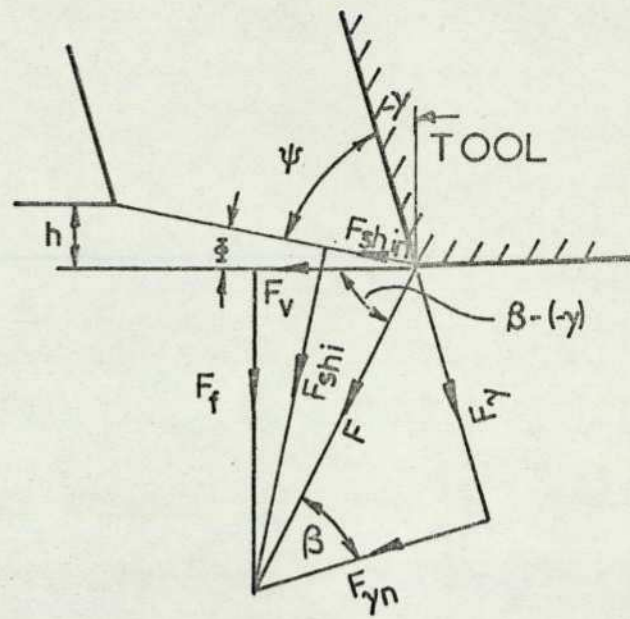


(b)

THE RESOLVING OF THE RESULTANT TOOL FORCE
 F INTO TWO COMPONENTS PLOUGHING FORCE
 P & TOOL FACE FORCE Q - AFTER ALBRECHT(59)

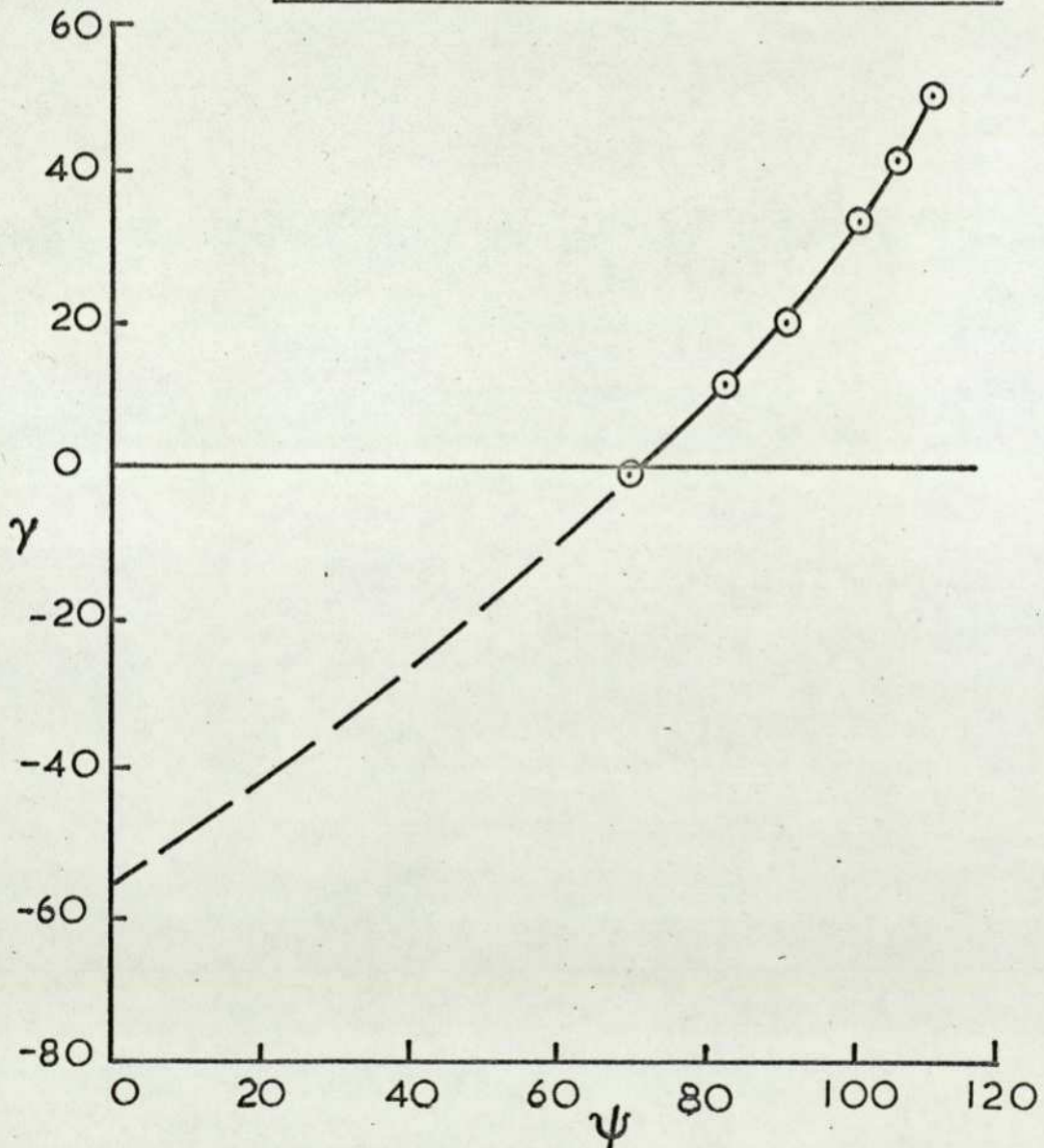


POSITIVE RAKE TOOL



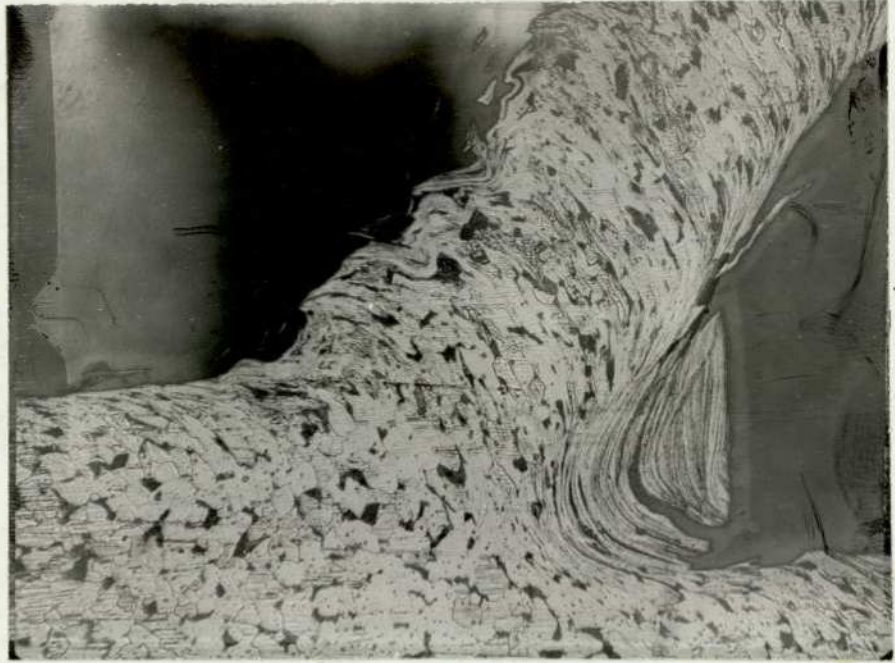
NEGATIVE RAKE TOOL

THE MERCHANT FORCES MODEL

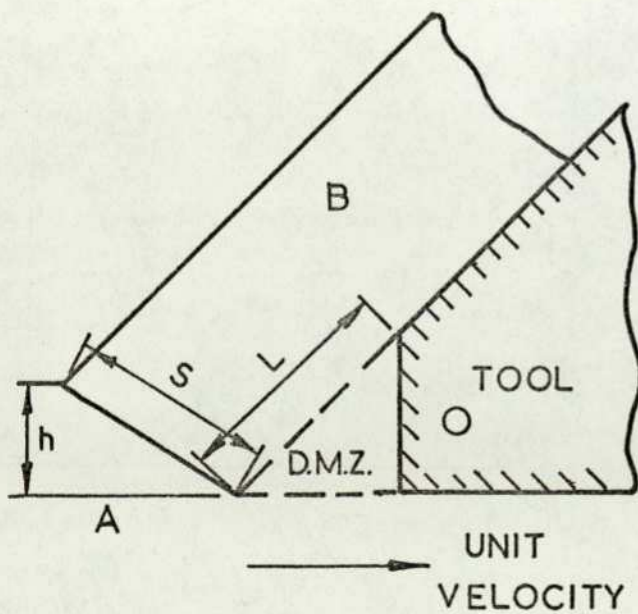


THE VARIATION OF THE ANGLE BETWEEN THE RAKE FACE & THE SHEAR PLANE ψ WITH THE

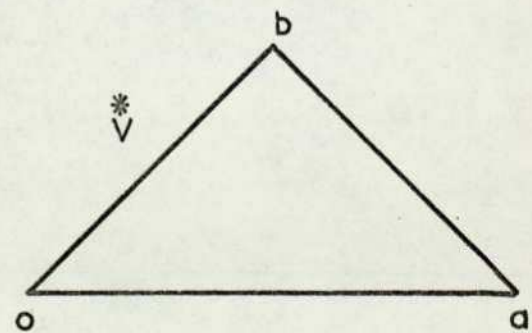
RAKE ANGLE γ AFTER RUBENSTEIN(64) FIG. 4.13



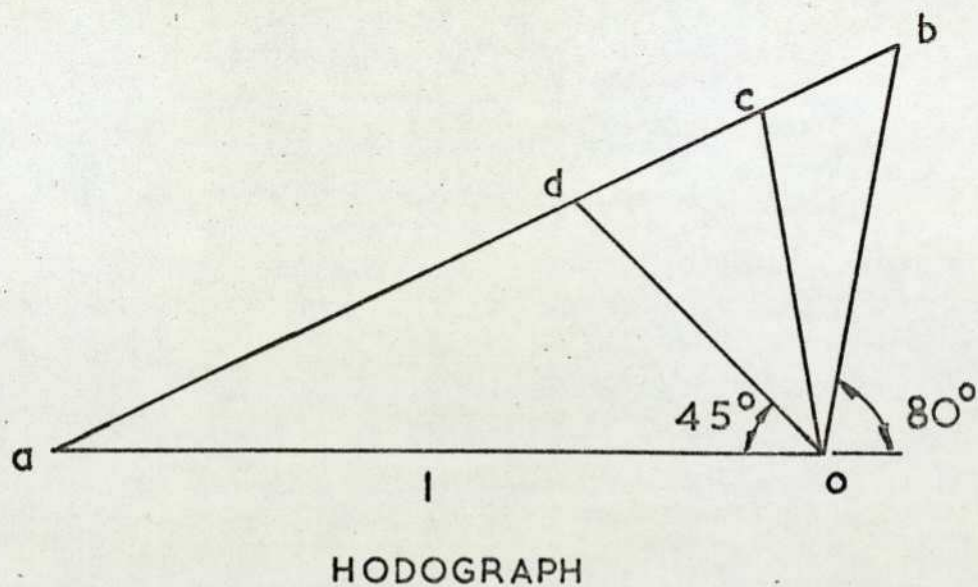
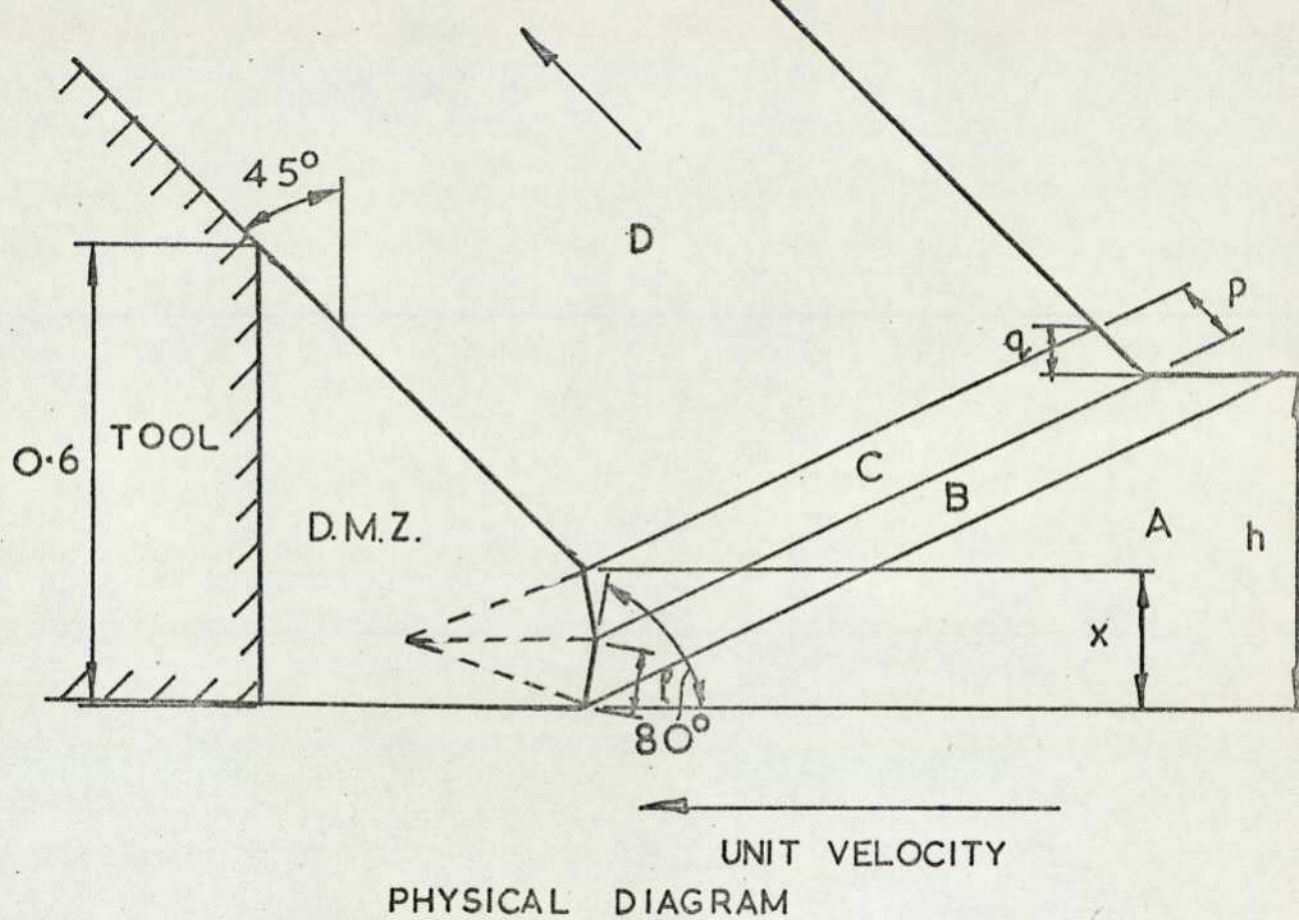
(a) PHOTOMICROGRAPH SHOWING SPECIAL PLASTIC
FIELD FORMED WHEN CUTTING WITH CONTROLLED
CONTACT LENGTH CUTTING TOOLS



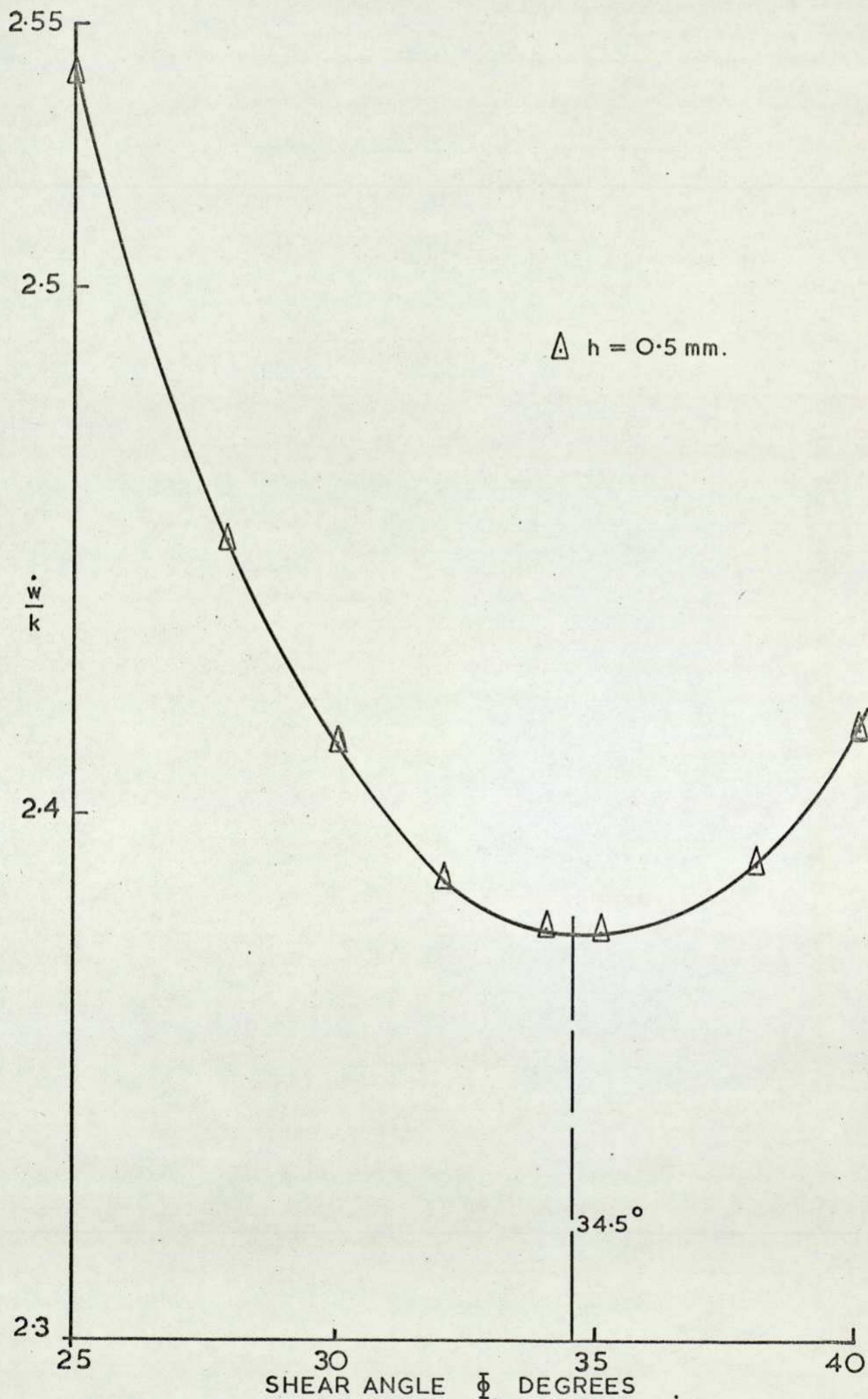
(b) PHYSICAL DIAGRAM



c. HODOGRAPH

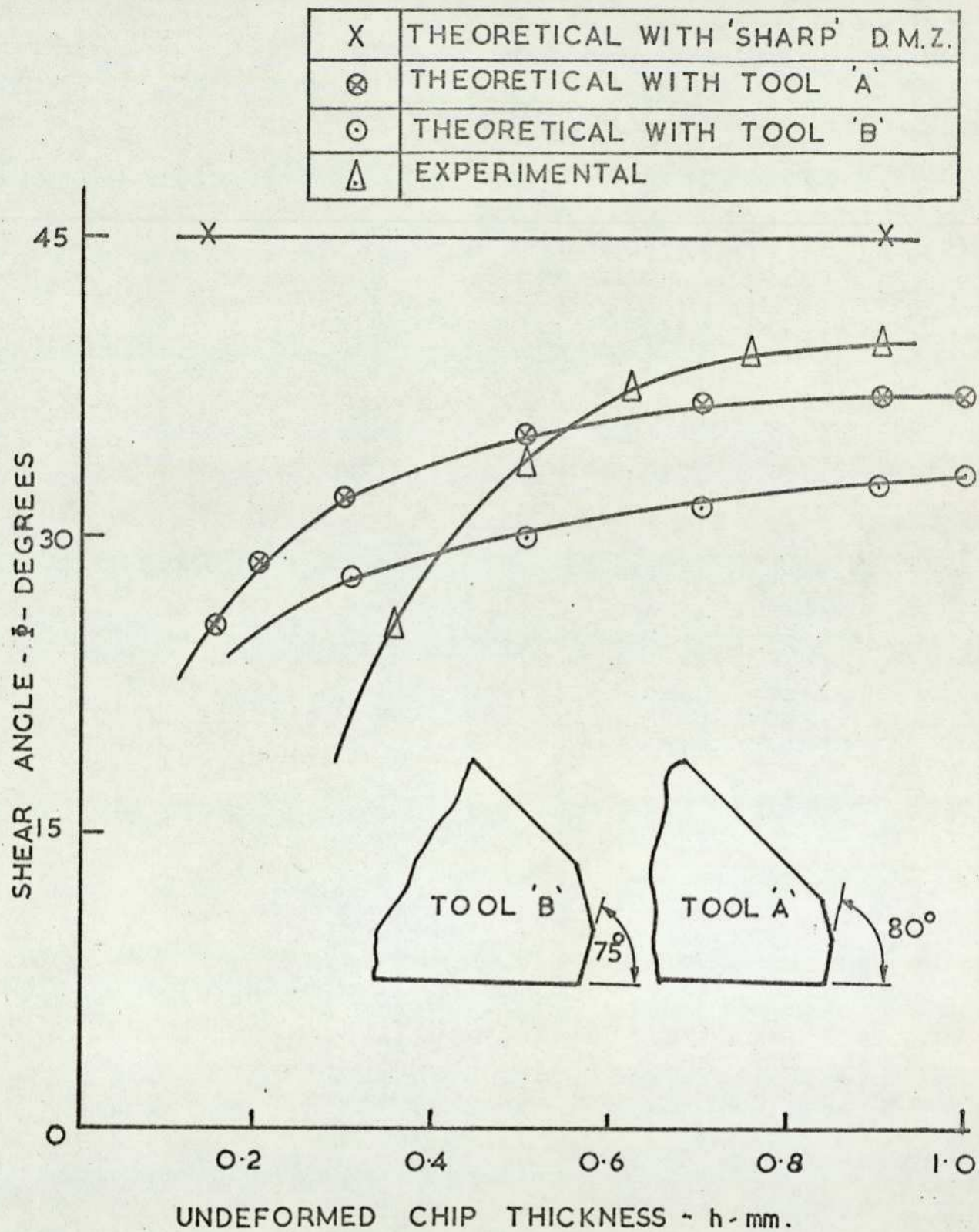


MODIFIED MODEL & HODOGRAPH FOR CUTTING
WITH CONTROLLED CONTACT LENGTH TOOLS
SHOWING 'BLUNT' DEAD METAL ZONE



THEORETICAL RELATIONSHIP BETWEEN $\dot{w}/k$
& SHEAR ANGLE FOR MODEL (IN FIG. 4.15)

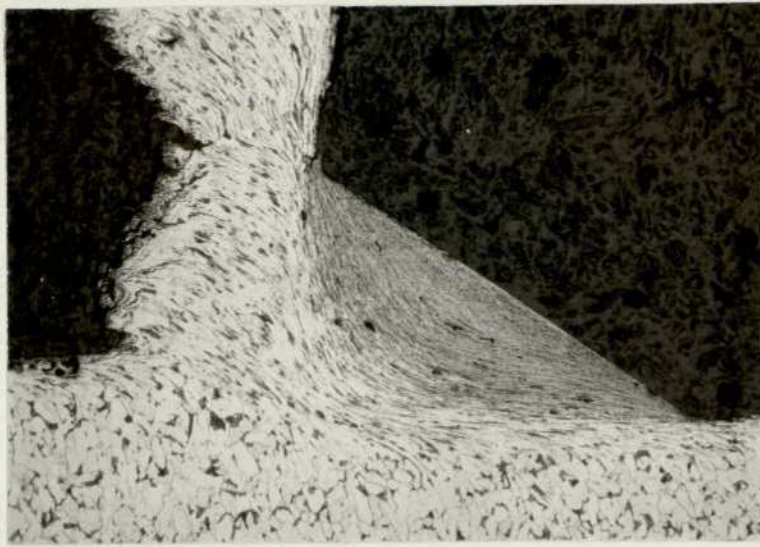
FIG. 4.16.



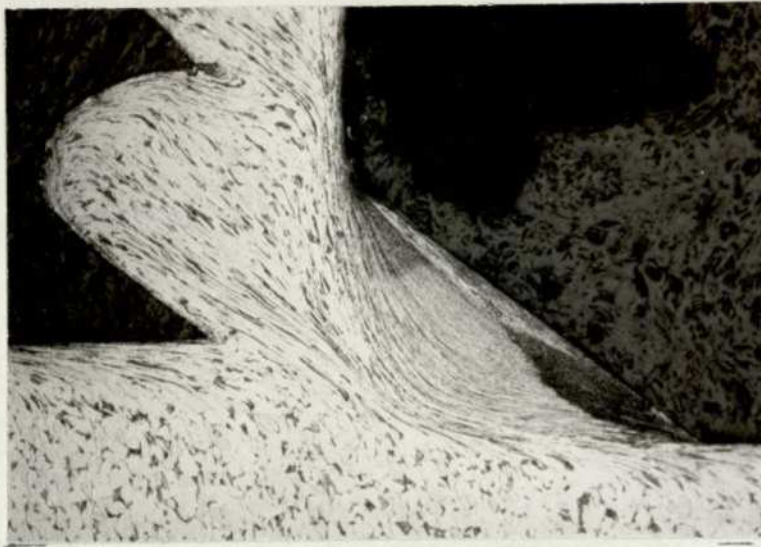
RELATIONSHIP BETWEEN UNDEFORMED CHIP THICKNESS & SHEAR ANGLE FOR THE MODEL SHOWN IN FIG 4.15.

WORKPIECE En1A. CUTTING SPEED 2m/min.

FIG. 4.17.



31 m/min.



60 m/min.



120 m/min.

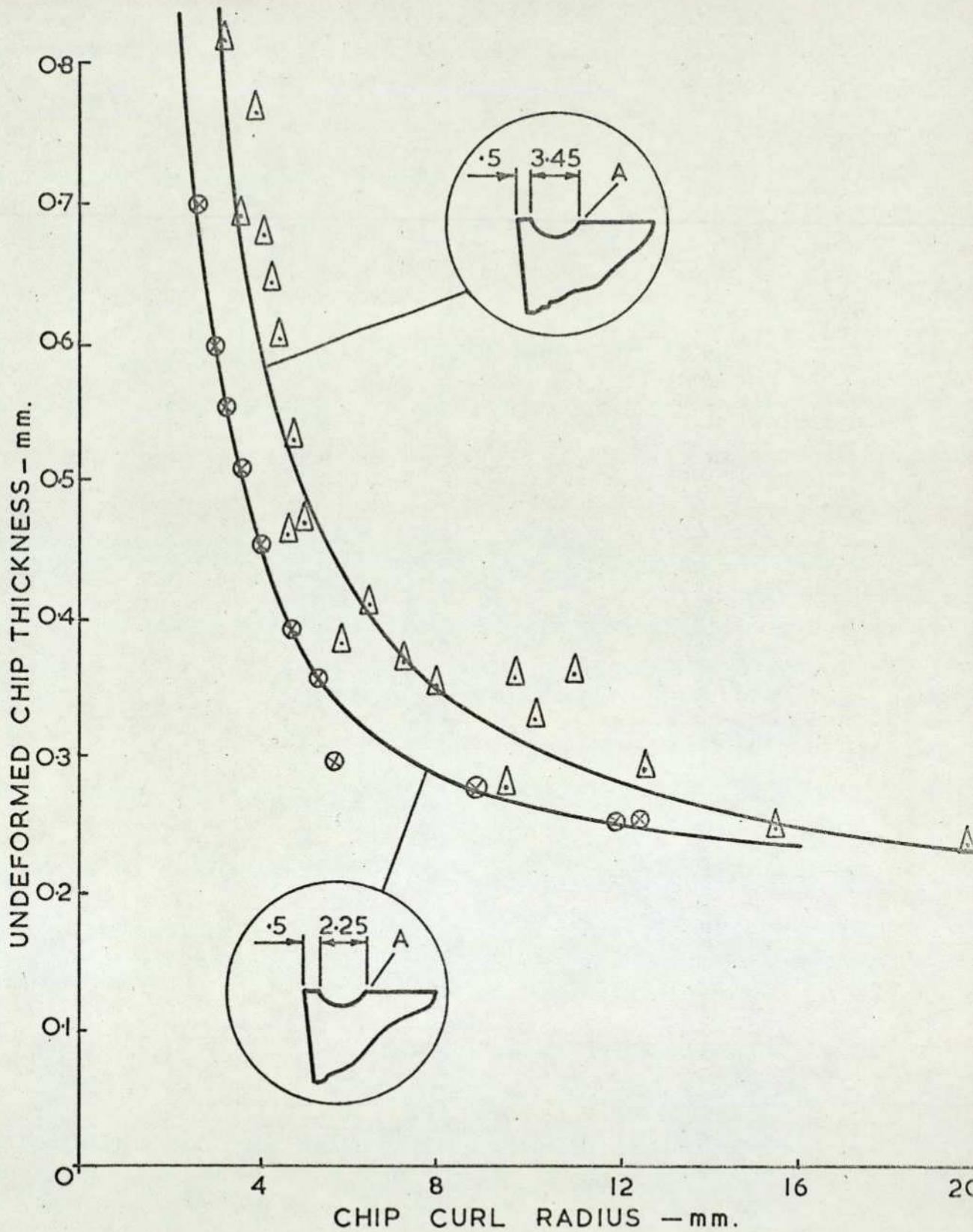
X 70

PHOTOMICROGRAPHS OF THE QUICKSTOPPED
CUTTING ACTION WHEN MACHINING AT
DIFFERENT SPEEDS WITH TOOLS HAVING
NEGATIVE PRIMARY LANDS

FEED 0.24 mm/rev. LAND LENGTH 0.75 mm.

PRIMARY RAKE ANGLE -60° MATERIAL CDS-I.

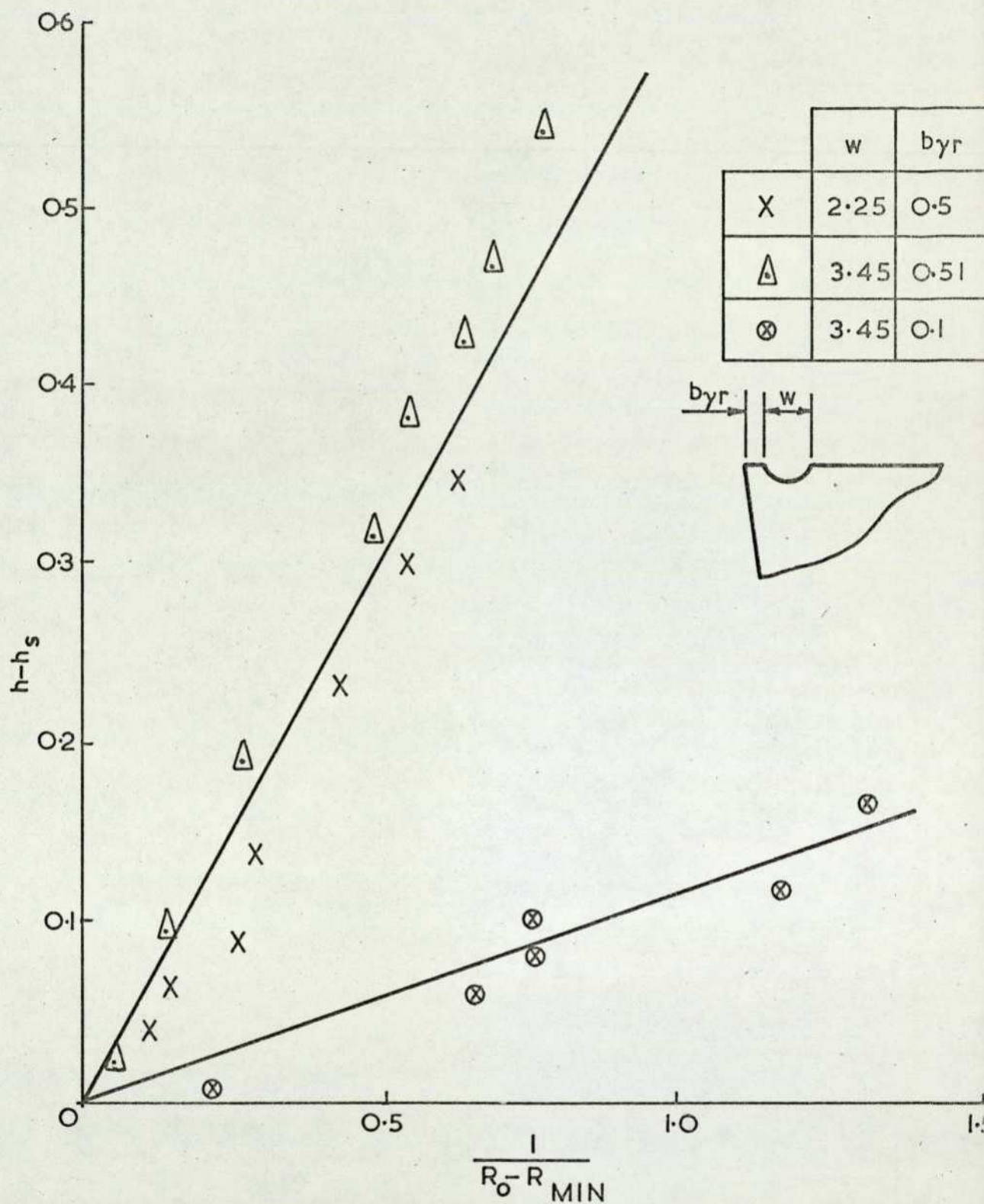
FIG. 4.18.



EXPERIMENTAL RESULTS SHOWING THE
UNDEFORMED CHIP THICKNESS — CHIP CURL
RADIUS RELATIONSHIP FOR TOOLS OF
DIFFERENT GROOVE WIDTH

MATERIAL En 1A. PRIMARY RAKE ANGLE 20° .

CUTTING SPEED 2.5 m/min.

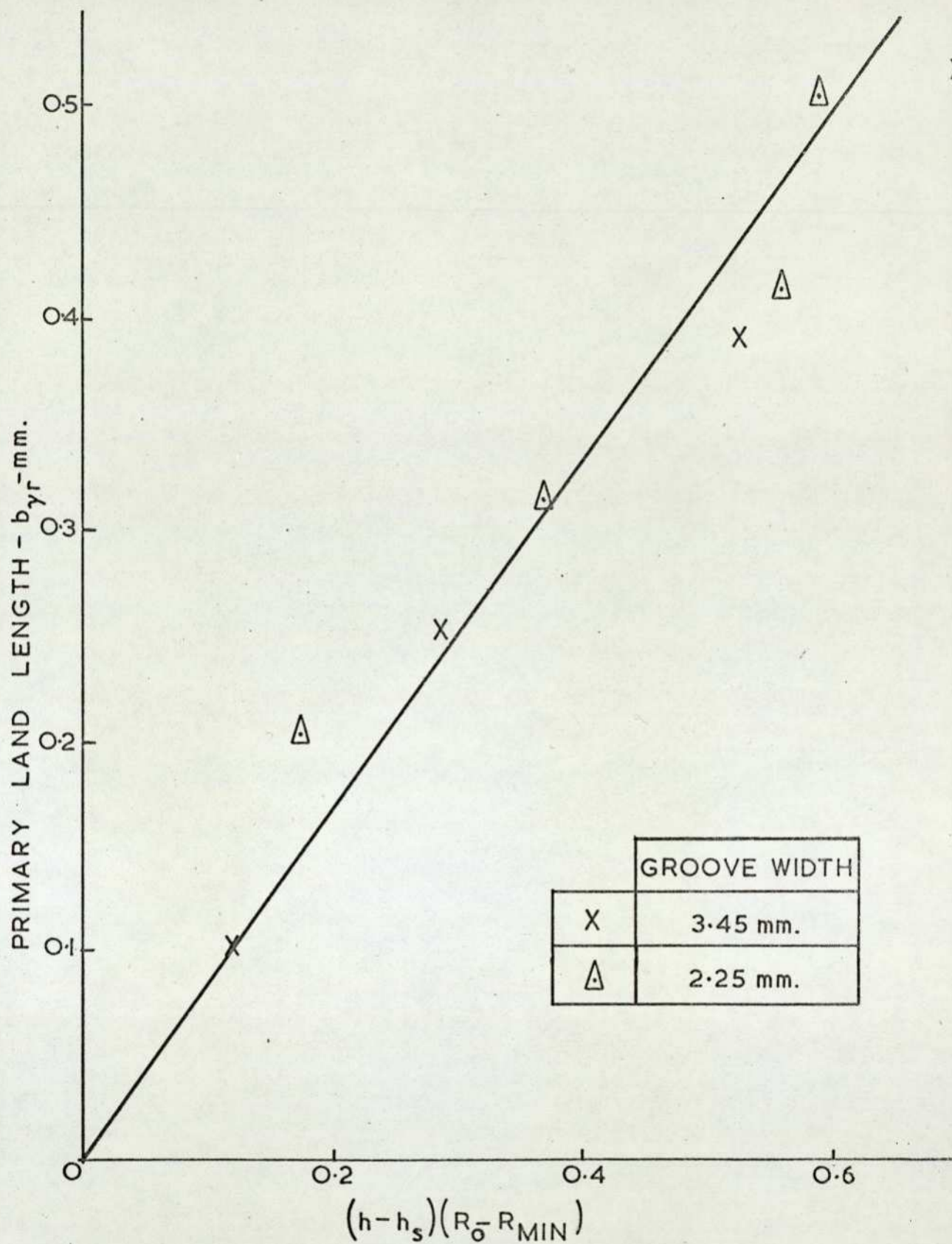


EXPERIMENTAL RESULTS SHOWING THE EFFECT
OF GROOVE WIDTH & PRIMARY LAND
LENGTH ON CHIP CURL RADIUS

MATERIAL En 1A 20° PRIMARY RAKE ANGLE.

CUTTING SPEED 2.5 m/min.

FIG. 4.20



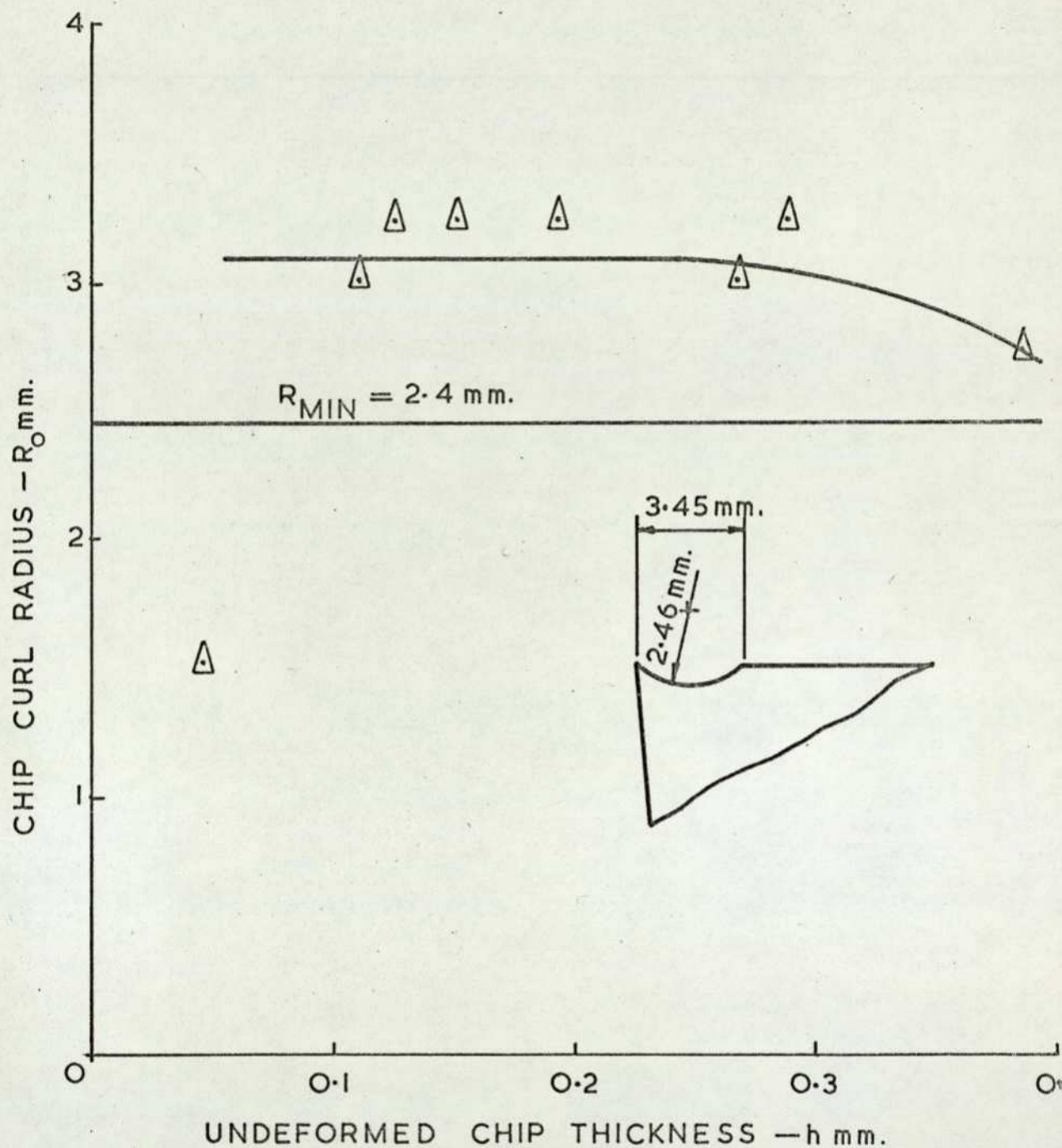
EXPERIMENTAL RELATIONSHIP BETWEEN b_{yr}

& $(h-h_s)(R-R_{MIN})$

MATERIAL En 1A. PRIMARY RAKE ANGLE 20°

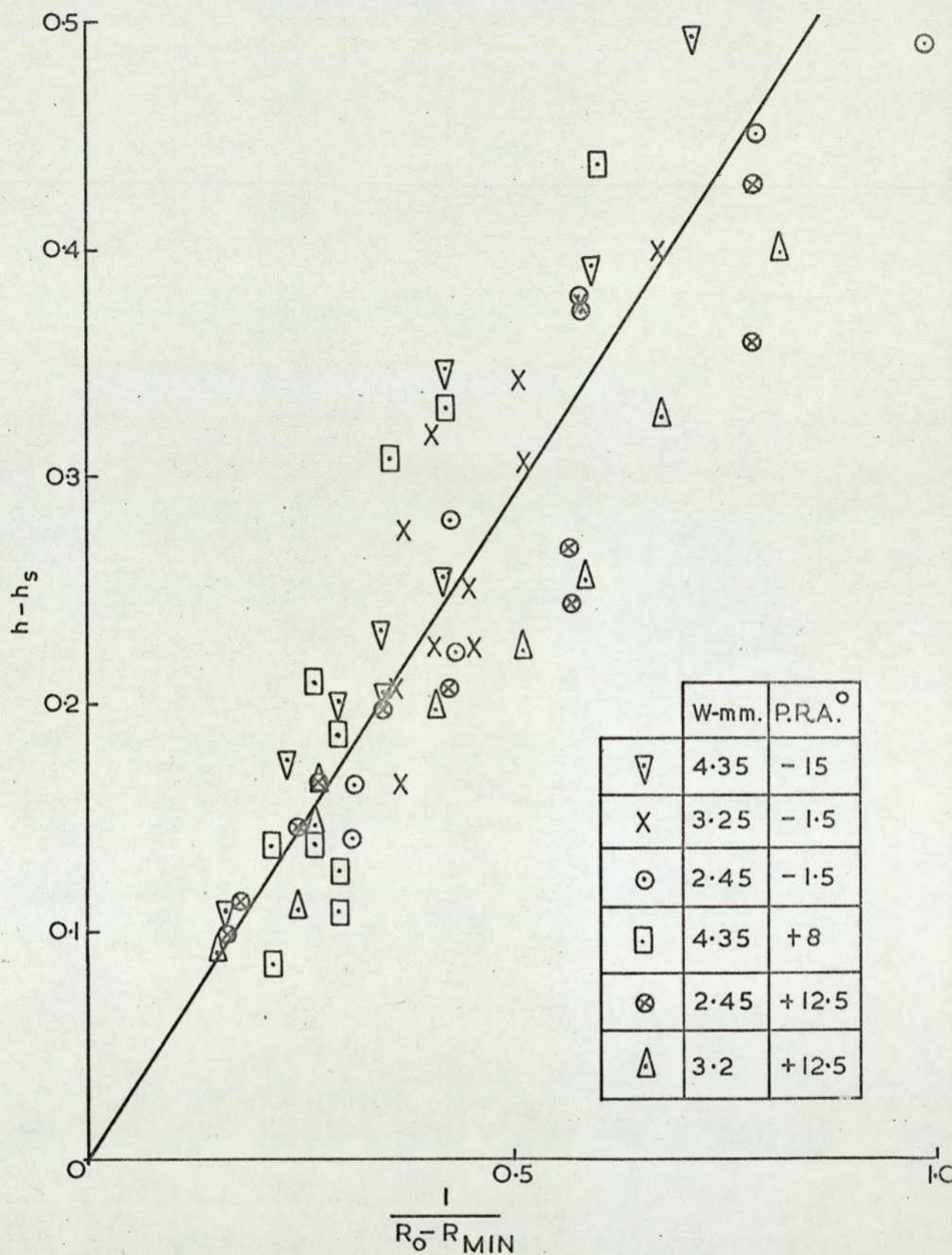
CUTTING SPEED 2.5 m/min.

FIG. 4.21.



EXPERIMENTAL RELATIONSHIP BETWEEN CHIP CURL
RADIUS & UNDEFORMED CHIP THICKNESS CUTTING
WITH GROOVED TOOL WITH NO PRIMARY LAND

MATERIAL En 1A, CUTTING SPEED 2.5 m/min.

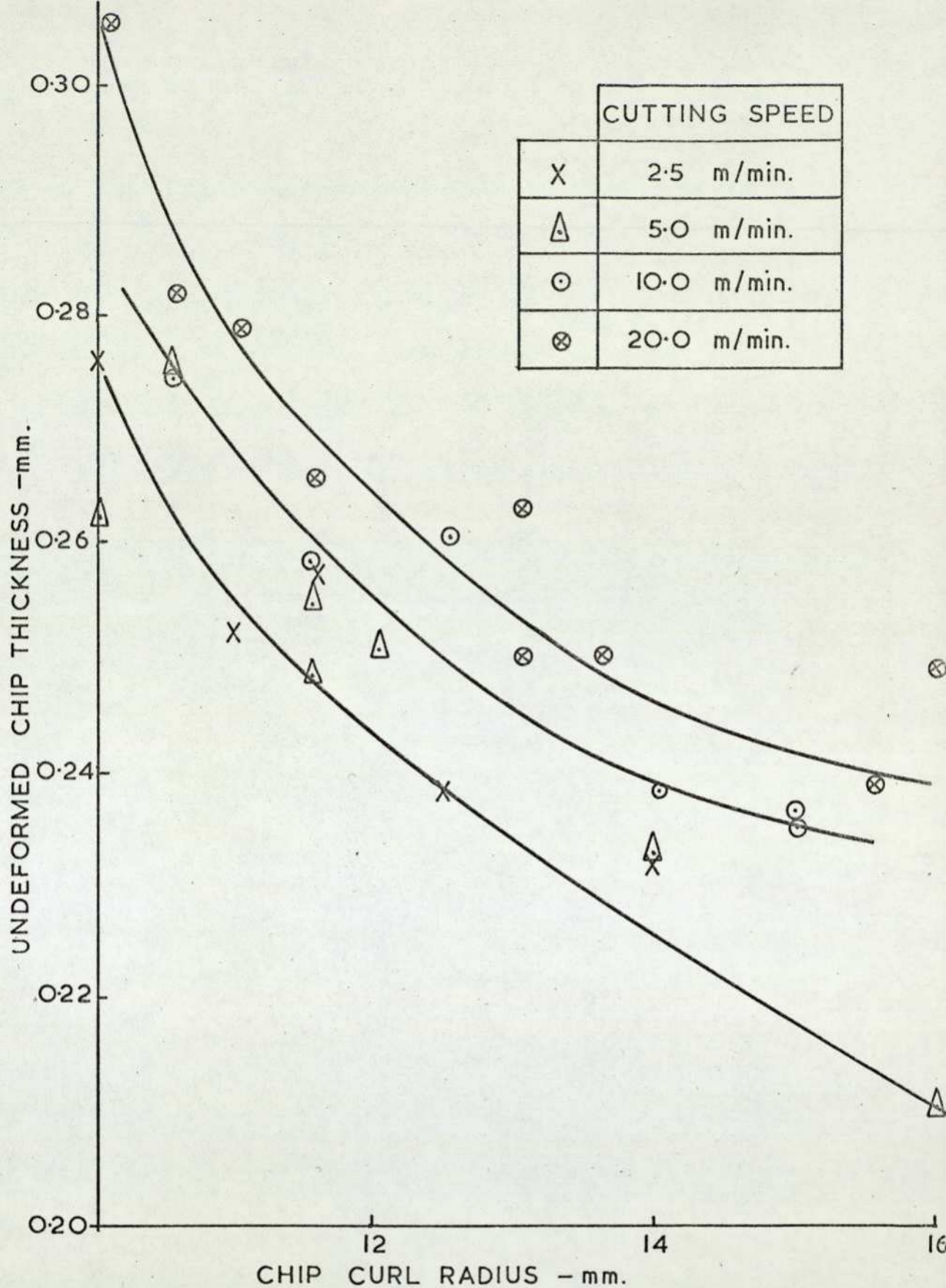


EXPERIMENTAL RESULTS SHOWING THE EFFECT
OF PRIMARY RAKE ANGLE & GROOVE WIDTH
ON CHIP CURL RADIUS

MATERIAL En 1A. PRIMARY LAND LENGTH 0.5 mm.

CUTTING SPEED 2.5 m/min.

FIG. 4.23.

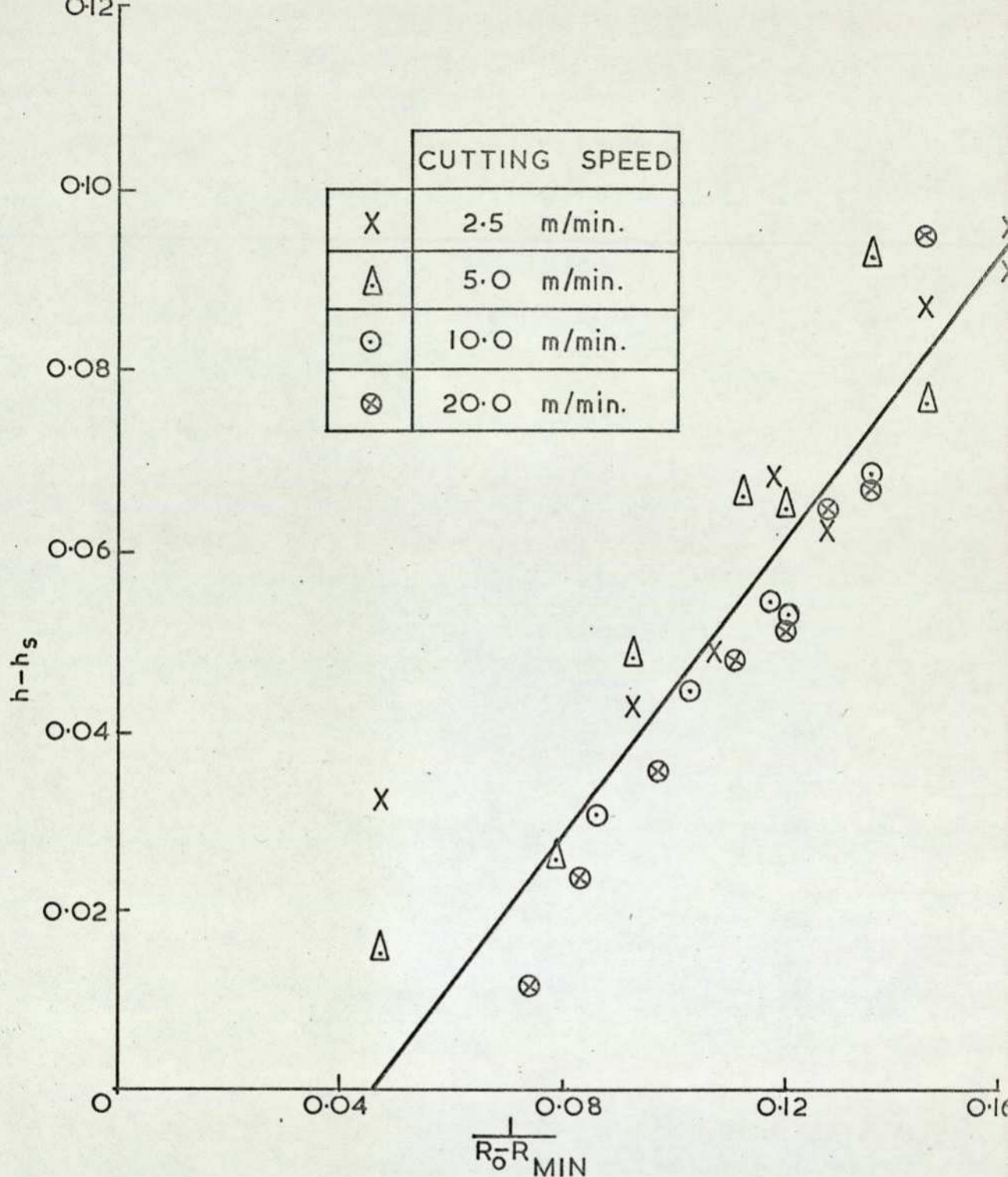


EXPERIMENTAL RESULTS SHOWING THE EFFECT OF CUTTING SPEED ON CHIP CURL RADIUS

MATERIAL En 1A. 20° PRIMARY RAKE ANGLE.

PRIMARY LAND LENGTH 0.44 mm.

GROOVE WIDTH 4.55 mm.



EXPERIMENTAL VALUES OF FIG. 4.24 REPLOTED TO
ILLUSTRATE THAT THE EFFECT ON CHIP CURL
RADIUS OF VARIATION IN CUTTING SPEED IS
ENTIRELY DUE TO CHANGES IN LENGTH OF THE
STICKING FRICTION ZONE

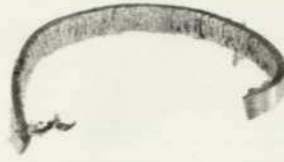
MATERIAL En 1A. PRIMARY RAKE ANGLE 20° .

PRIMARY LAND LENGTH 0.44 mm.

GROOVE WIDTH 4.55 mm.

FIG. 4.25.

FEED mm/rev



0.78



0.65



0.5



0.4



0.25

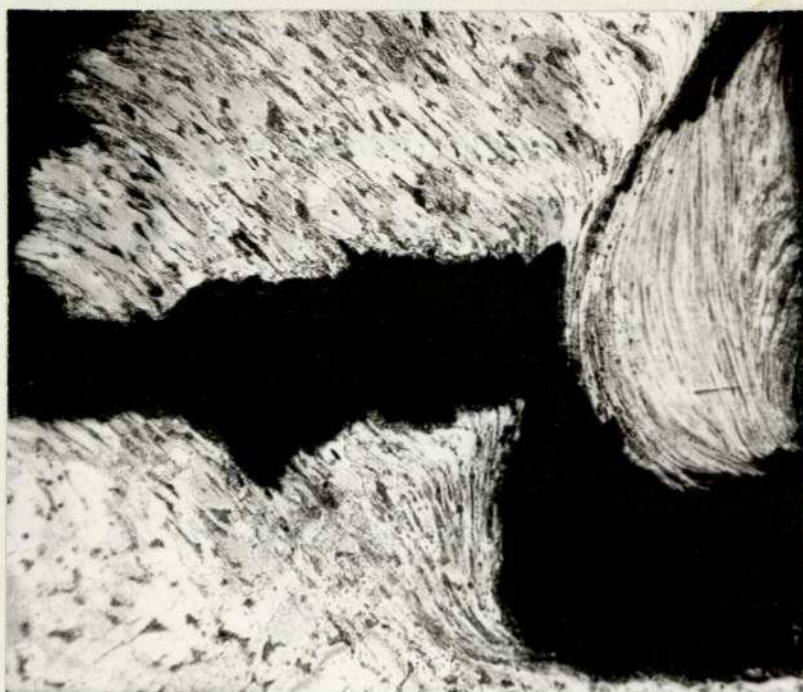


0.15



0.1

CHIPS PRODUCED WITH DOUBLE RAKE ANGLE
TOOL HAVING TAPERED LAND



TOOL

2.4 mm. FROM EDGE



TOOL

2.8 mm. FROM EDGE X 100

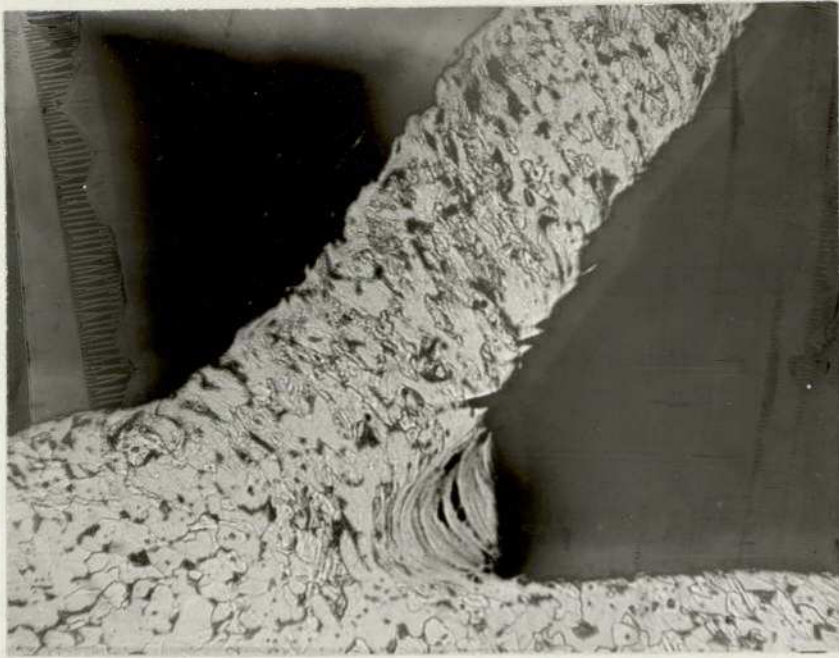
PHOTOMICROGRAPHS AT INCREASING DISTANCE

FROM EDGE OF WORKPIECE

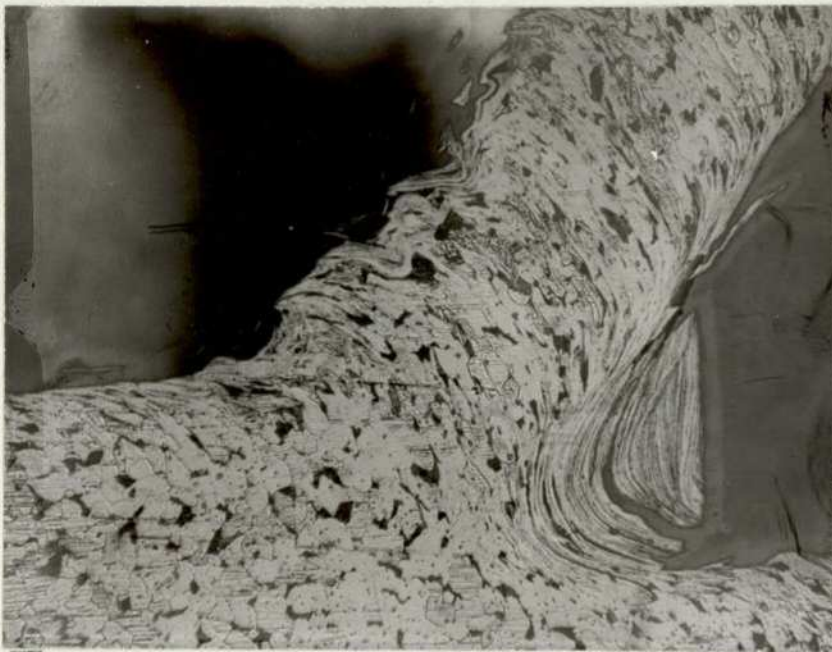
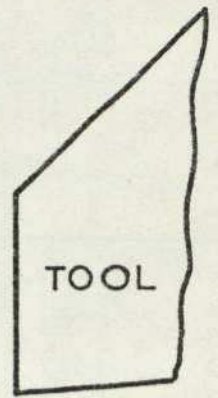
MATERIAL En 1A. CUTTING SPEED 2.5 m/min.

PRIMARY RAKE ANGLE 0° .

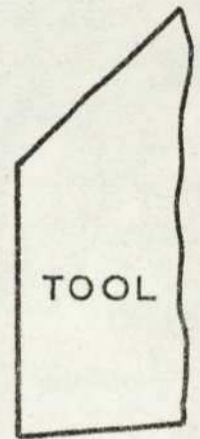
FIG.4.27a



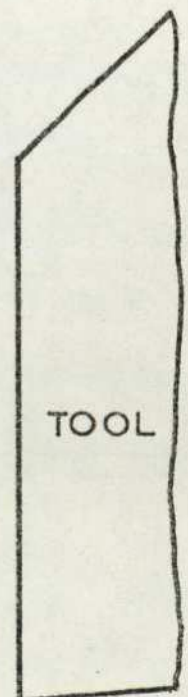
AT EDGE



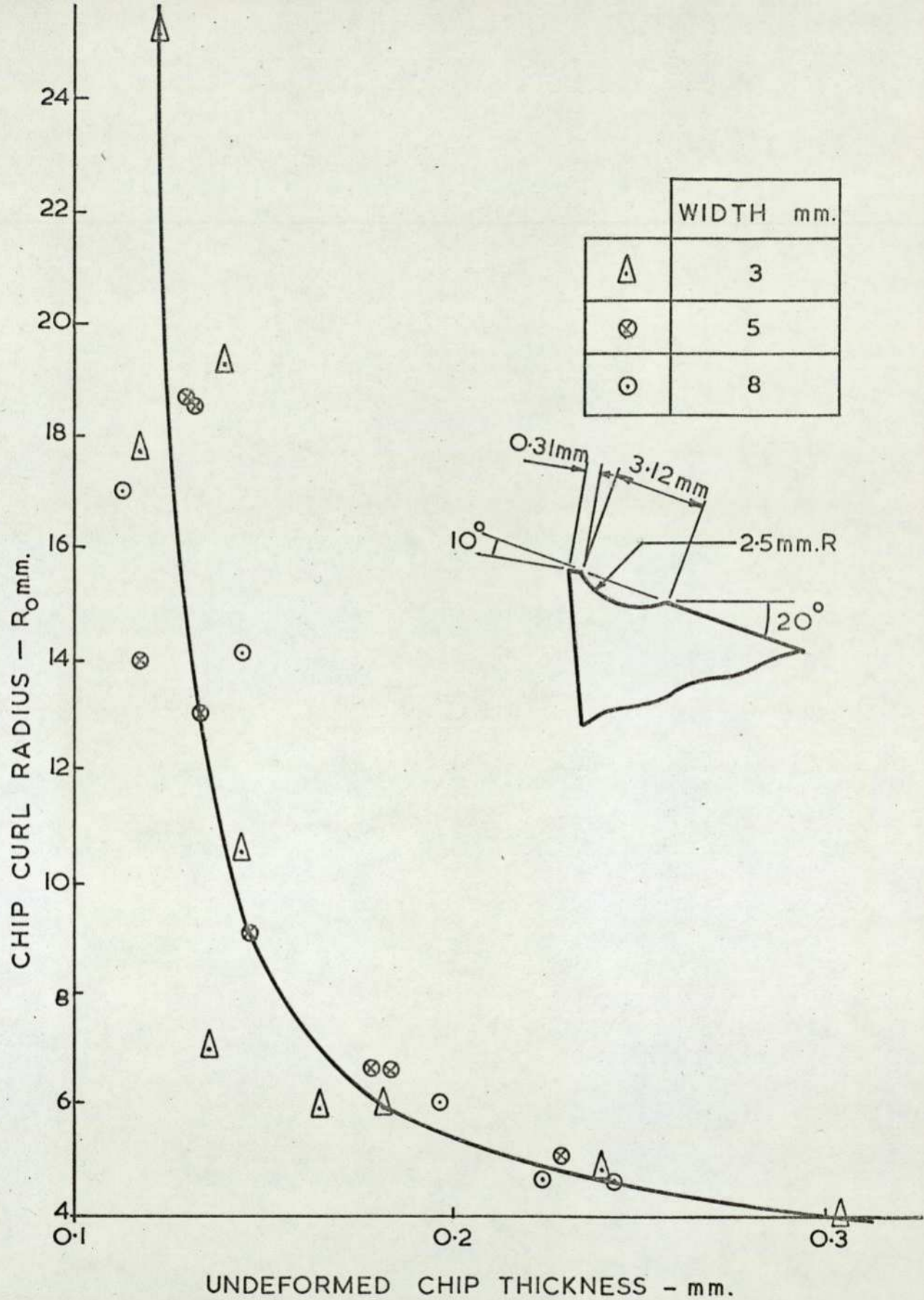
0.6mm.FROM EDGE



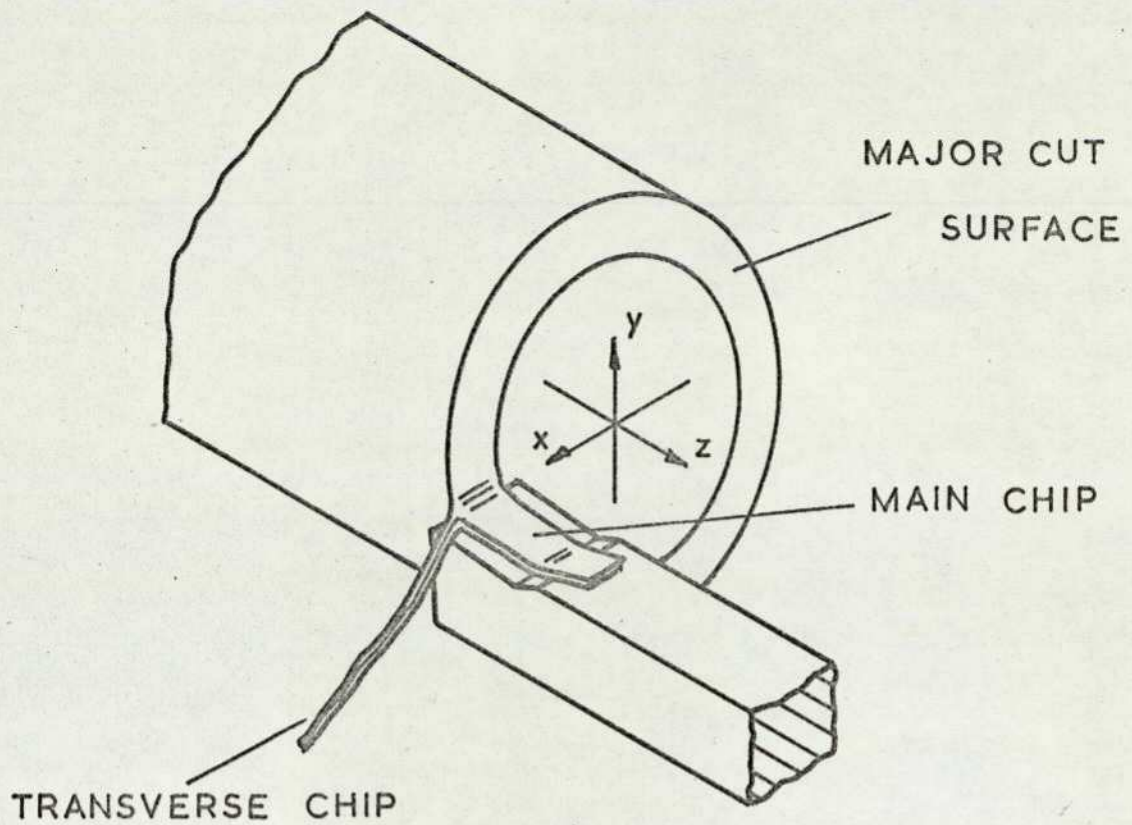
1.8mm. FROM EDGE



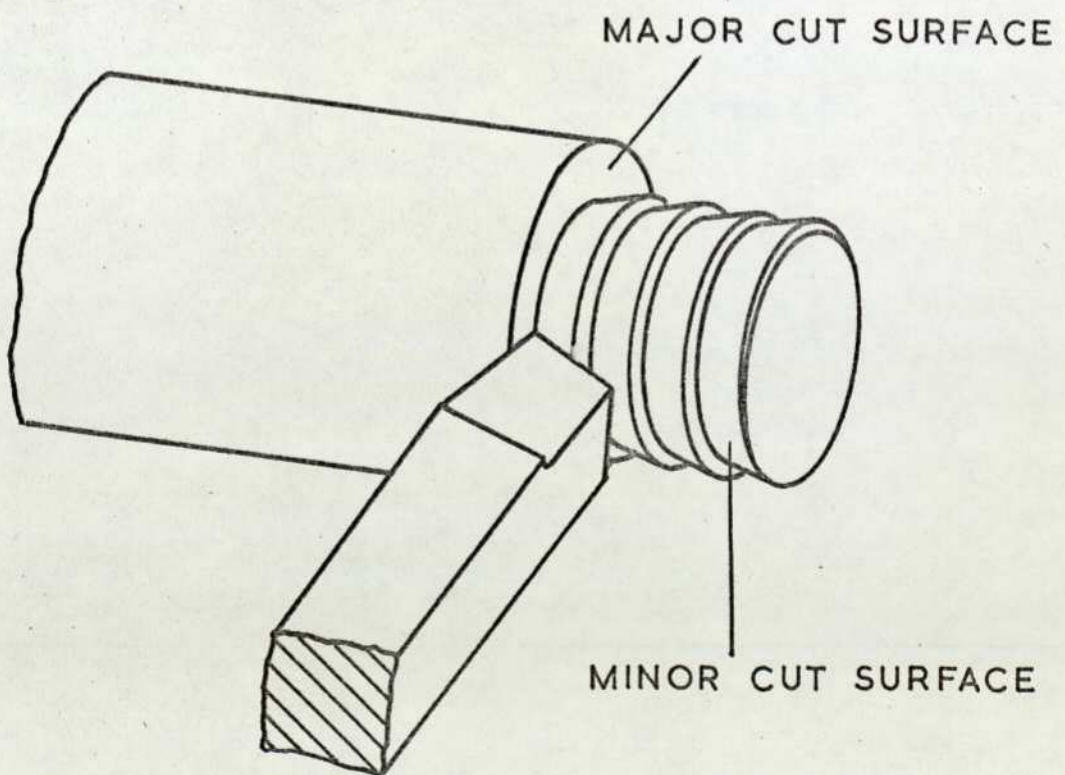
X 100



EXPERIMENTAL RELATIONSHIP BETWEEN CHIP
CURL RADIUS & UNDEFORMED CHIP THICKNESS
FOR DIFFERENT WIDTHS OF CUT



(a) ORTHOGONAL MACHINING WITH TRANSVERSE CHIP

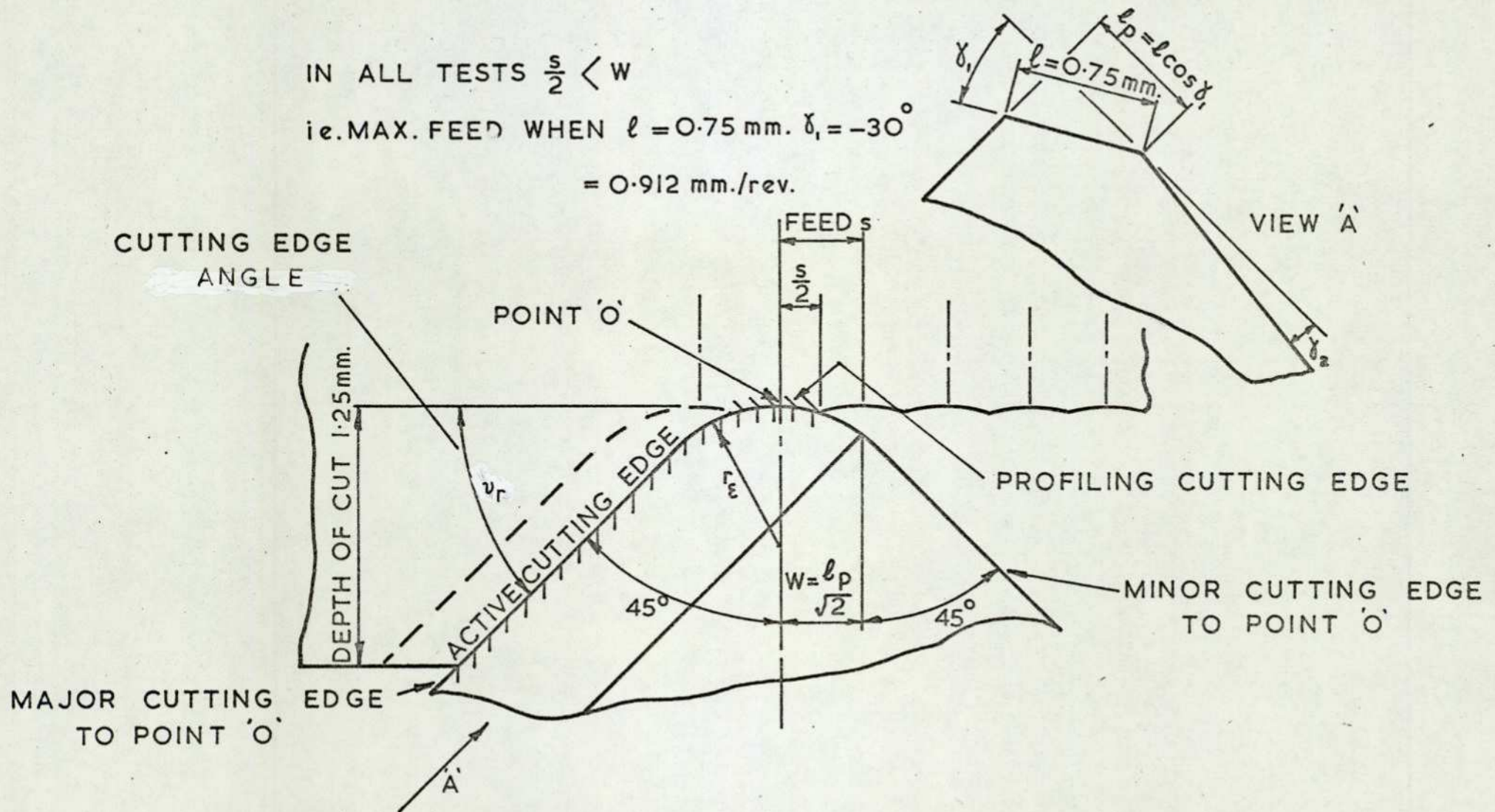


(b) OBLIQUE MACHINING SHOWING MAJOR
& MINOR CUTTING SURFACES

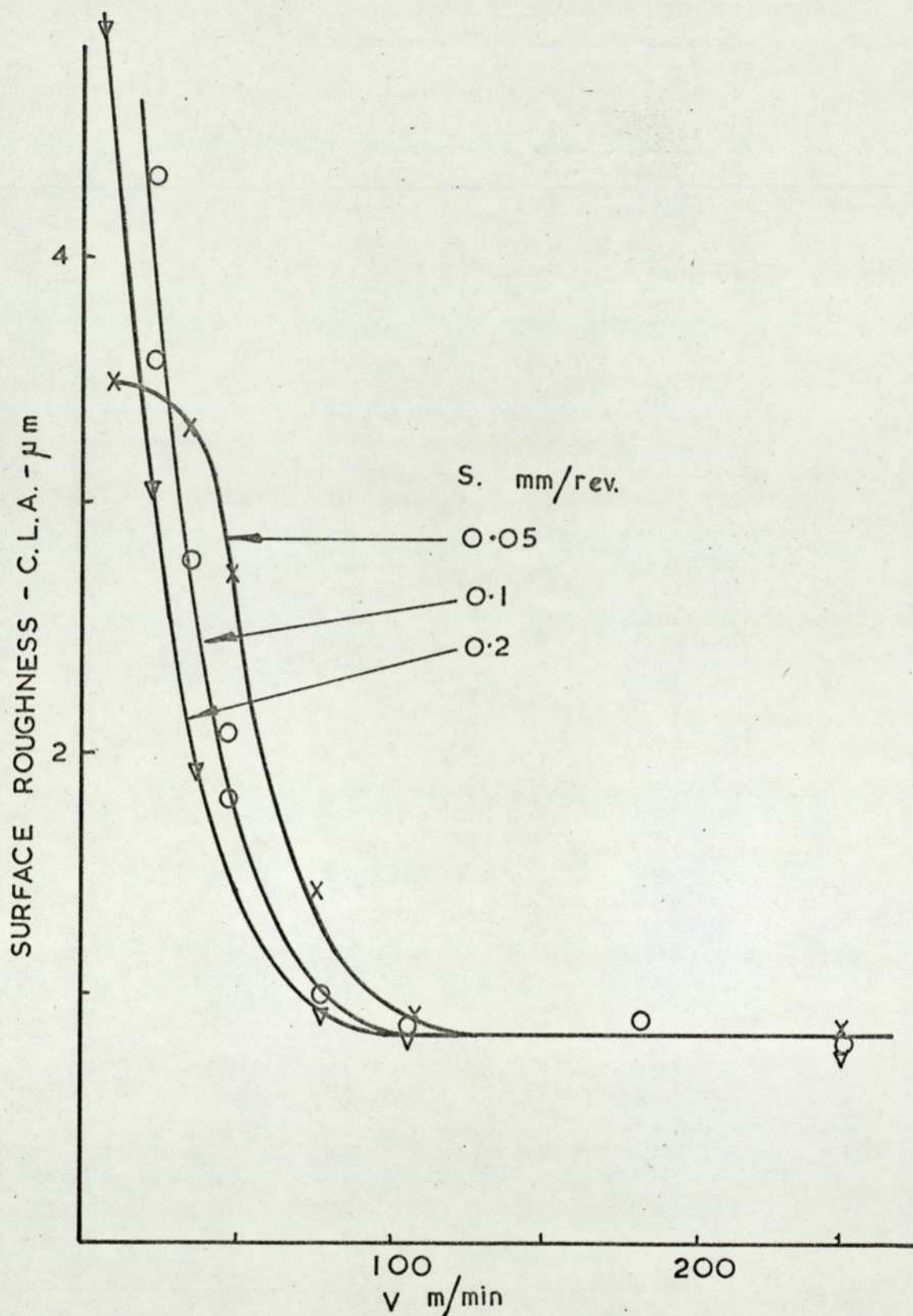
IN ALL TESTS $\frac{s}{2} < W$

ie. MAX. FEED WHEN $l = 0.75 \text{ mm. } \delta_1 = -30^\circ$

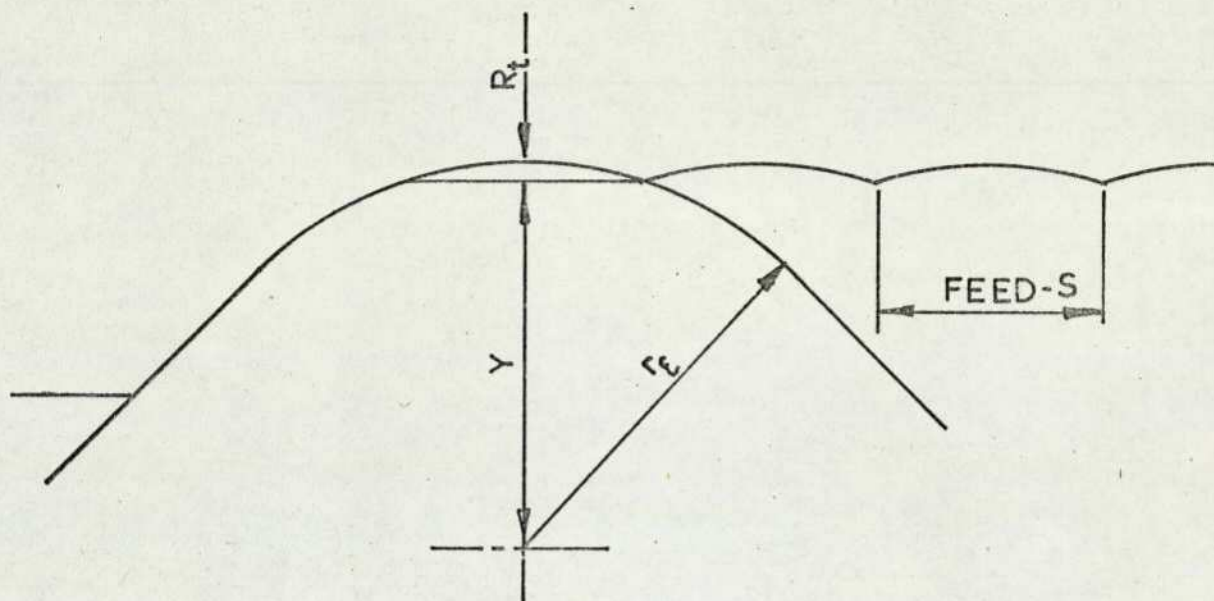
$= 0.912 \text{ mm./rev.}$



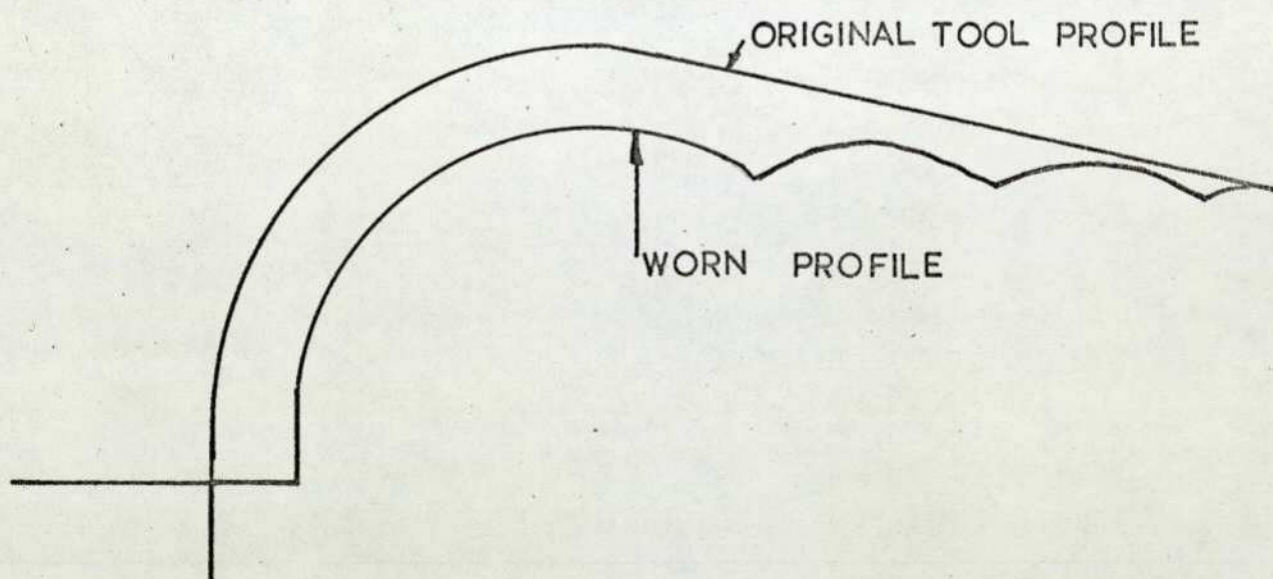
OBLIQUE MACHINING & THE EFFECT OF THE PROFILING CUTTING
EDGE & LAND LENGTH ON THE MACHINED SURFACE



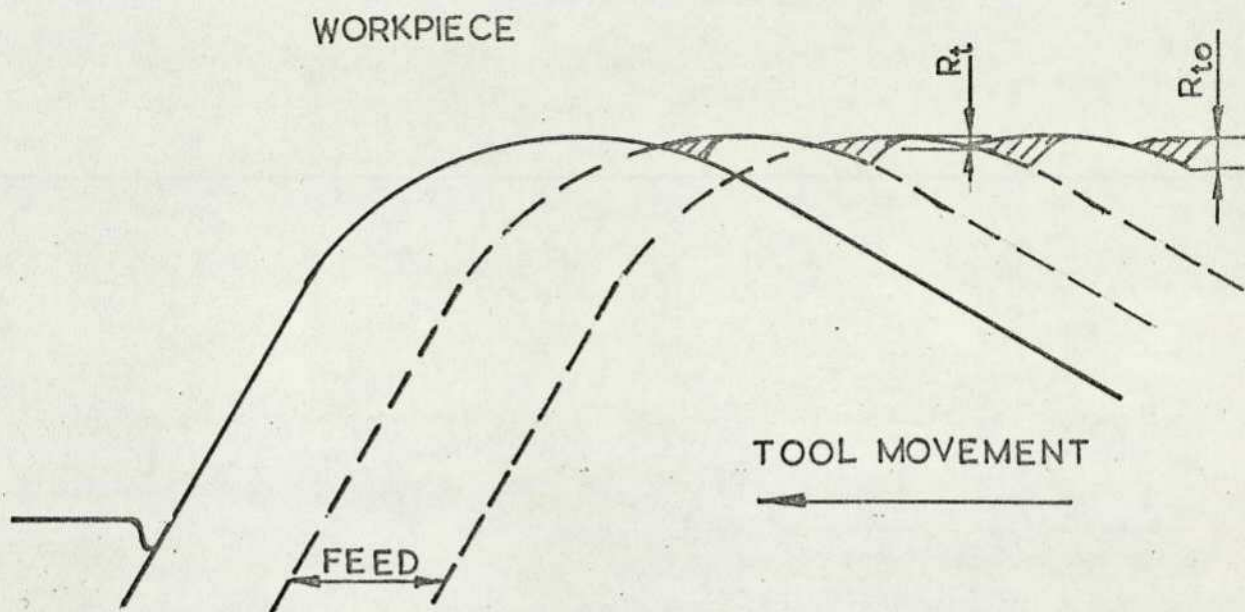
VARIATION OF ARITHMETIC AVERAGE ROUGHNESS -
C.L.A. μm -VERSUS CUTTING SPEED FOR PLUNGE
TYPE CUTS MADE AT DIFFERENT VALUES OF
FEED - AFTER SHAW ET-AL (80)



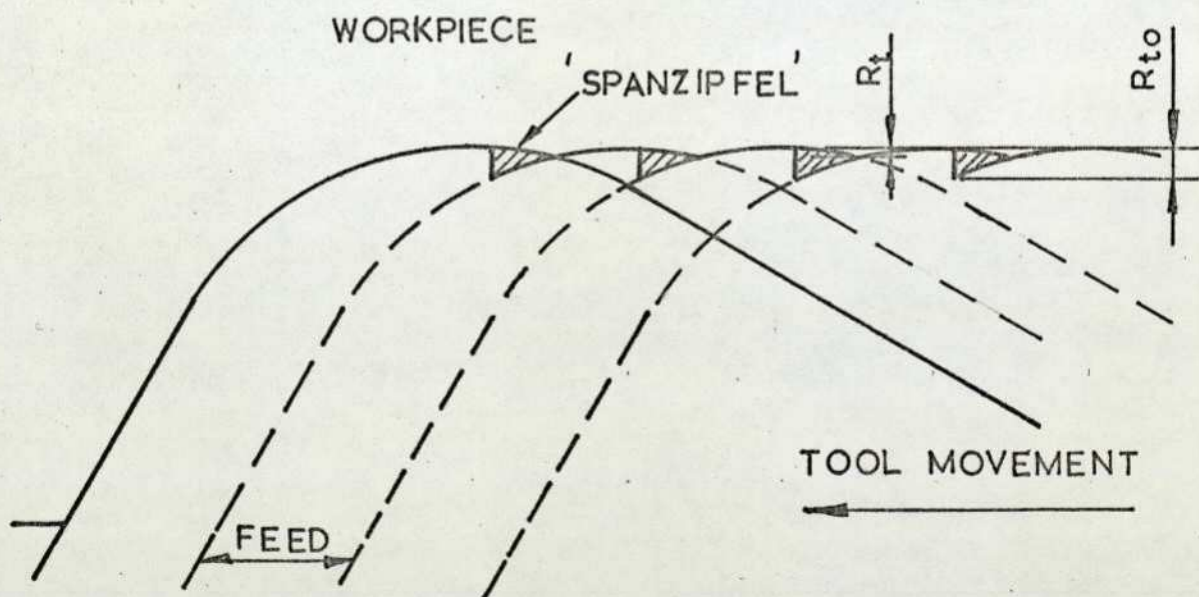
(a) IDEAL SURFACE PROFILE WHEN MACHINED
SURFACE IS GENERATED BY CORNER RADIUS ALONE



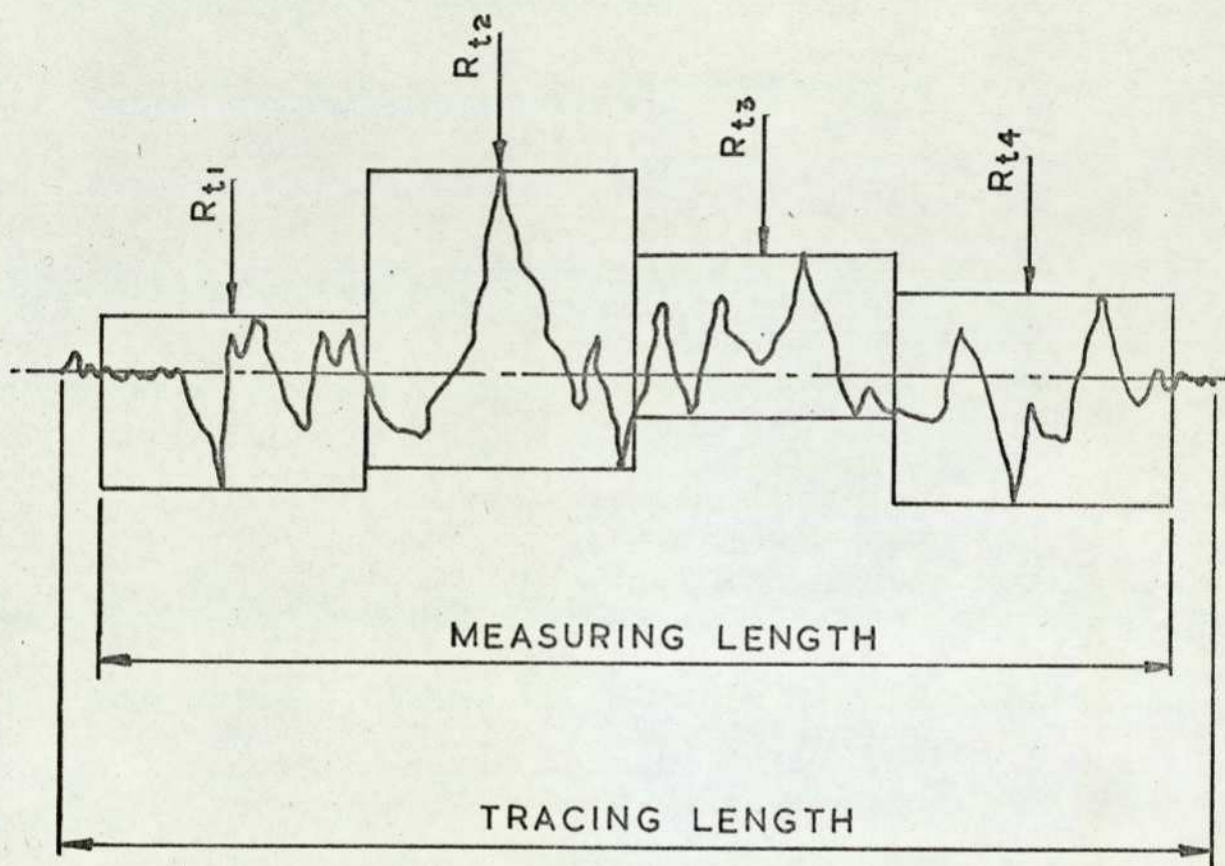
(b) GROOVE WEAR ON PROFILING CUTTING EDGE



(a) EFFECT OF SIDEFLOW ON SURFACE ROUGHNESS



(b) THE SOKOLOWSKI EFFECT



MEAN TOTAL HEIGHT $R_{tm} = \frac{1}{4} \sum_1^4 R_t$

METHOD OF ASSESSING THE ROUGHNESS OF
THE PRIMARY SURFACE

MOUNTING MEDIUM	DETAILS OF PREPARATION
1. Bakelite	Heated to 160°C for 3 mins at 30 N/mm ² pressure, allowed to cool.
2. Diallyl Phthalate (Glass Fibre Filled Resin)	Heated to 160° for 3 mins at 30 N/mm ² pressure, allowed to cool.
3. Bakelite, Nickel and Copper Plated	Chemically cleaned, electro plated with Ni for 1½ hours at a current density of 100 amp/m ² and then electro plated with Cu for 1 hour 350 amp/m ² . Mounted in Bakelite as 1.
4. Diallyl Phthalate Nickel & Copper Plated	As 3. but mounted in Diallyl Phthalate.
5. Araldite Impregnated with Aluminium Oxide	Mixture in the ratio Araldite 10 Hardener 2.4 Al ₂ O ₃ 5 Preheated to 30°C and then de-gassed in a vacuum and cured at 80°C for ½ hour and 60°C 12 hours.

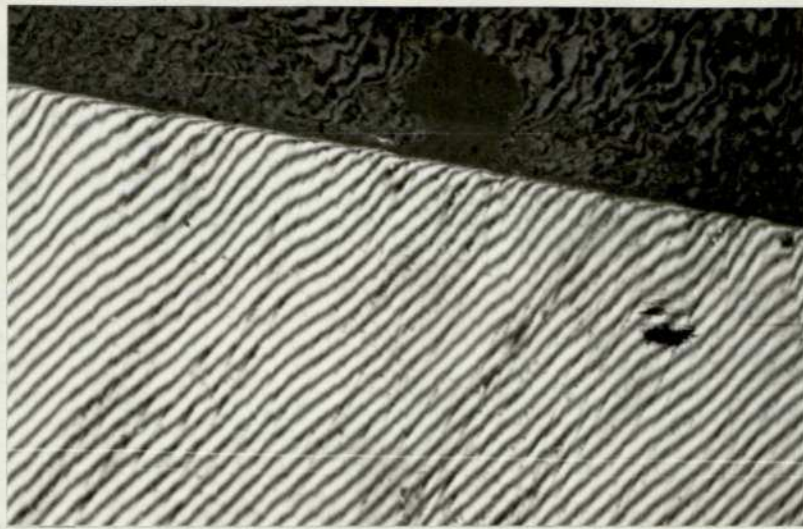
Electrolyte for Nickel Plating - Watts Solution

Ni SO₄ 140g Ni Cl₂ 28g Boric Acid 15.5g Water 500g

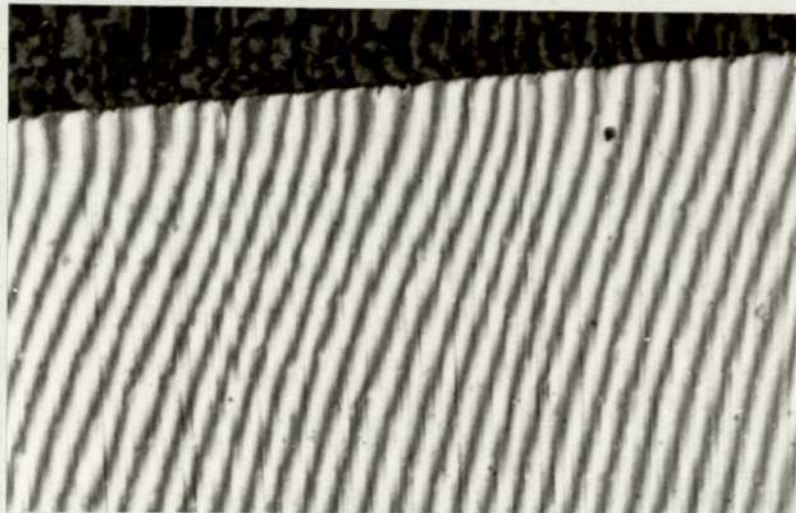
Electrolyte for Copper Plating

Cu SO₄ crystals 250g/L Conc H₂ SO₄ 40g/L.

TABLE SHOWING DETAILS OF EDGE PREPARATION
TECHNIQUE.



1. BAKELITE UNIDIRECTIONAL POLISH

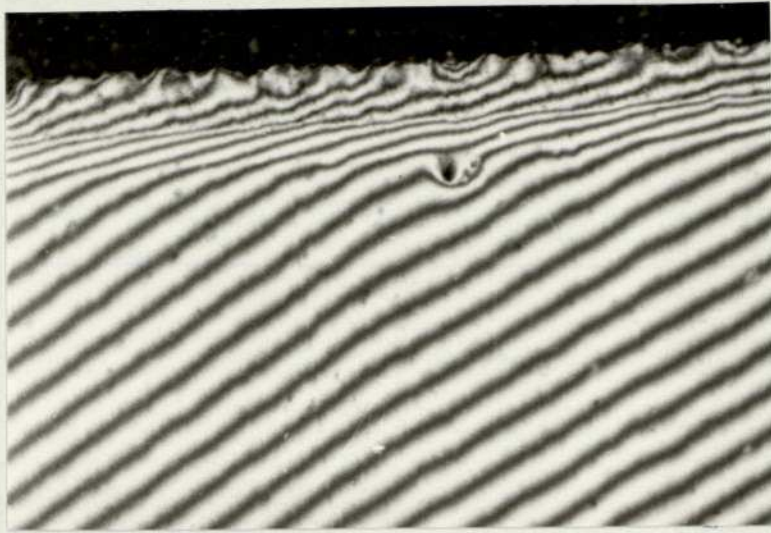


2. DIALLYL PHTHALATE UNIDIRECTIONAL POLISH

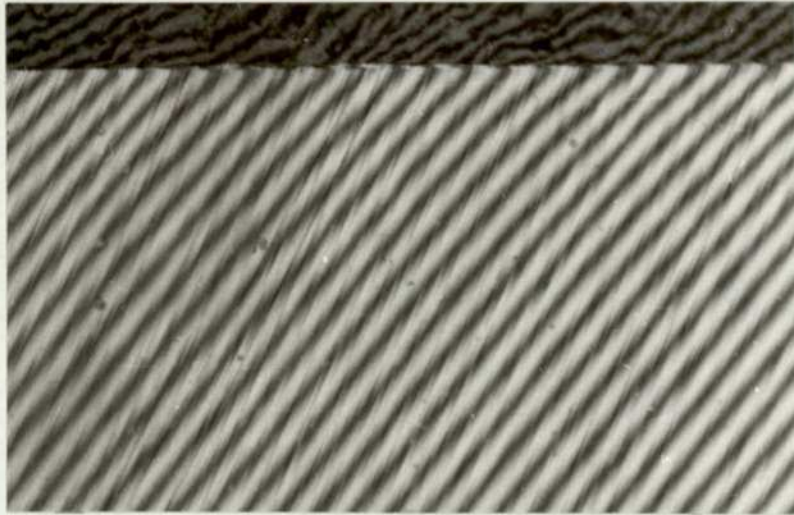


3. BAKELITE PLATED UNIDIRECTIONAL POLISH

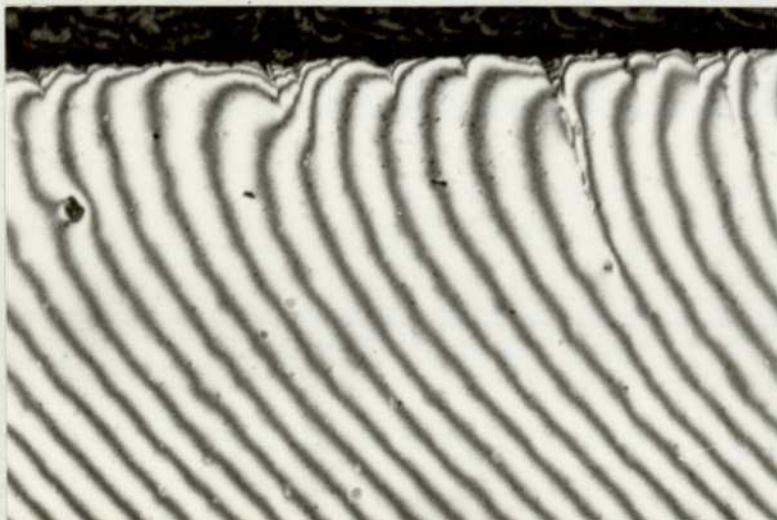
EFFECT OF MOUNTING & POLISHING ON EDGE
RETENTION. X 300



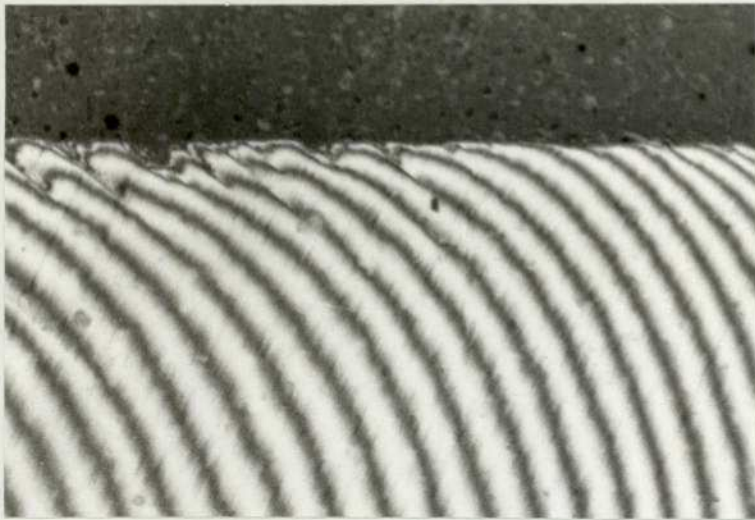
4. DIALLYL PHTHALATE PLATED UNIDIRECTIONAL POLISH



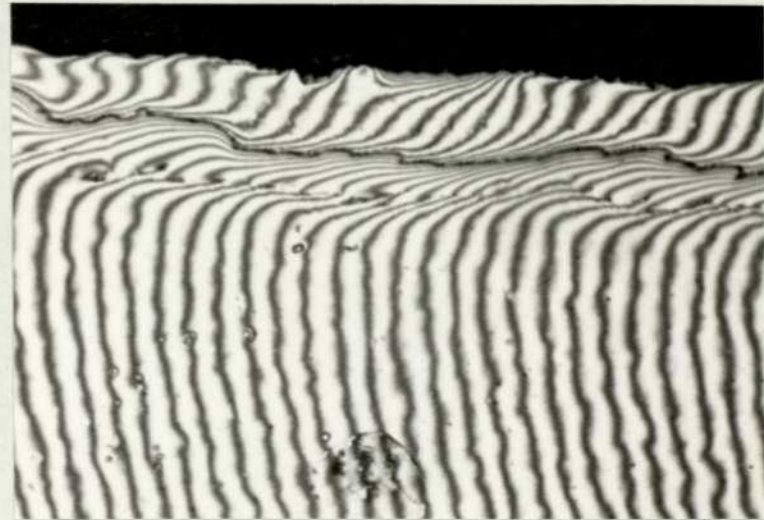
5. ARALDITE IMPREGNATED WITH ALUMINIUM OXIDE UNIDIRECTIONAL POLISH



6. BAKELITE MULTIDIRECTIONAL POLISH



7. DIALLYL PHTHALATE MULTIDIRECTIONAL POLISH



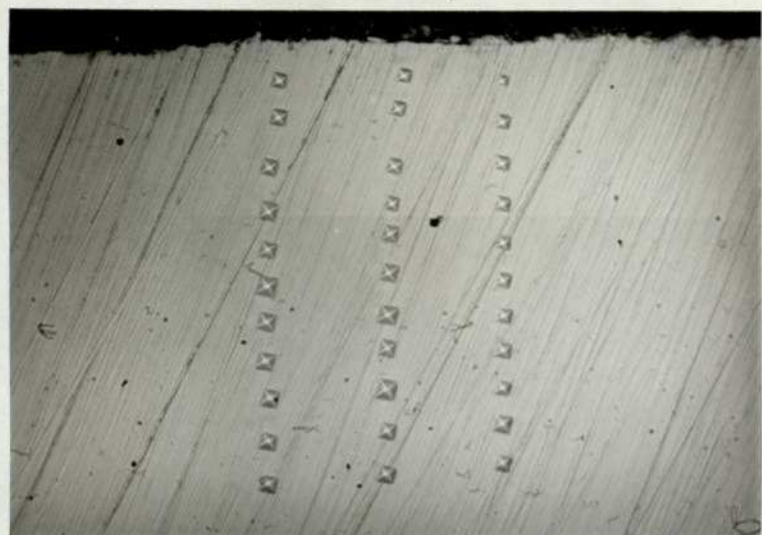
8. BAKELITE PLATED MULTIDIRECTIONAL POLISH



9. DIALLYL PHTHALATE PLATED MULTIDIRECTIONAL POLISH

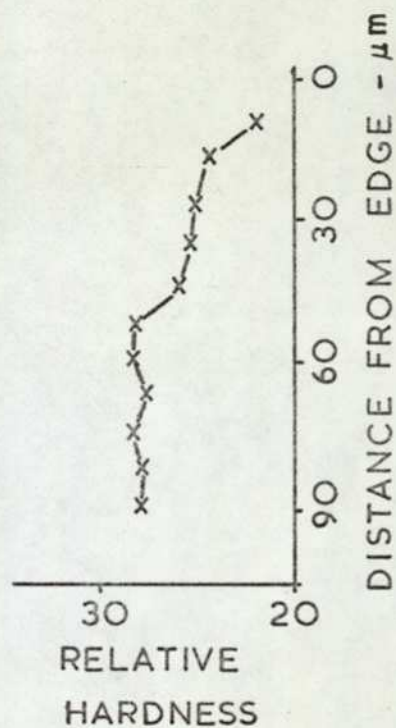


10. ARALDITE WITH ALUMINIUM OXIDE MULTIDIRECTIONAL POLISH



X 700

1. UNETCHED

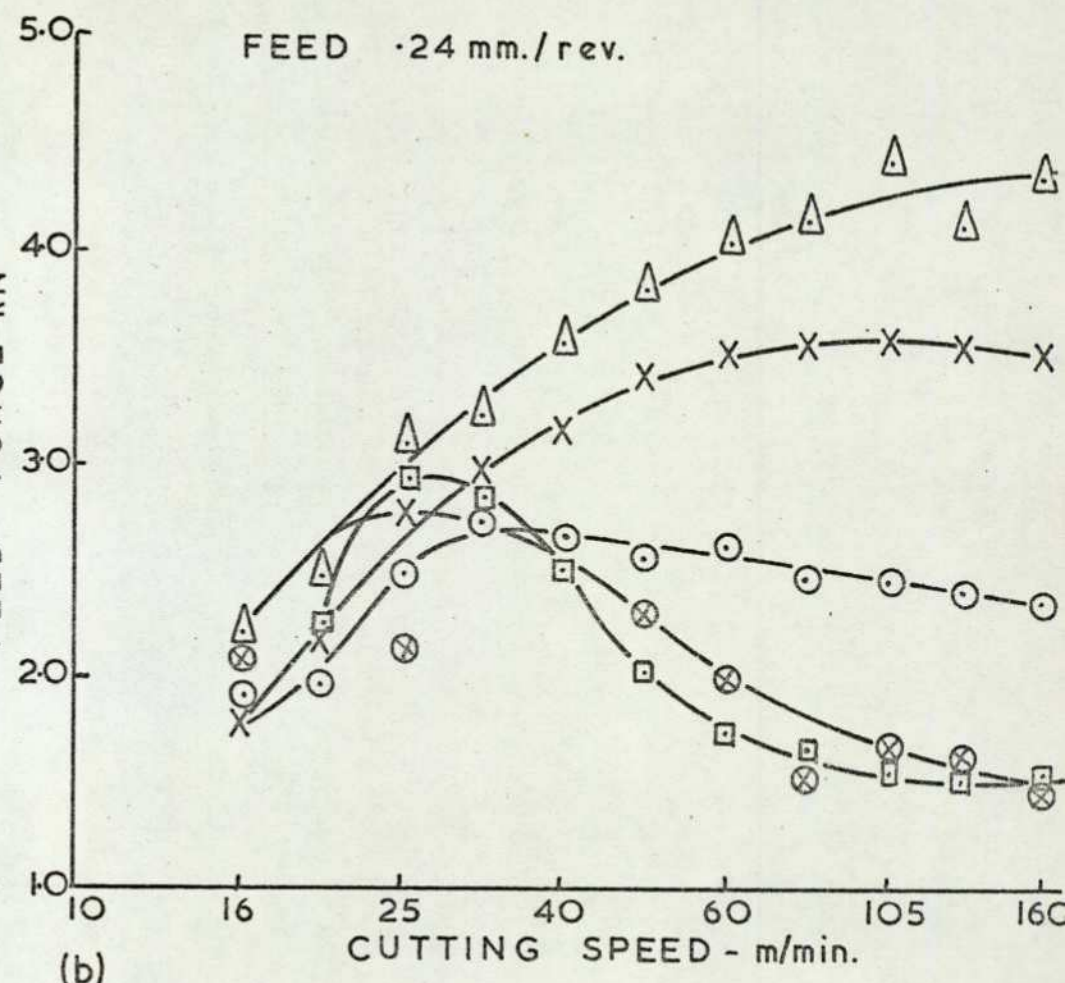
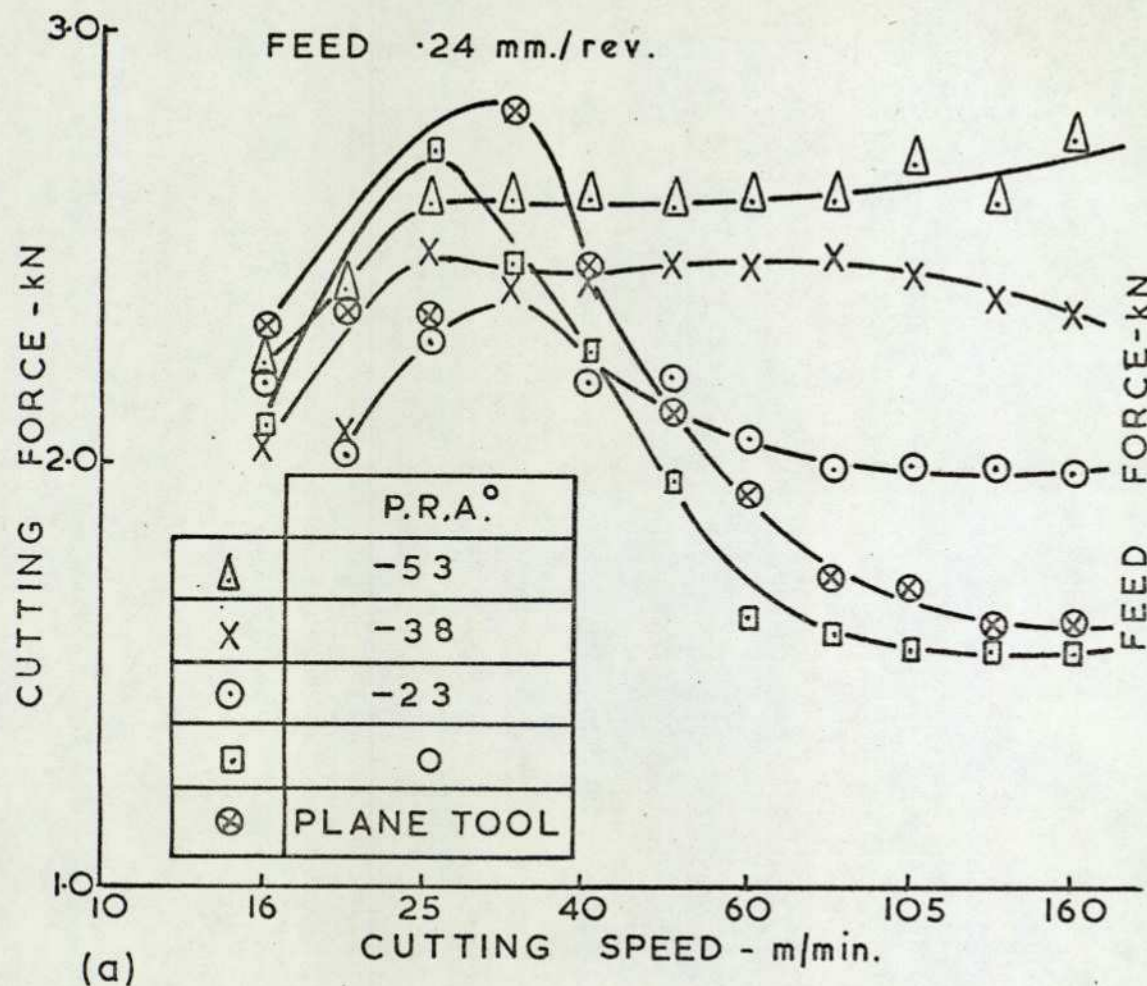


X 700

2. SAME SURFACE ETCHED

EXAMINATION OF THE PLASTICALLY DEFORMED LAYER.

1. USING MICRO HARDNESS
2. VISUAL EXAMINATION



VARIATION OF CUTTING & FEED FORCES WITH CUTTING SPEED WHEN USING TOOLS OF DIFFERENT RAKE FACE CONFIGURATION.

MATERIAL CDS I. P 30 CARBIDE TOOLS. LAND LENGTH 0.75mm.

WIDTH OF CUT 4mm.

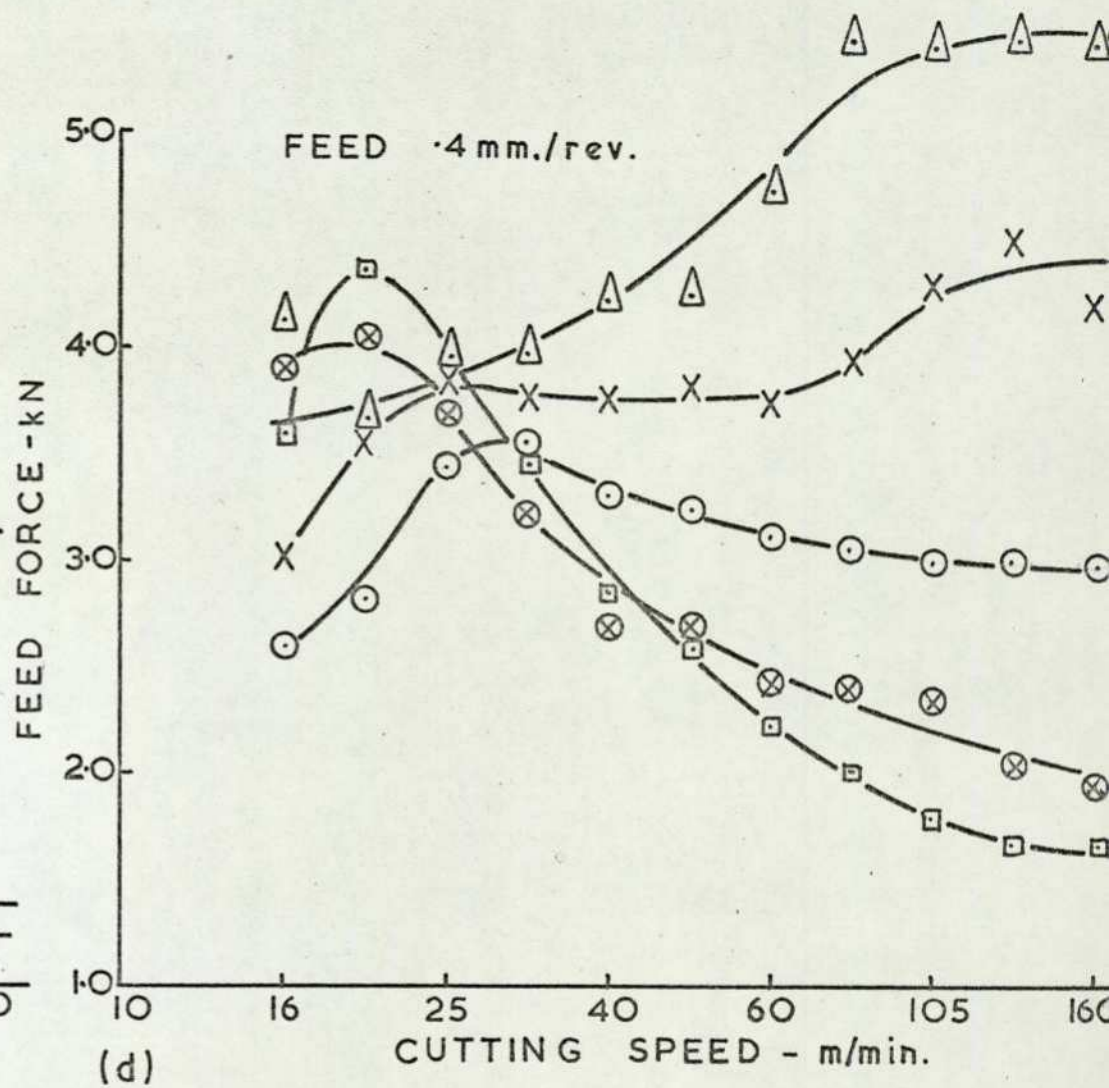
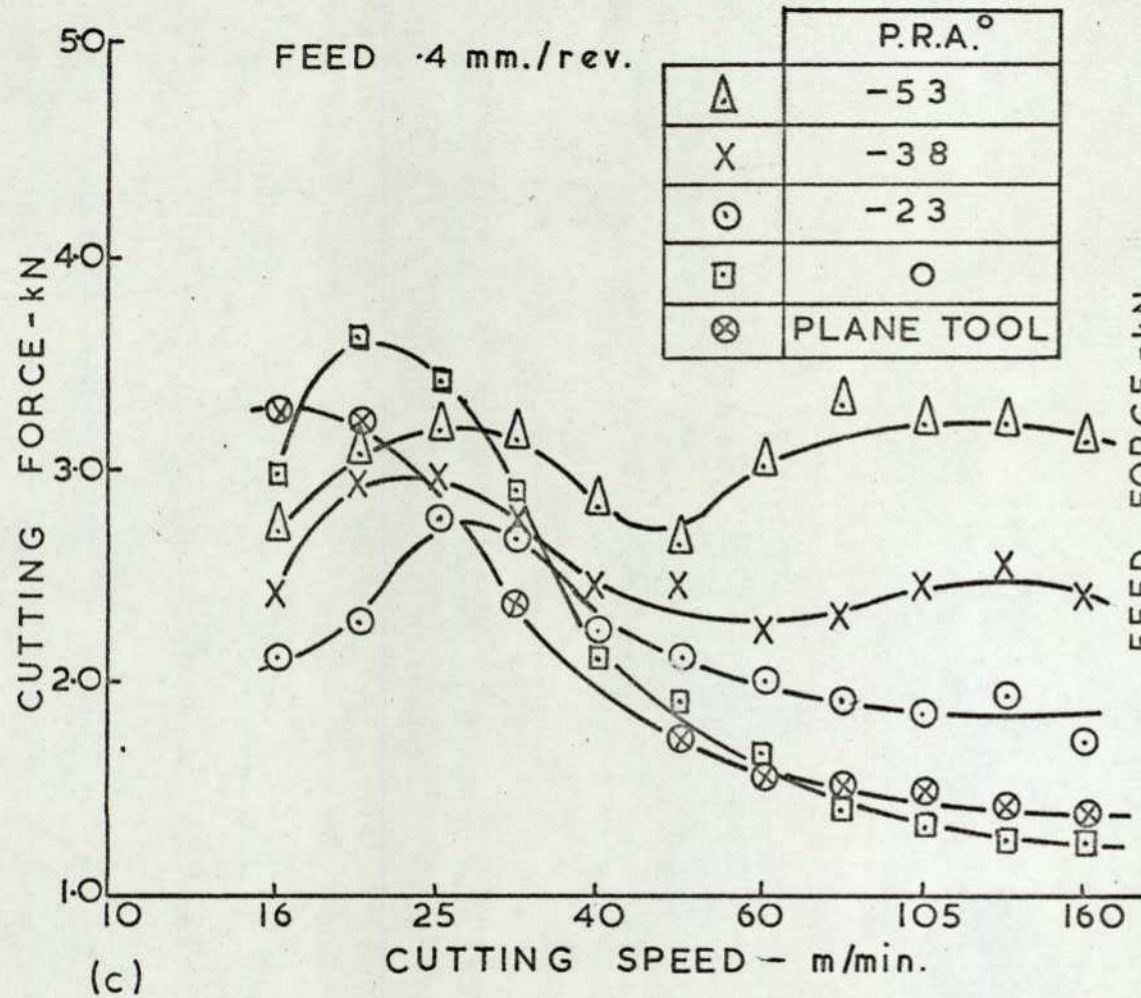
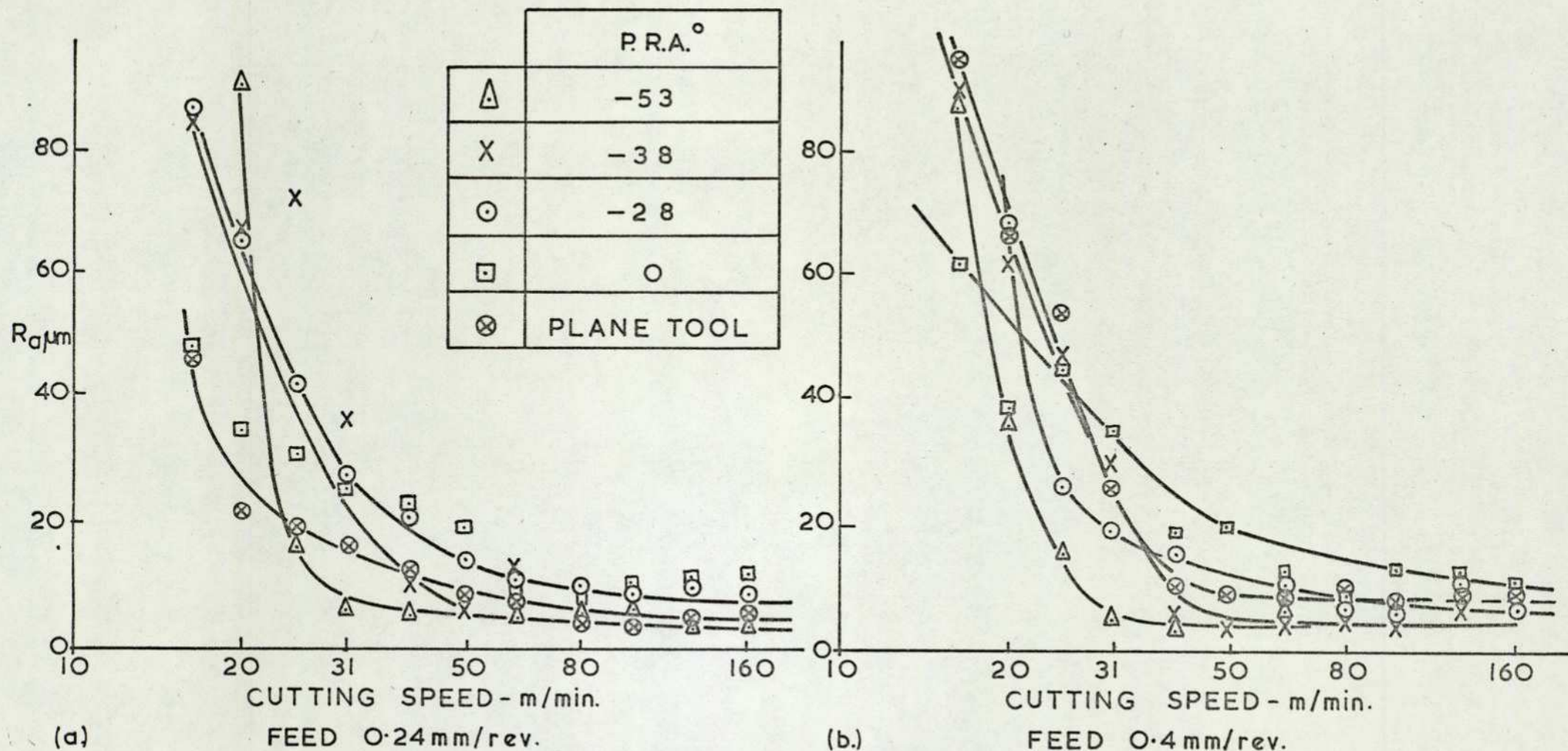


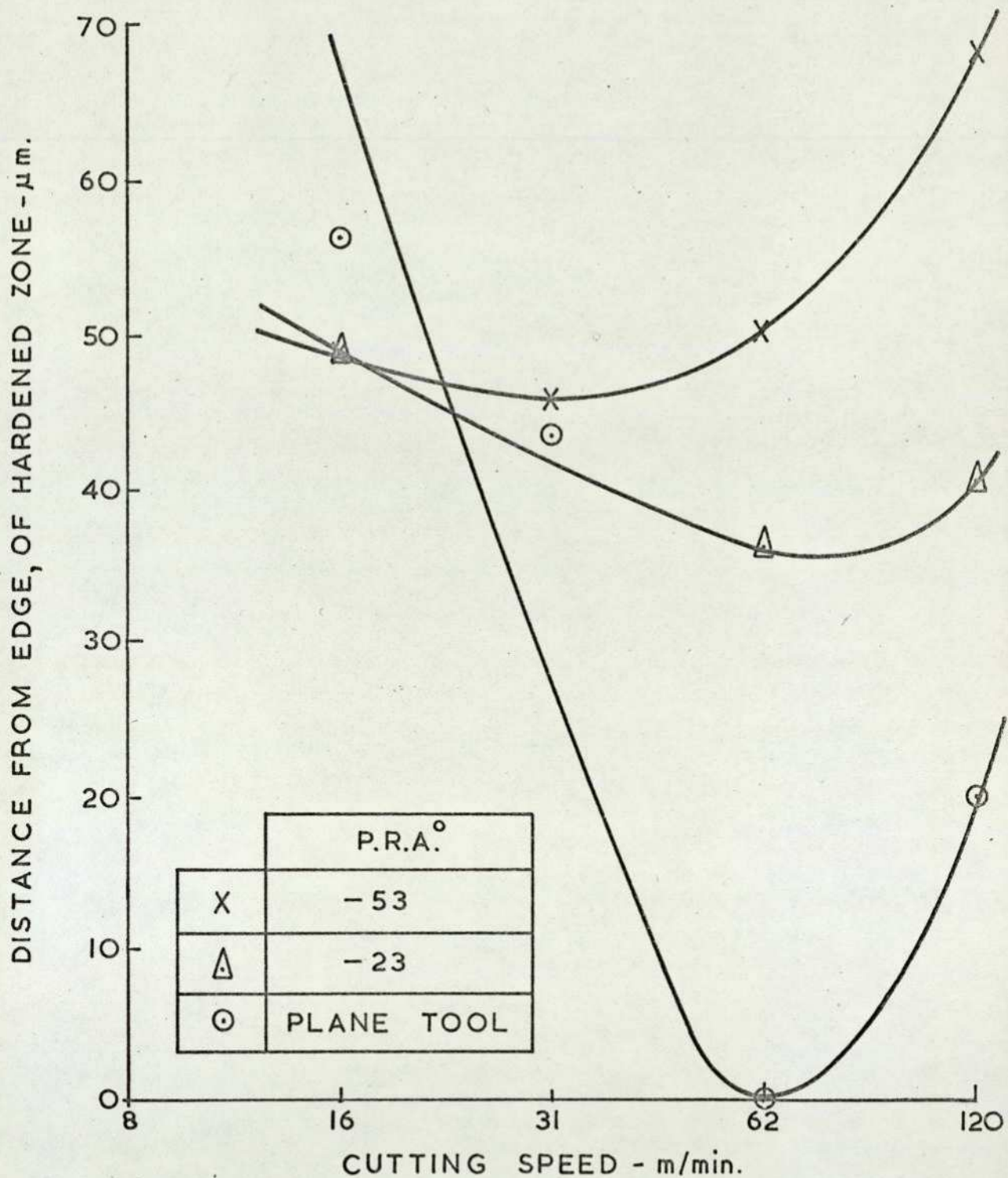
FIG. 5.10.b.



VARIATION OF SURFACE ROUGHNESS WITH CUTTING SPEED WHEN ORTHOGONALLY MACHINING WITH TOOLS OF DIFFERENT PRIMARY RAKE ANGLE

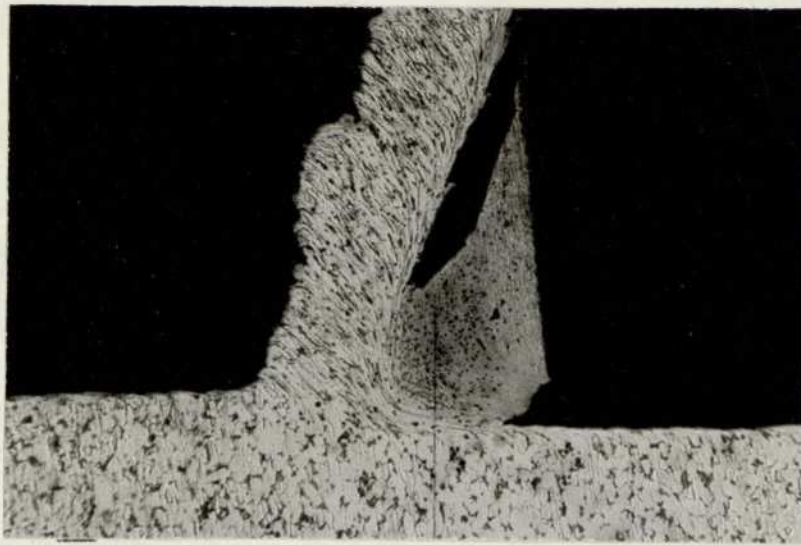
MATERIAL CDS I. P30 CARBIDE TOOLS. LAND LENGTH 0.75 mm.

FIG. 5.11.

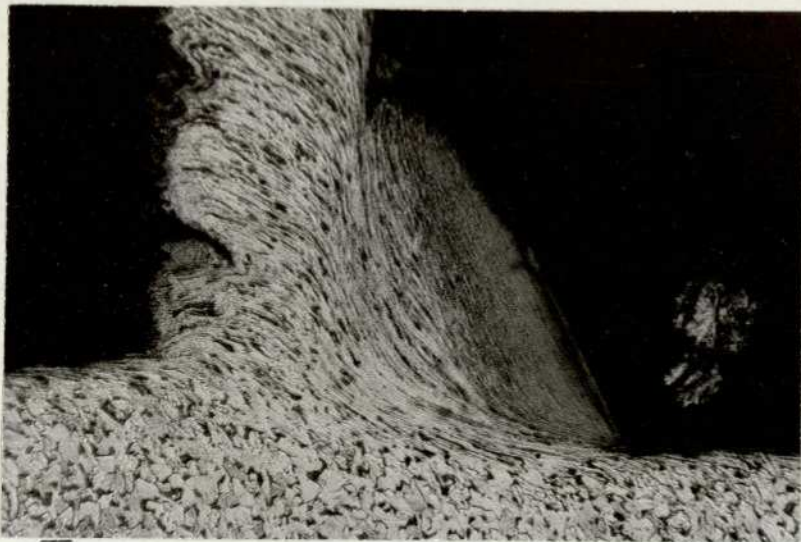


THE EFFECT OF PRIMARY RAKE ANGLE & CUTTING
SPEED ON THE DEPTH OF THE WORK HARDENED
ZONE WHEN MACHINING ORTHOGONALLY

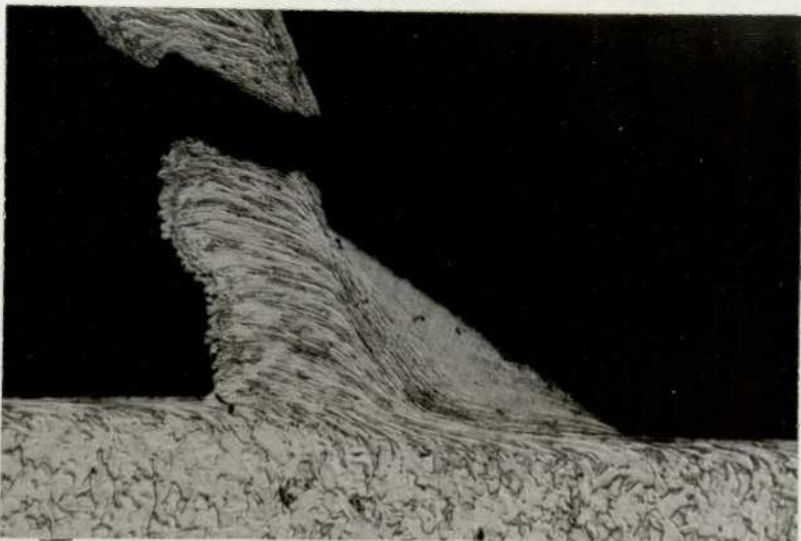
MATERIAL CDS I. FEED 0.24 mm./rev.



7° P.R.A.



-23° P.R.A.



-53° P.R.A.

x 80

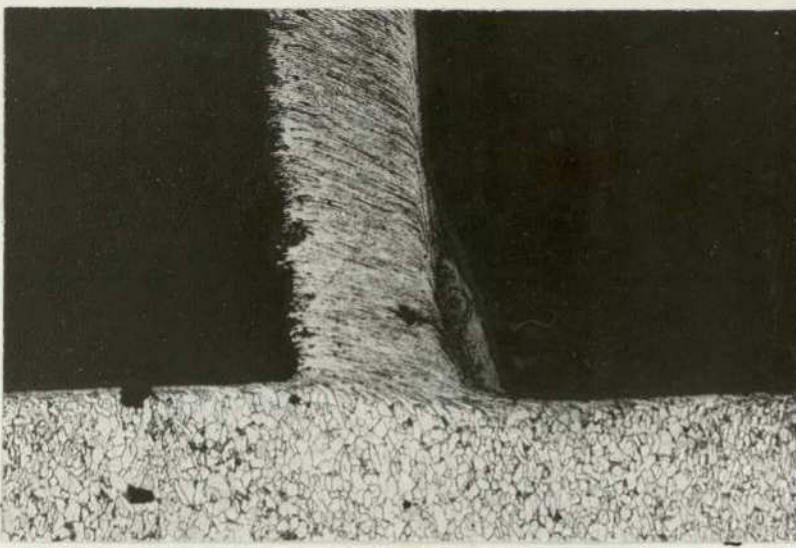
THE EFFECT OF PRIMARY RAKE ANGLE ON THE
SHAPE OF THE SPECIAL BUILT-UP-EDGE

CUTTING SPEED 32 m/min. 0.24 mm.FEED. 0.76 mm.LAND LENGTH

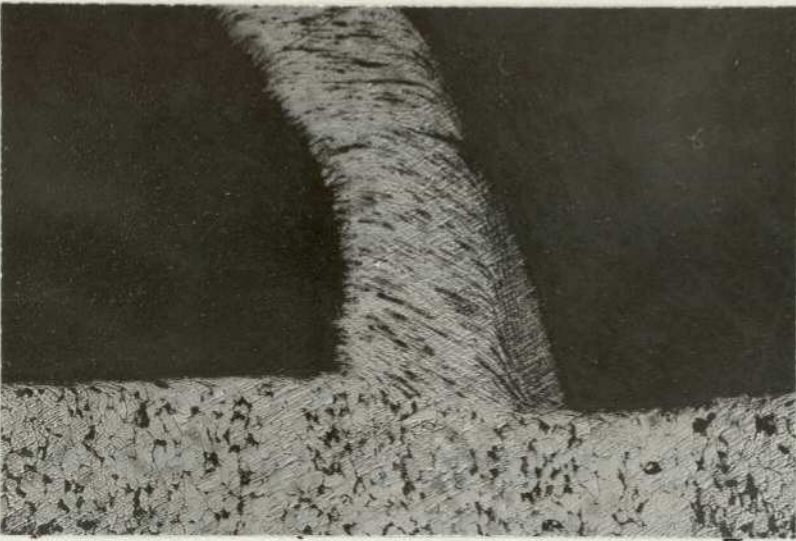
WORKPIECE MATERIAL C D S I. $\gamma_2 + 7^\circ$

FIG. 5.13

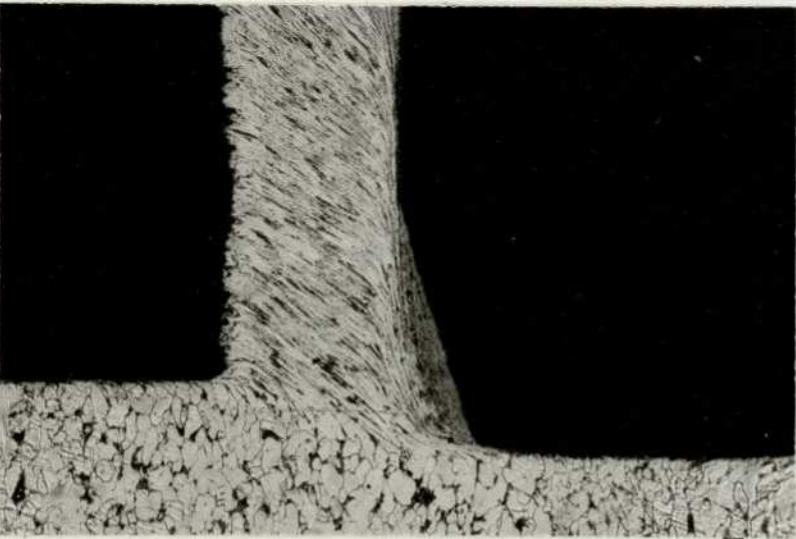
U.C.T. mm



0.05



0.01



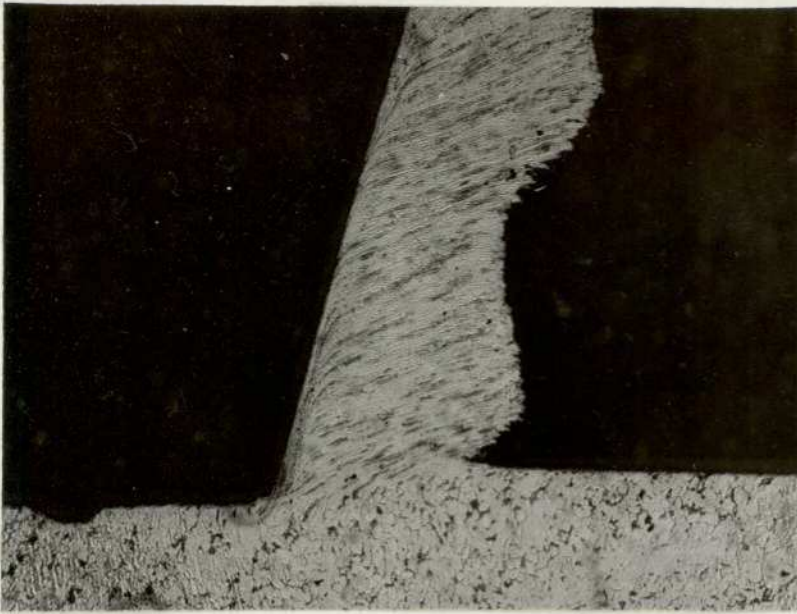
0.20

X 120

THE EFFECT OF LAND LENGTH ON THE SHAPE OF
THE SPECIAL BUILT-UP-EDGE

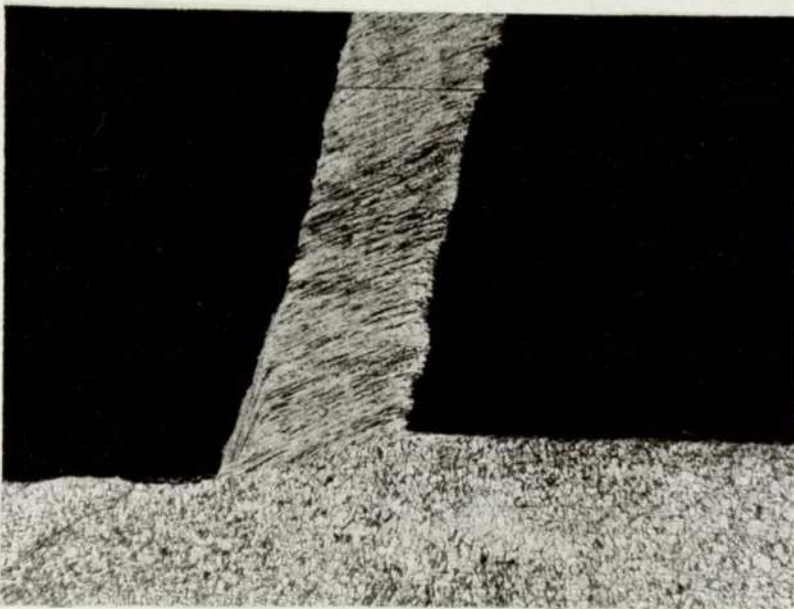
CUTTING SPEED 100 m/min. 0.35mm. LAND LENGTH.

WORKPIECE MATERIAL CDS I. $\gamma_2 + 7^\circ, \gamma_1 + 16^\circ$ FIG. 5.14 a

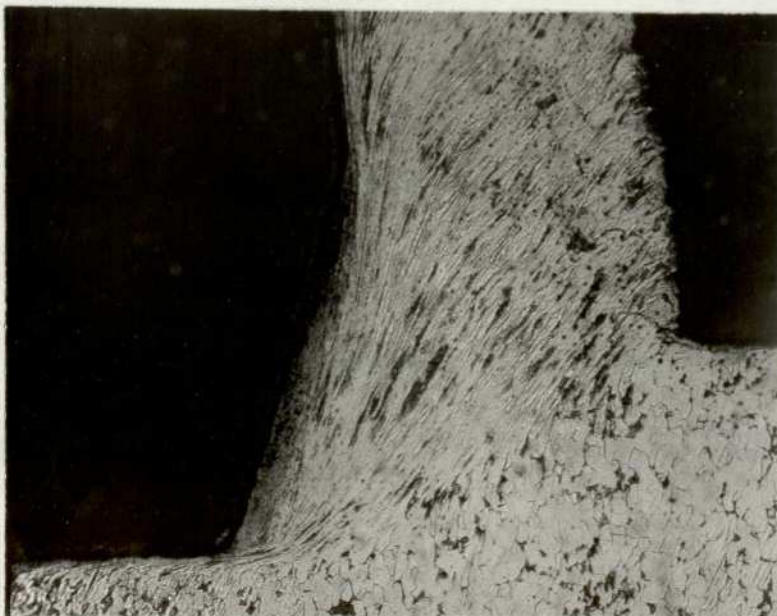


U.C.T. - mm

0.1



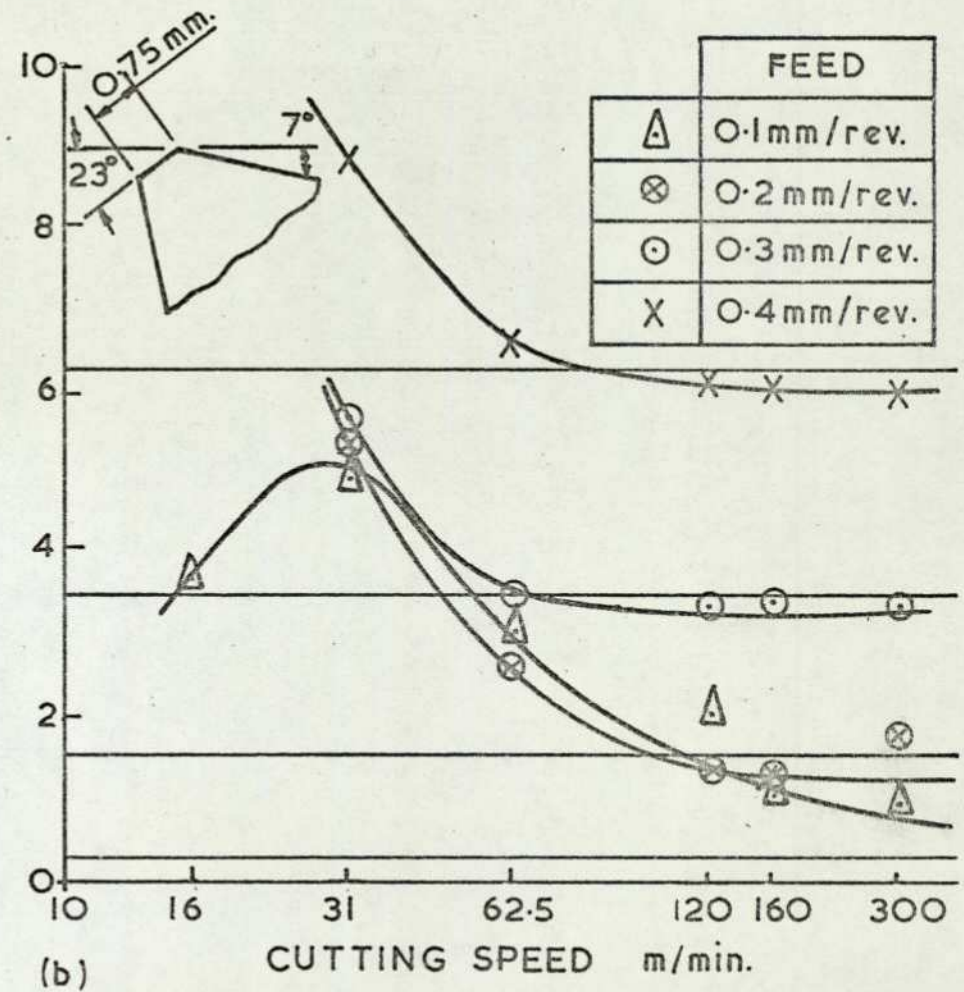
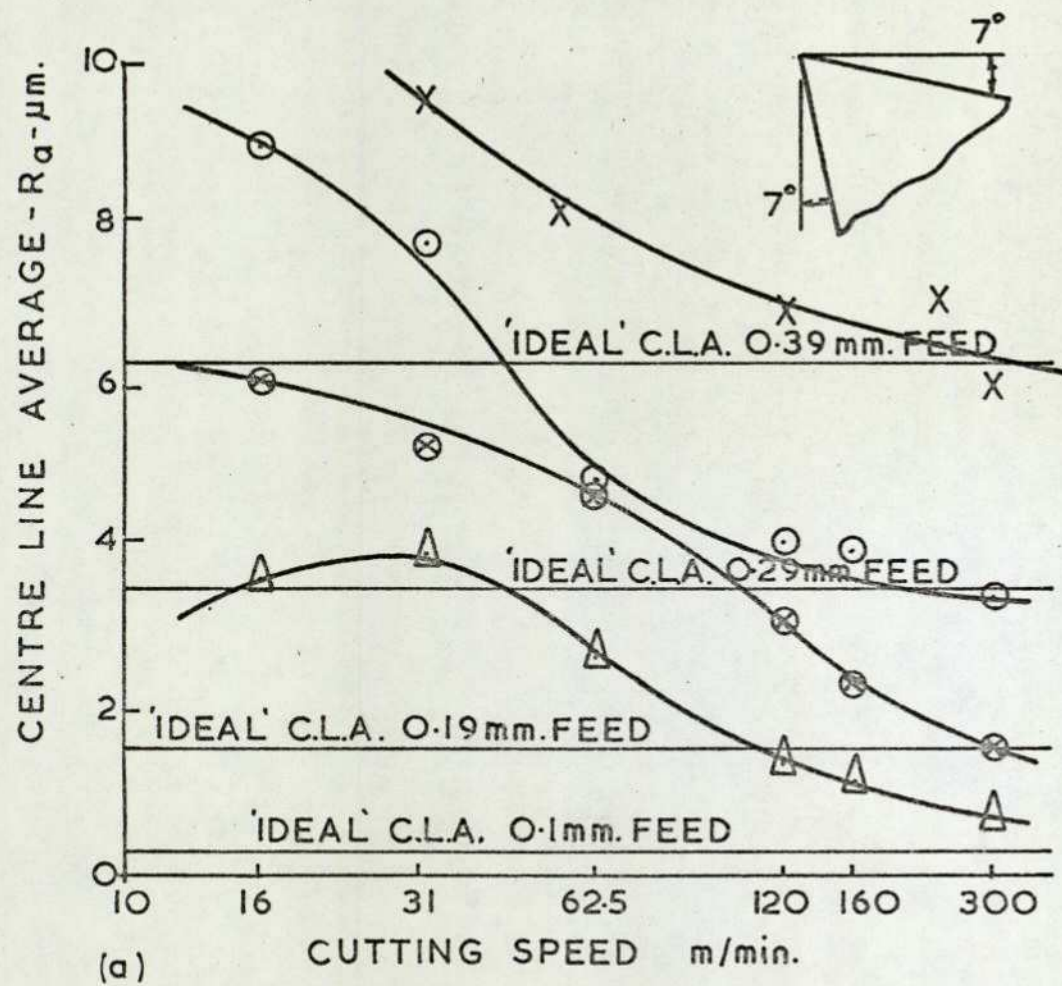
0.2



0.3

LAND LENGTH - 0.55 mm.

FIG. 5.14 b



VARIATION OF SURFACE ROUGHNESS WITH CUTTING SPEED WHEN MACHINING
OBLIQUELY AT VARIOUS FEEDS (a) PLANE TOOL

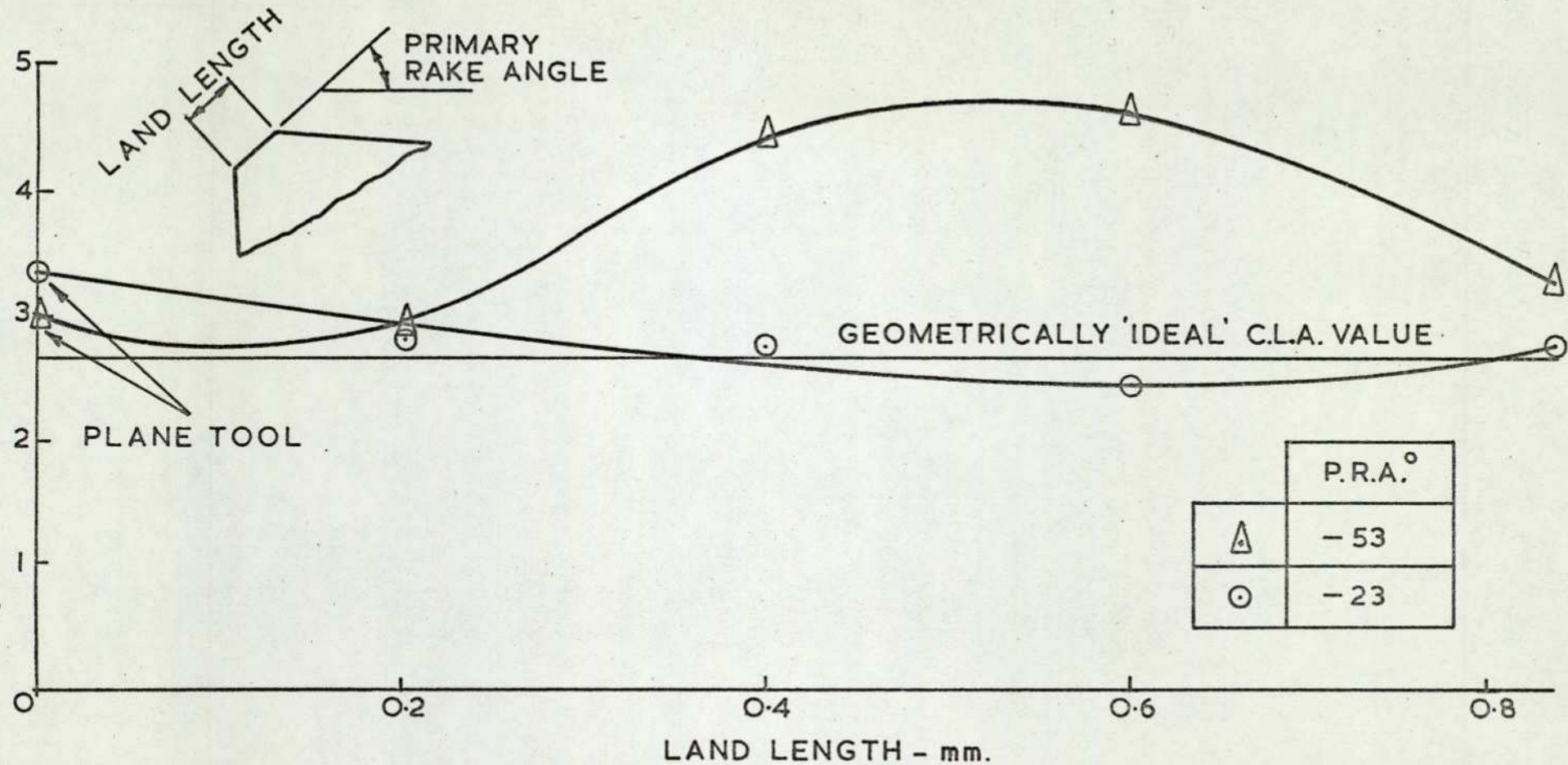
(b) CONTROLLED CONTACT LENGTH TOOL

MATERIAL En 8. CUTTING EDGE ANGLE 45°

CORNER RADIUS 0.8 mm.

FIG. 5.15.

CENTRE LINE AVERAGE HEIGHT - R_a - μm .

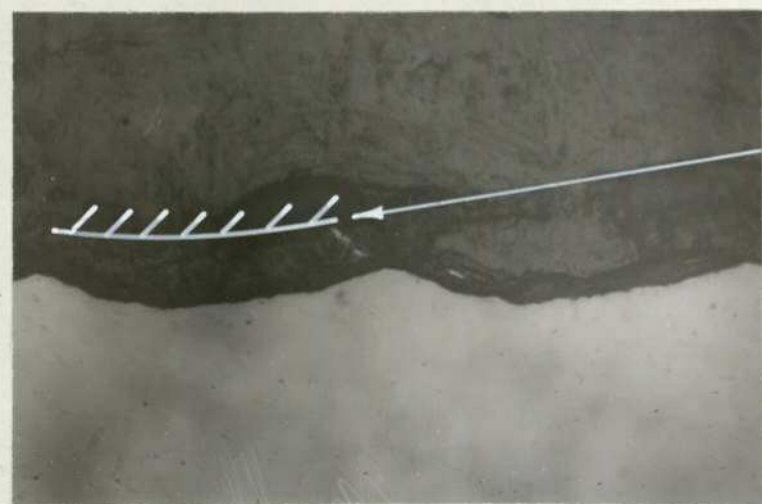


THE EFFECT OF LAND LENGTH ON SURFACE ROUGHNESS WHEN OBLIQUELY MACHINING WITH C.C.L. TOOLS OF DIFFERING PRIMARY RAKE ANGLE

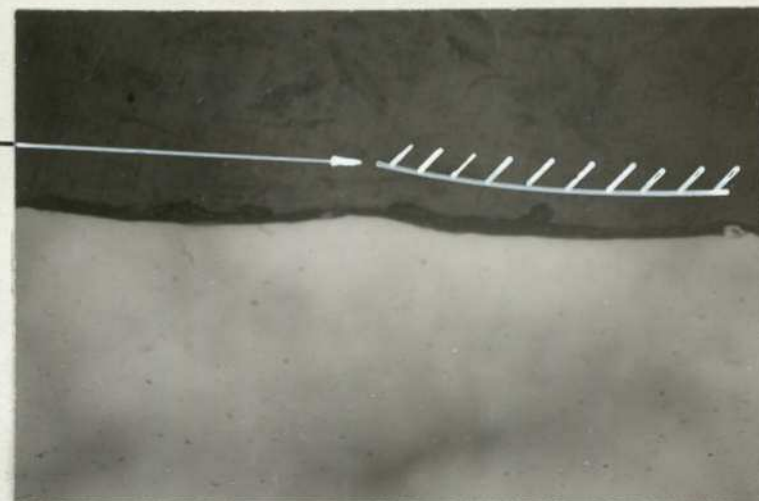
MATERIAL En 8. CUTTING SPEED 120 m/min. FEED 0.254 mm/rev.

CUTTING EDGE INCLINATION ANGLE 45°. CORNER RADIUS 0.8 mm.

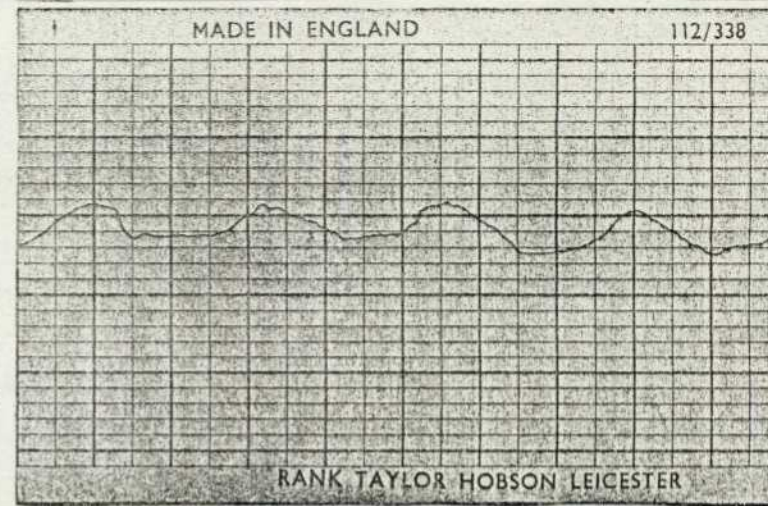
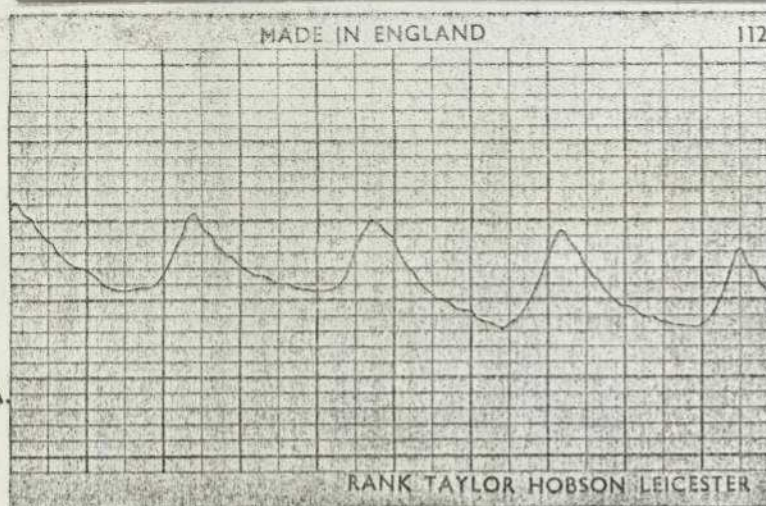
FIG. 5.16.



TOOL PROFILE



X100



X100

X100

THE EFFECT OF PRIMARY RAKE ANGLE ON SURFACE ROUGHNESS WHEN

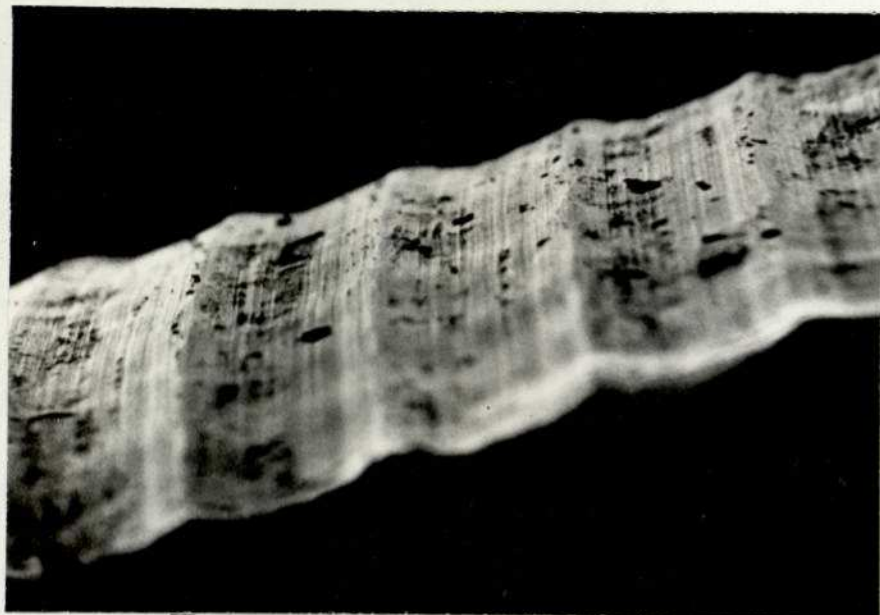
OBLIQUELY MACHINING

FEED 0.24 mm./rev.

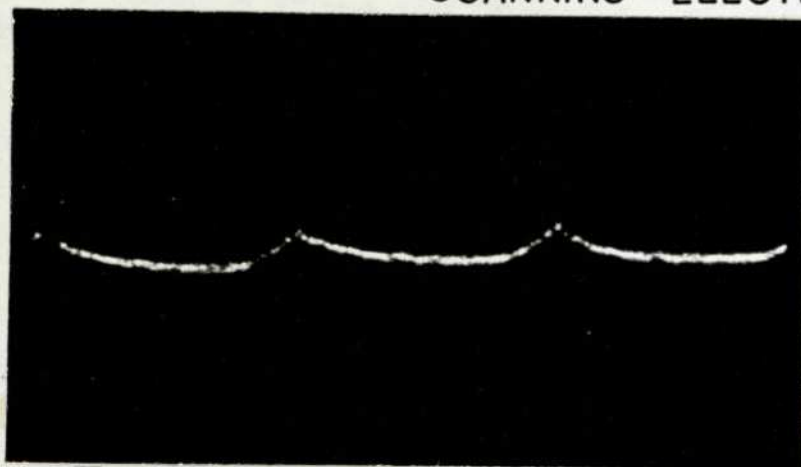
MATERIAL En 8. LAND LENGTH 0.6 mm. CUTTING SPEED 120 m/min.

DEPTH OF CUT 1.25 mm. TOOL CORNER RADIUS 0.8 mm. CUTTING EDGE ANGLE 45°

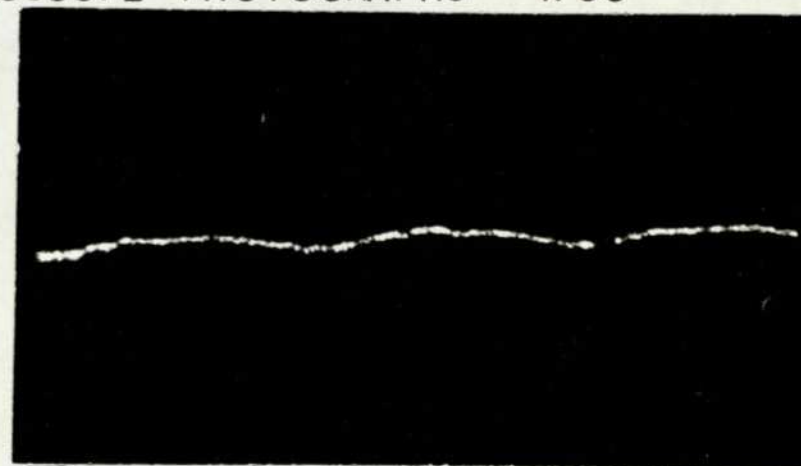
FIG. 5.17a



SCANNING ELECTRON MICROSCOPE PHOTOGRAPHS X 30



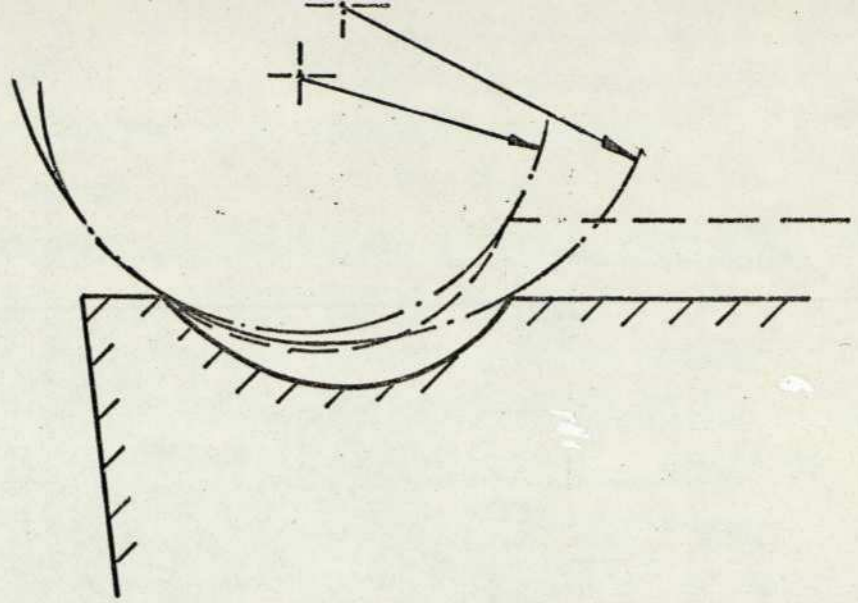
- 53 PRA°



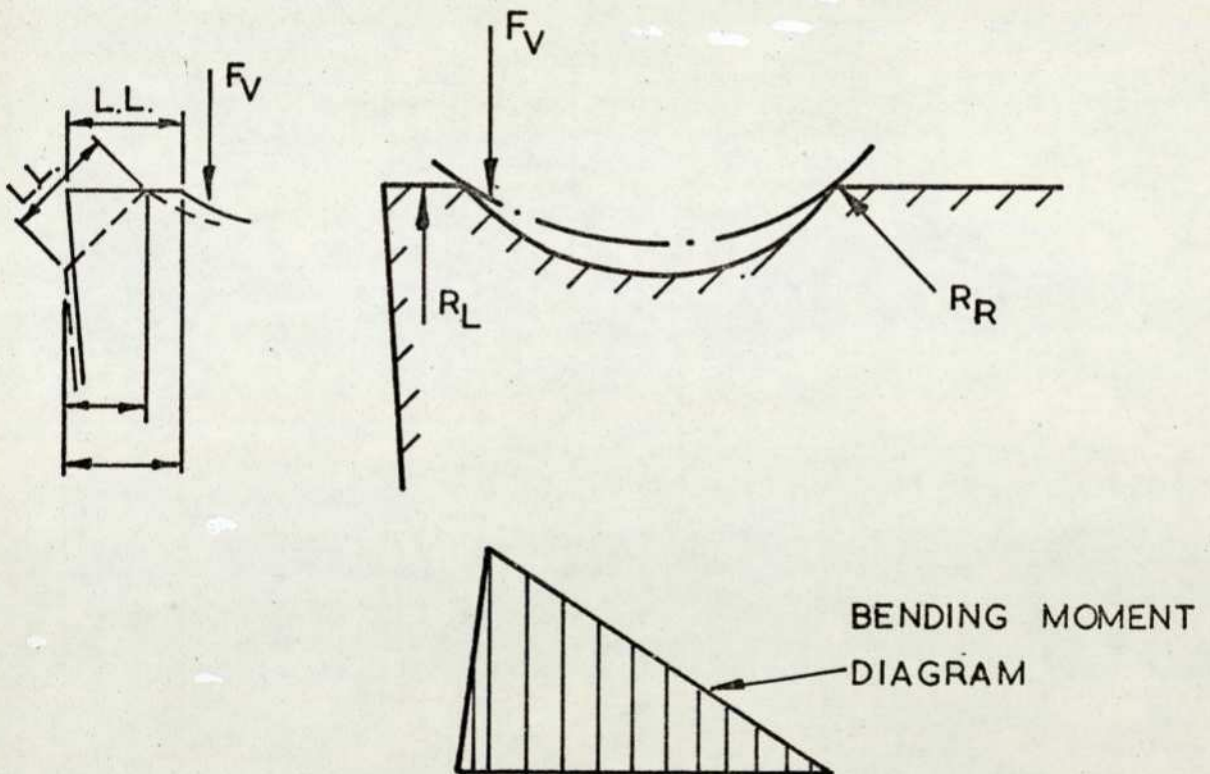
- 23° PRA

LIGHT SECTIONING MICROSCOPE PHOTOGRAPHS X 140

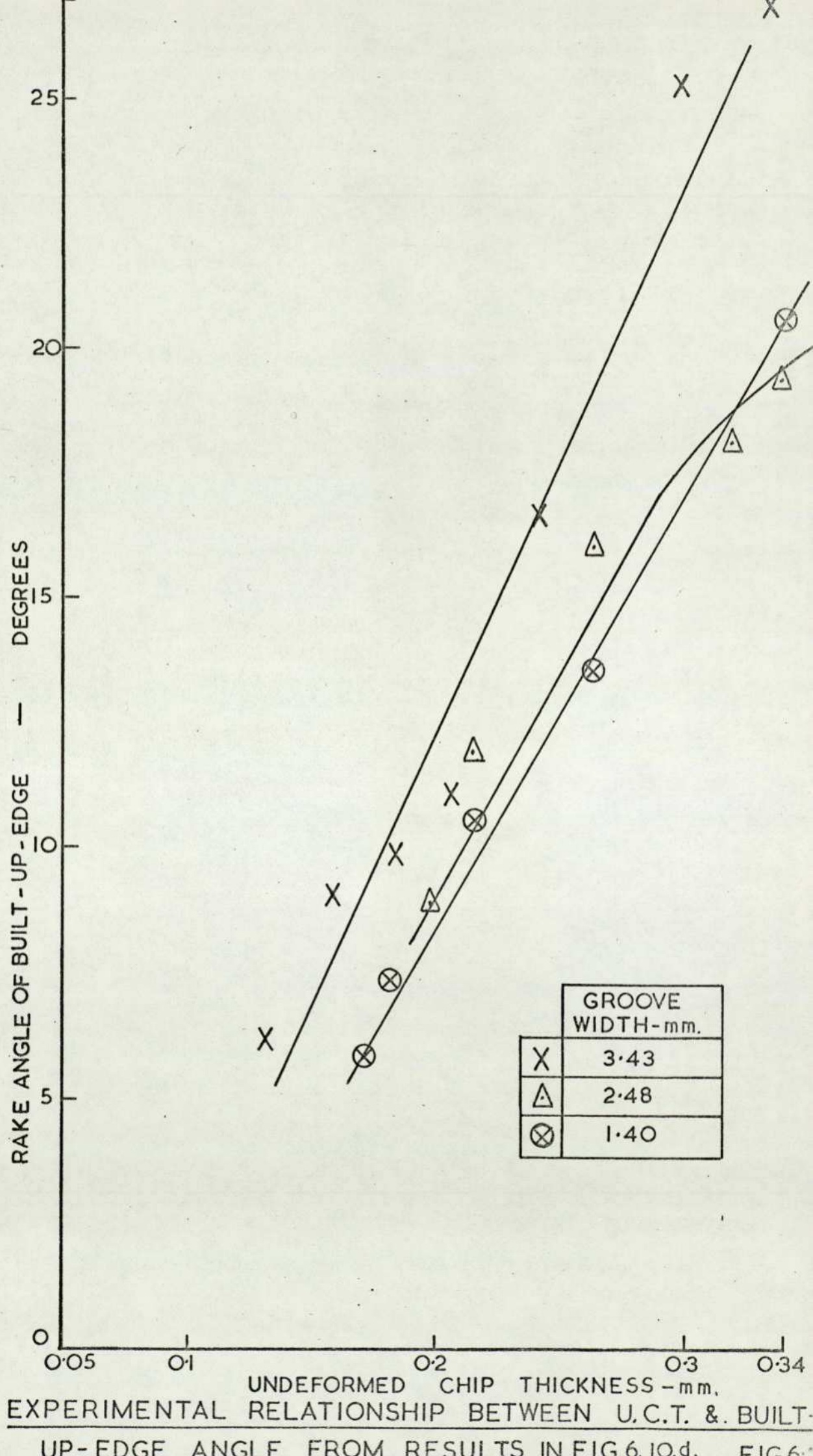
FIG 5.17b

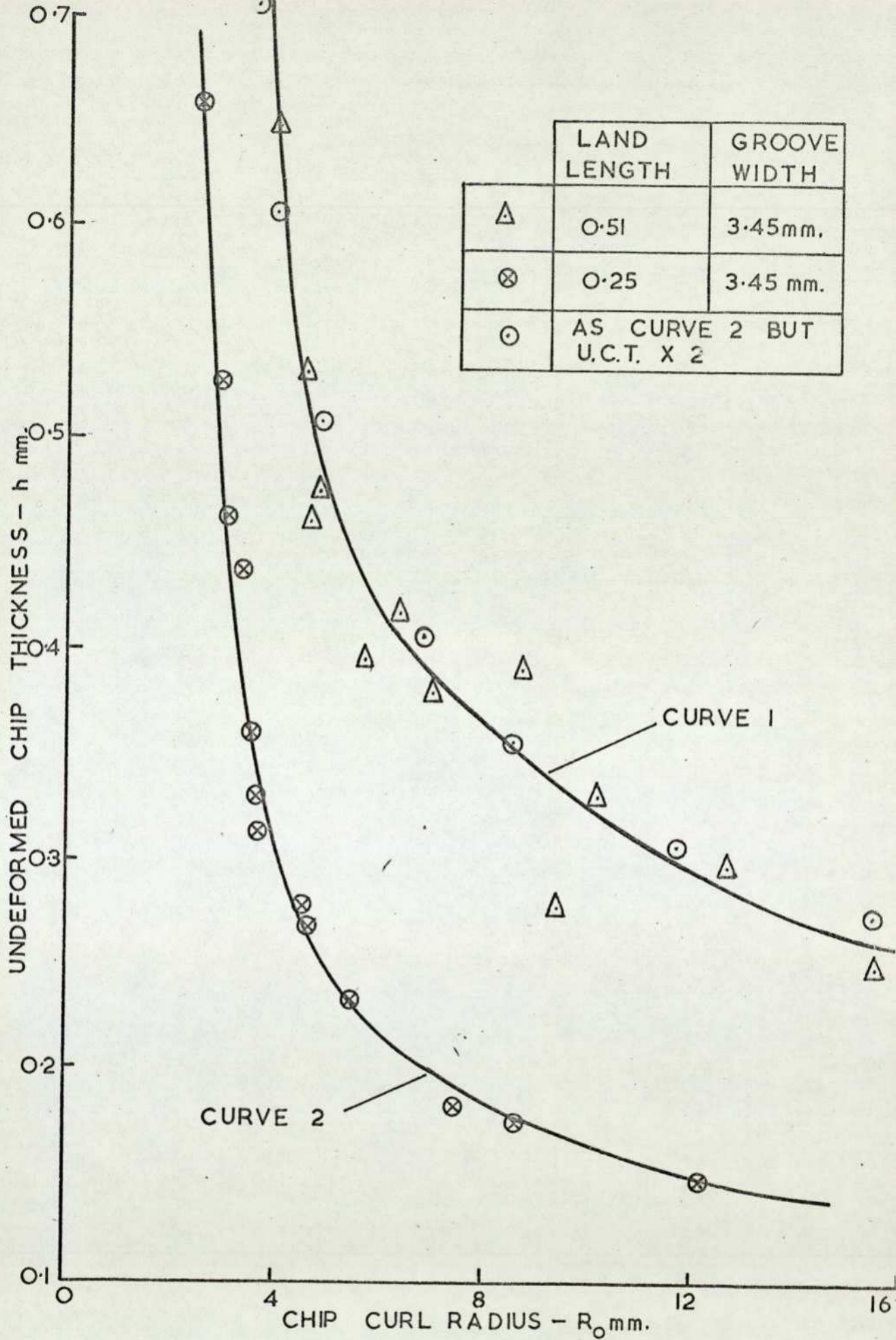


a) EFFECT OF HEIGHT OF CHIP GROOVE HEEL



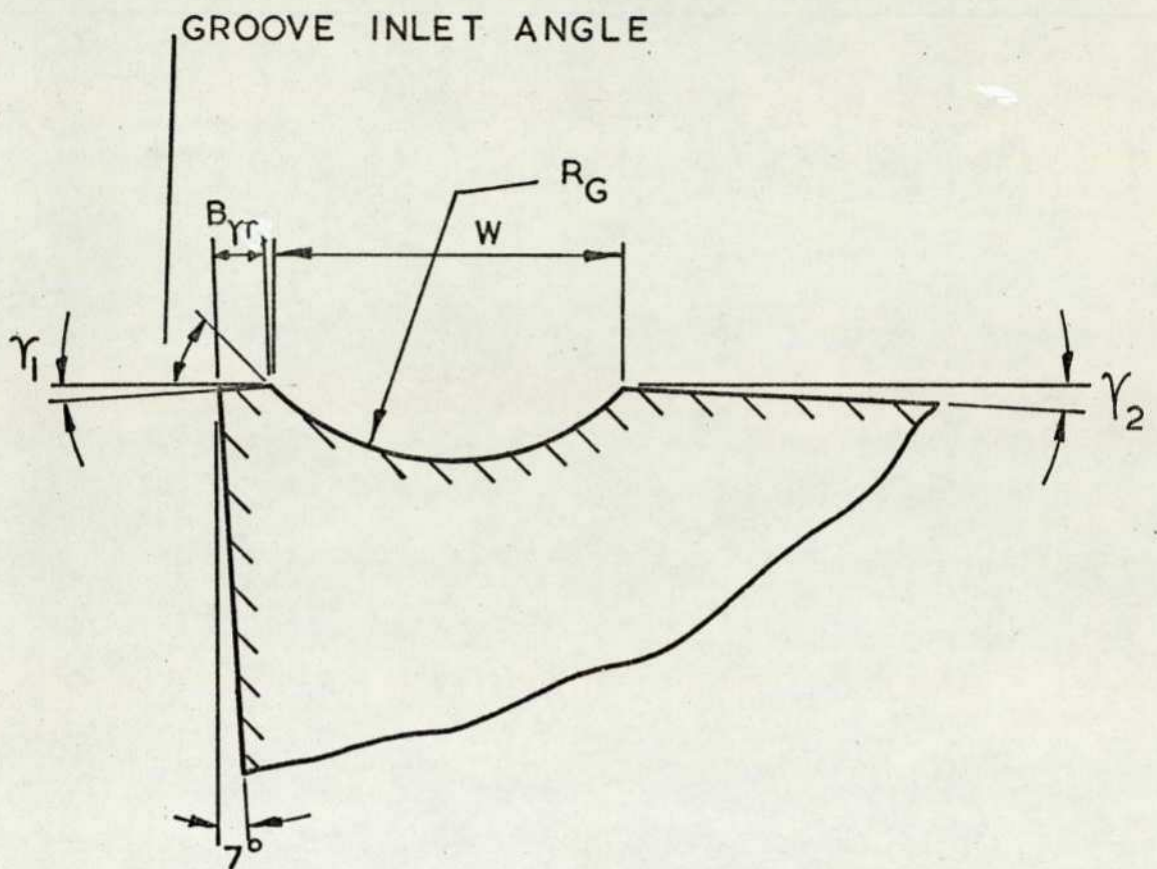
b) BENDING MOMENT ON THE CHIP





EXPERIMENTAL RELATIONSHIP BETWEEN UNDEFORMED
CHIP THICKNESS & CHIP CURL RADIUS WITH
DIFFERENT LAND LENGTHS

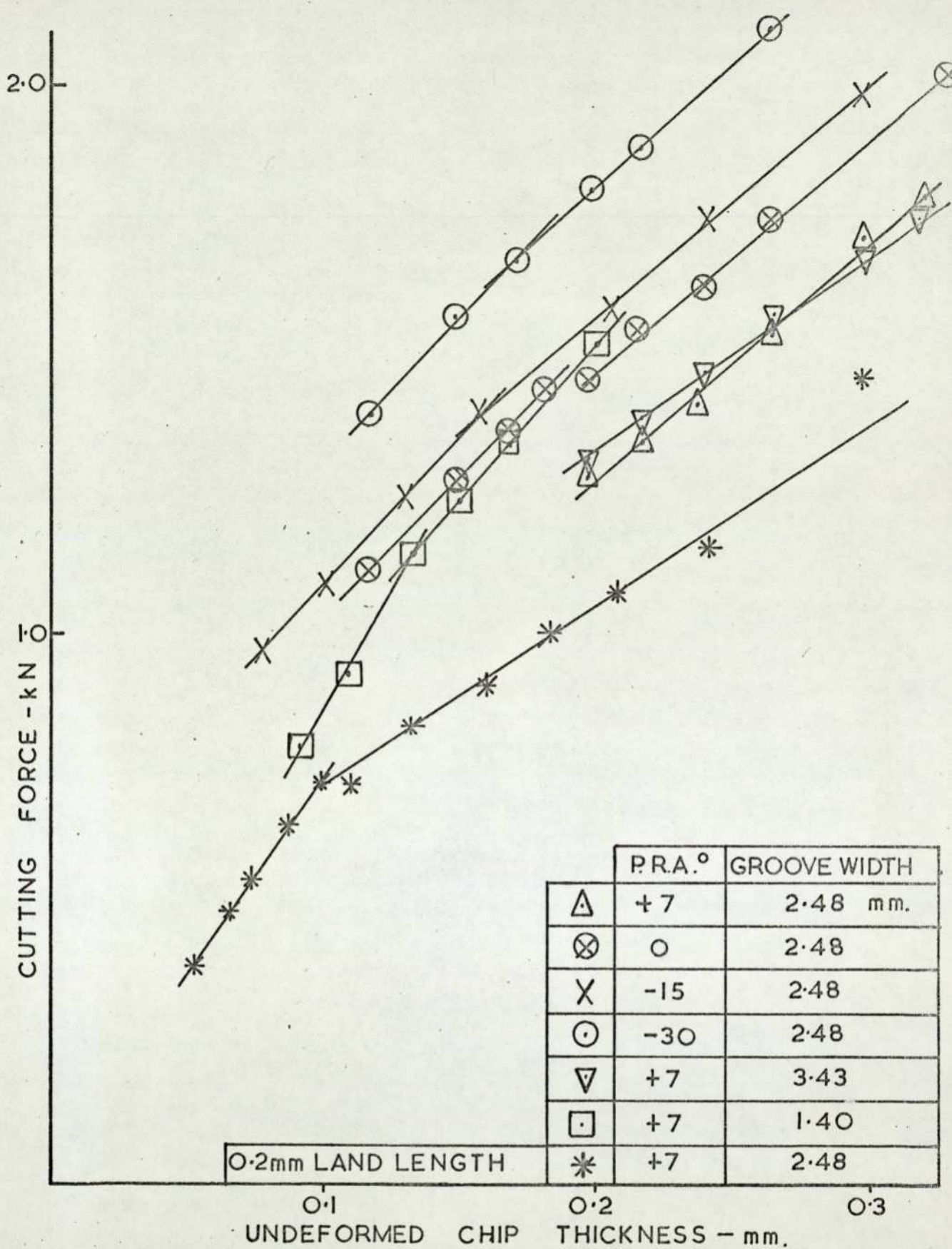
WORKPIECE MATERIAL En 1A, CUTTING SPEED 2 m/min. FIG.6.



DIMENSIONS OF TOOLS DESCRIBED IN SECTION 6.4.4.						
TOOL	γ_1°	γ_2°	$B_{\gamma O}$	W_{mm}	R_{Gmm}	INLET $^\circ$ ANGLE
A	+7	+7	1.2 mm	1.4	1.4	30
B	+7	+7	0.2 ..	1.4	1.66	25
C	+7	+7	0.2 ..	1.4	2.042	20
D	+7	+7	0.2 ..	1.4	2.25	15

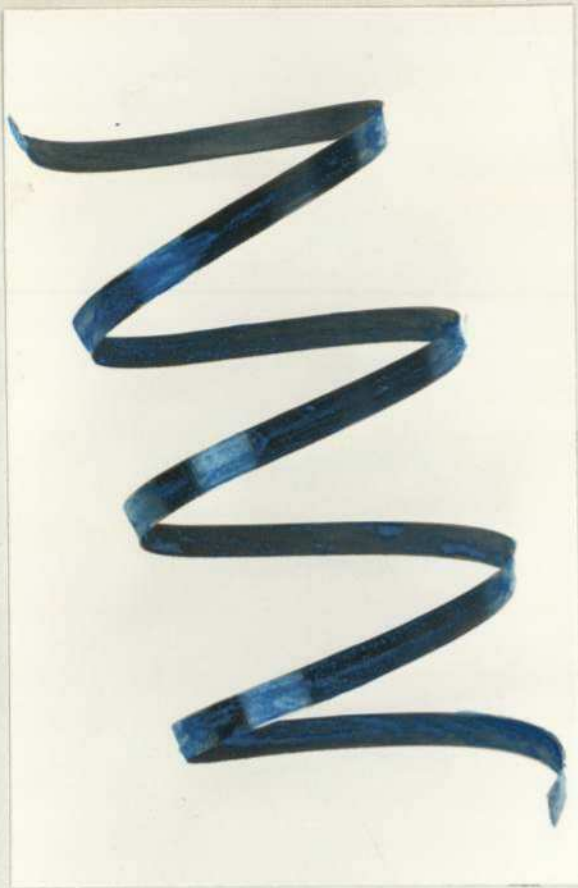
TOOL CONFIGURATION FOR CHIP BREAKING TESTS

TOOLS USED FOR TESTS DESCRIBED IN SECTION 6.3, HAVE CONSTANT 45° INLET ANGLE & DIMENSIONS AS SHOWN IN FIGS. 6.10. & 6.11.

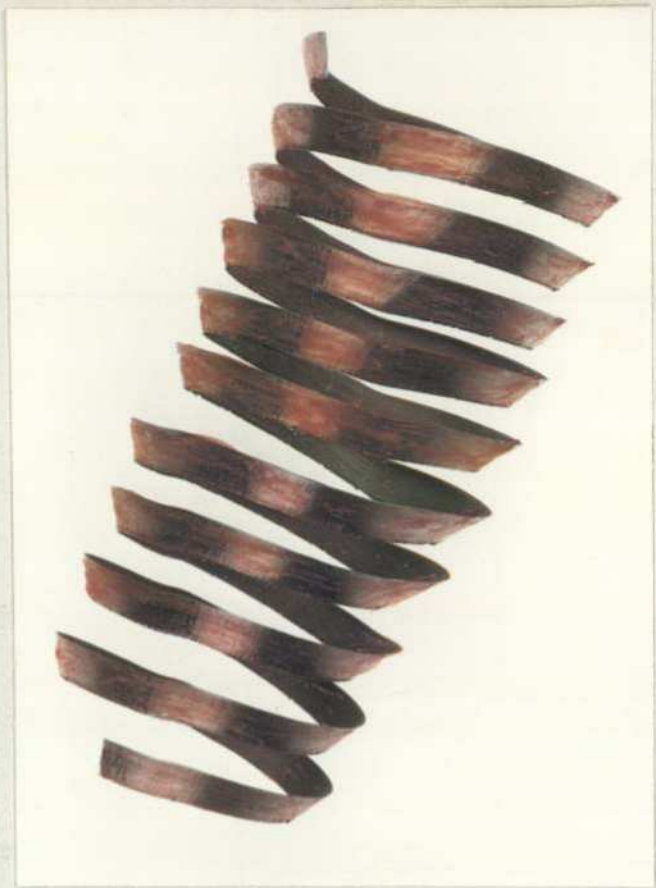


VARIATION OF CUTTING FORCE WITH UNDEFORMED
CHIP THICKNESS FOR VARIOUS PRIMARY RAKE
ANGLES

35 mm. LAND LENGTH CUTTING SPEED 120 m/min.
 WORKPIECE MATERIAL En1B.



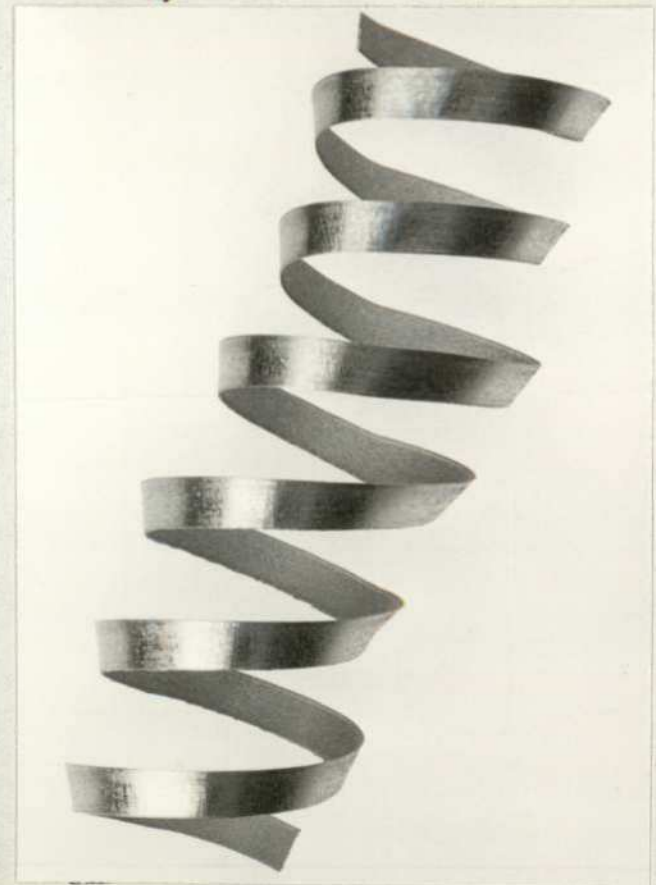
U.C.T. .053 mm.



.074 mm.



.086 mm.



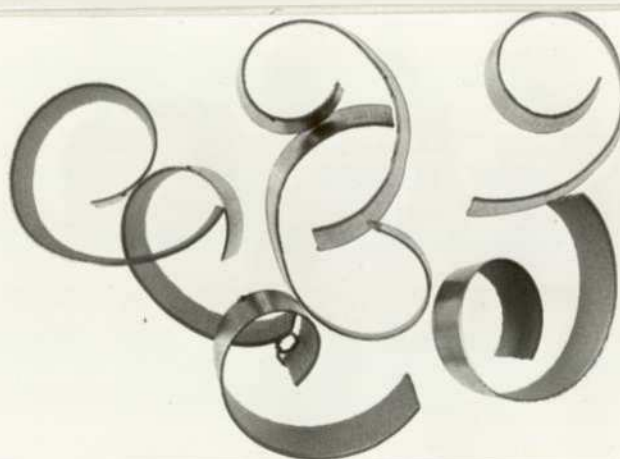
.109 mm.

X 1

VARIATION OF CHIP FORM & COLOUR OF SURFACE
OXIDE WITH UNDEFORMED CHIP THICKNESS



·132 mm.



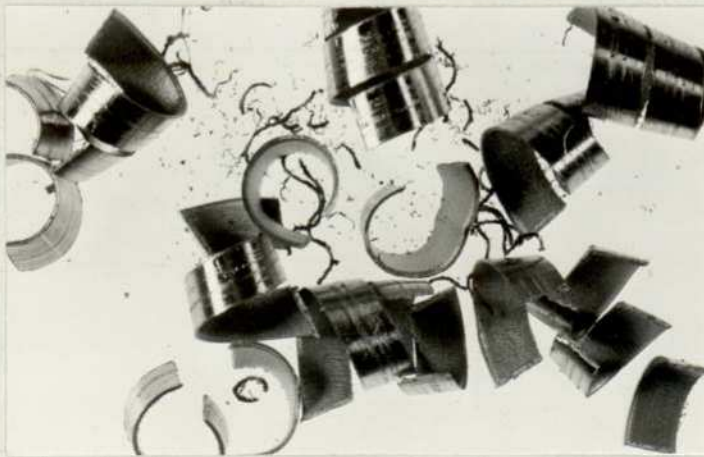
·206 mm.



·264 mm.

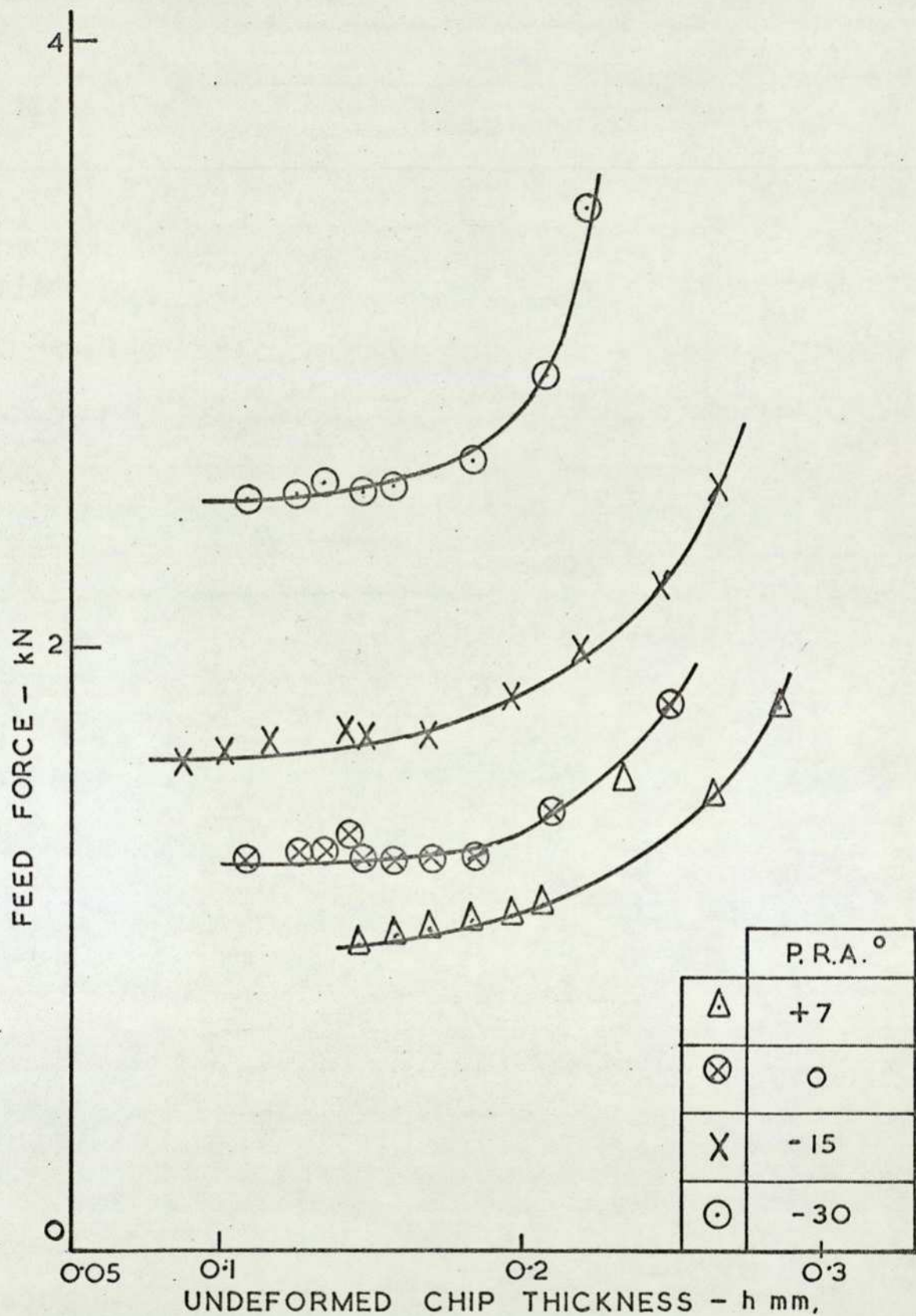


·34 mm.



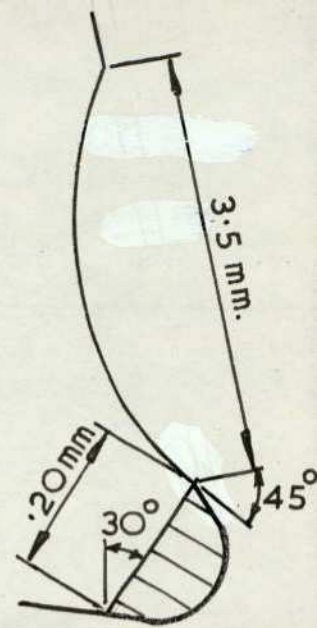
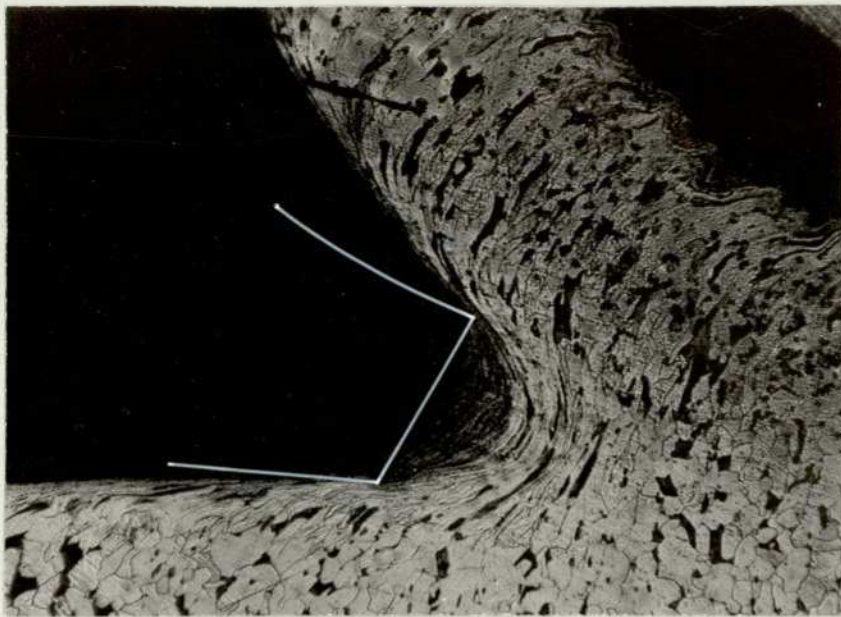
·4 mm.

FIG. 6.6 b.

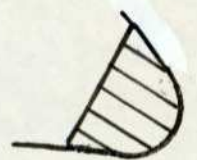
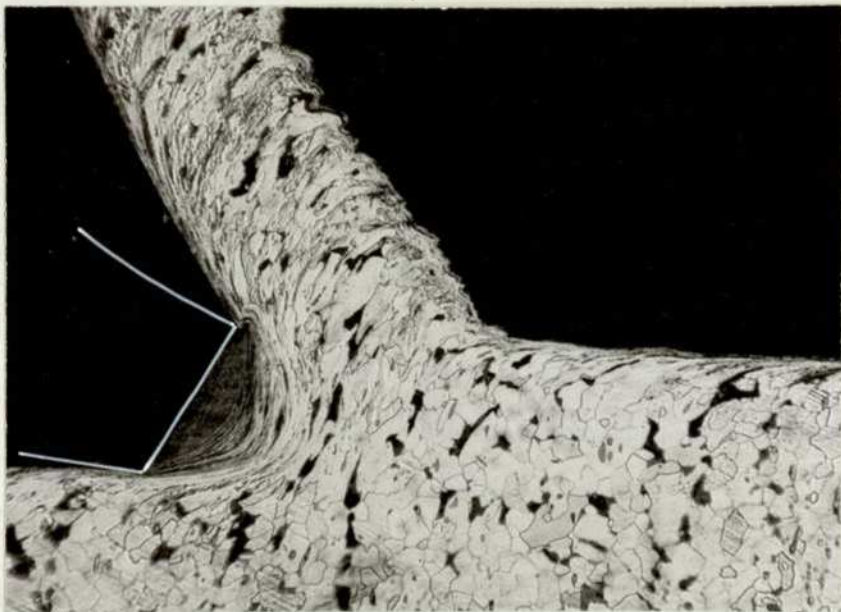


VARIATION OF FEED FORCE WITH UNDEFORMED
CHIP THICKNESS FOR VARIOUS PRIMARY RAKE
ANGLES

CUTTING SPEED 120 m/min. WORKPIECE MATERIAL EN1A.
 GROOVE WIDTH 2.48 mm. LAND LENGTH 0.35 mm.



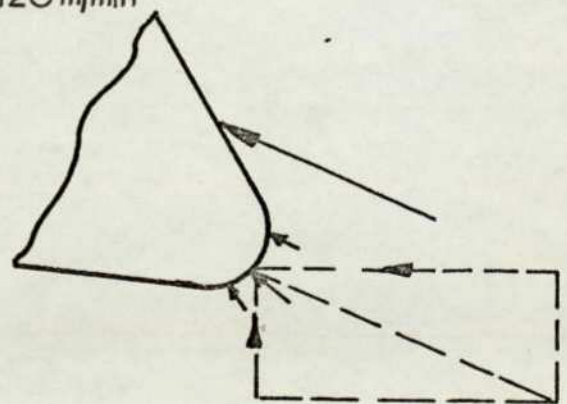
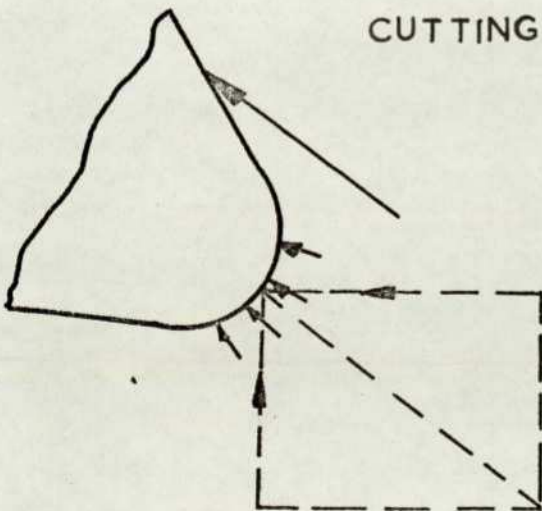
U.C.T. 0.45 mm



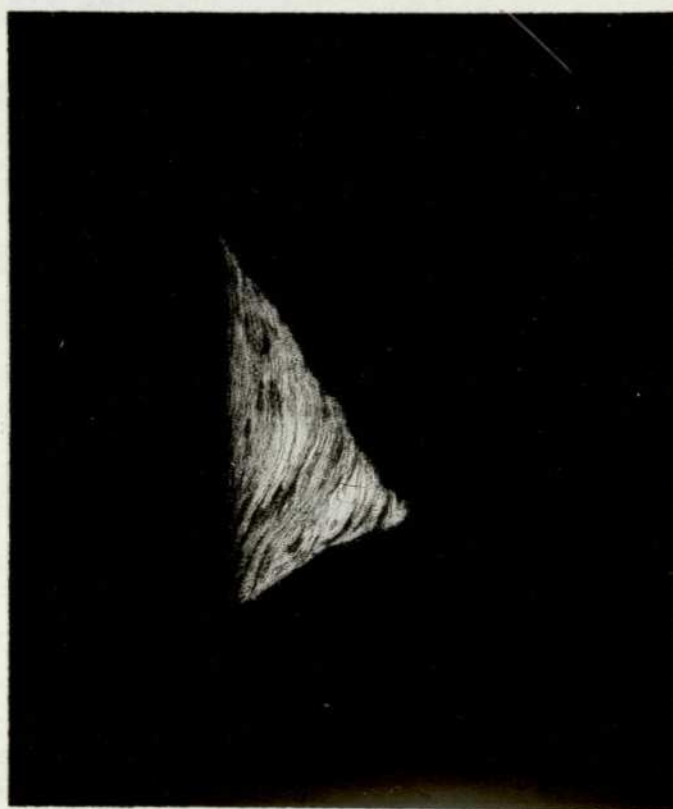
U.C.T. 0.30 mm.

X110

CUTTING SPEED 120 m/min

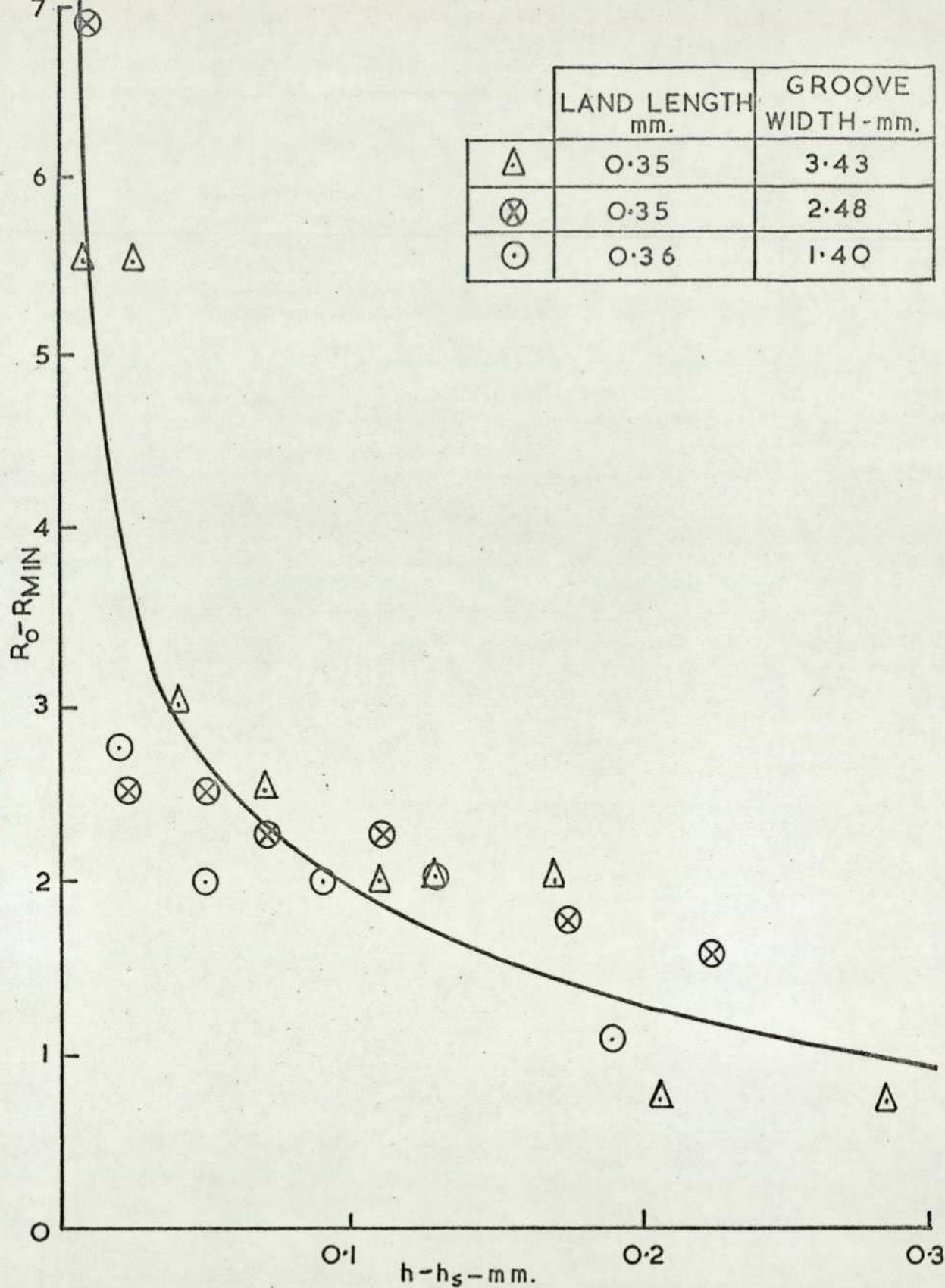


THE EFFECT OF INCREASE IN PLOUGHING FORCE
DUE TO THE ROUNDING OF THE SPECIAL
BUILT-UP-EDGE CAUSED BY FEED INCREASE



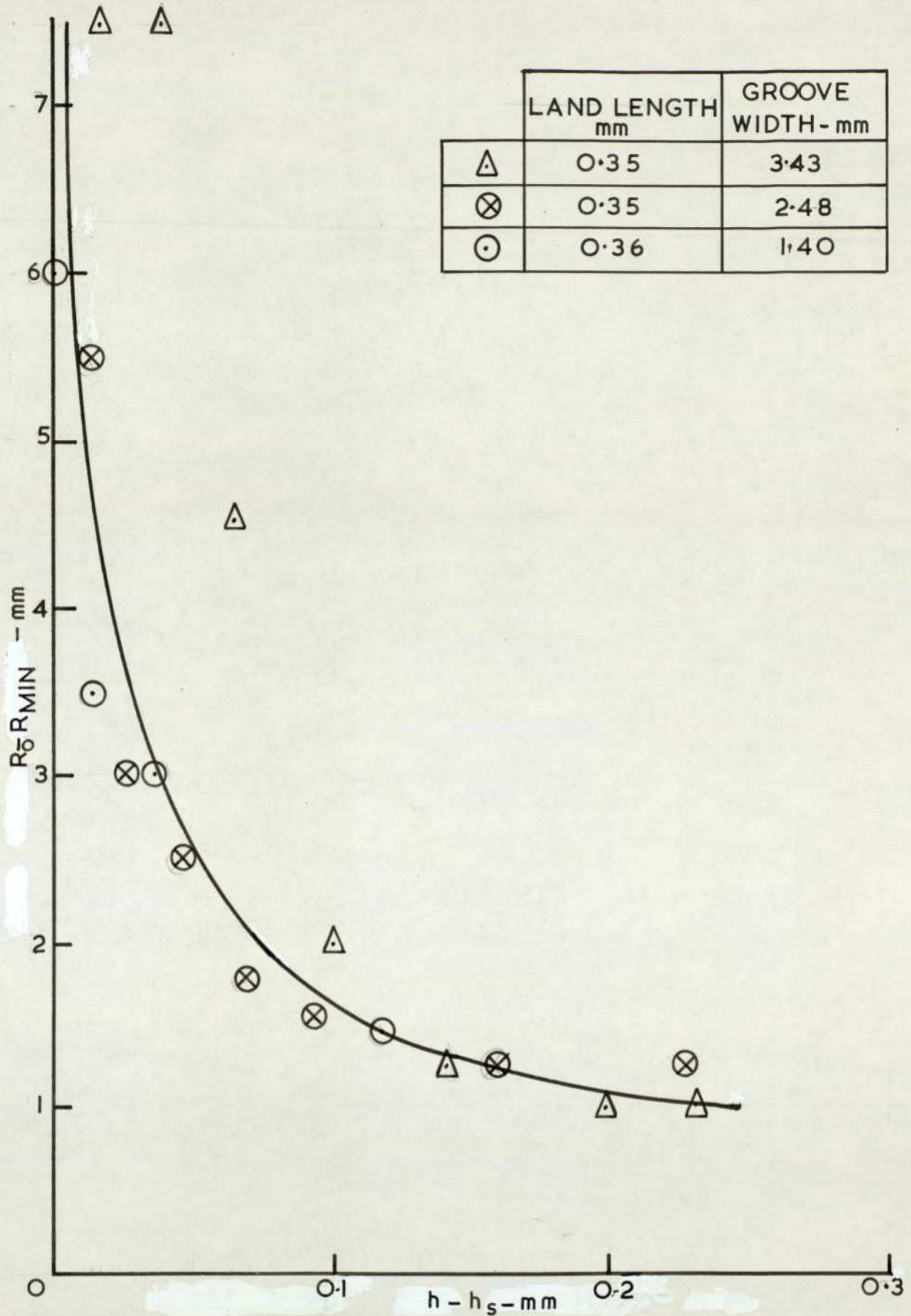
XII O

PHOTOMICROGRAPH OF THE CROSS SECTION
OF A TRANSVERSE CHIP



EXPERIMENTAL RELATIONSHIP BETWEEN $h - h_s$ & $R_o - R_{min}$
FOR $+7^\circ$ PRIMARY RAKE ANGLE TOOL

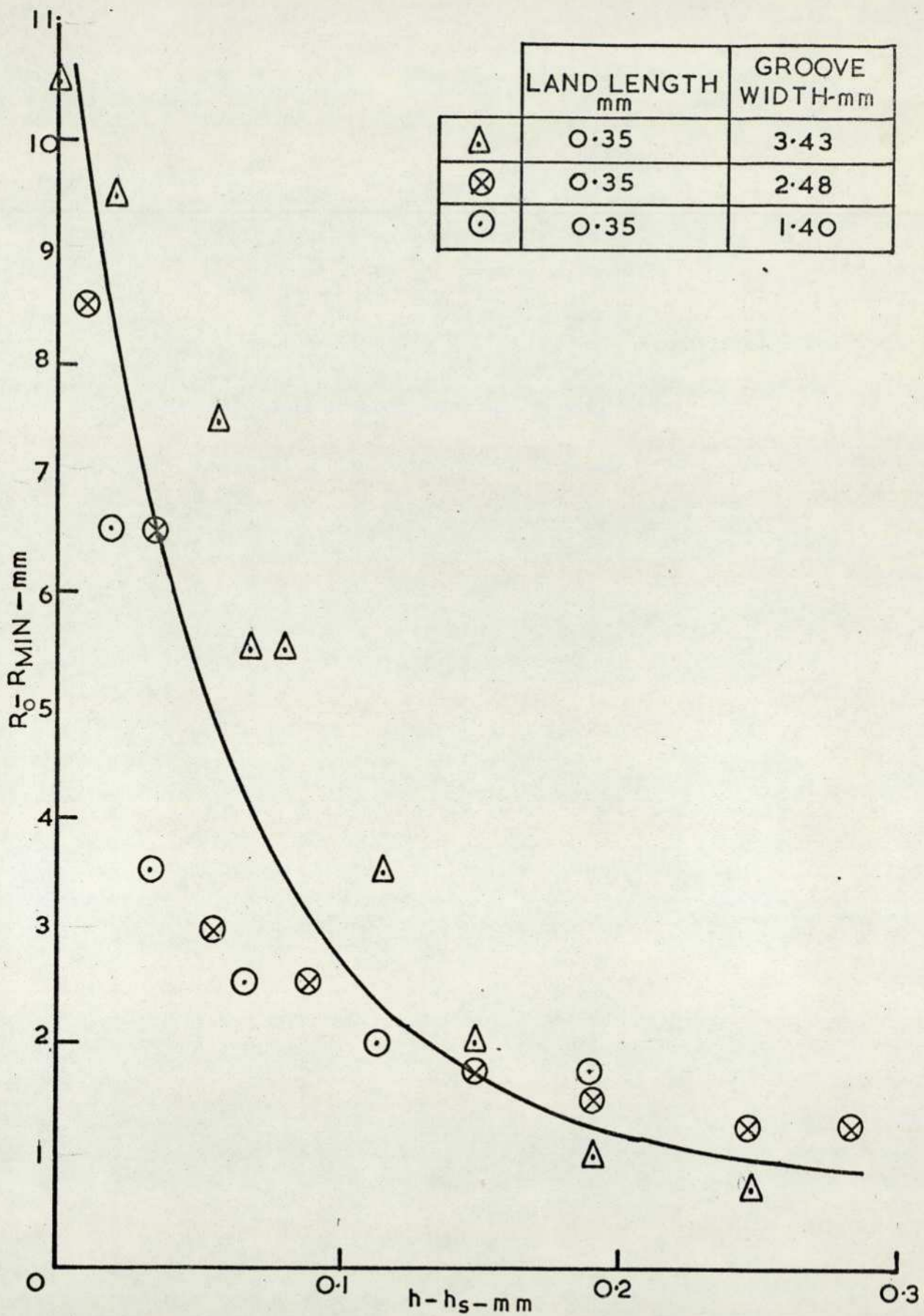
WORKPIECE MATERIAL EN1B. CUTTING SPEED 120 m/min.



EXPERIMENTAL RELATIONSHIP BETWEEN $h - h_s$ & $R_0 R_{MIN}$
FOR 0° PRIMARY RAKE ANGLE TOOL

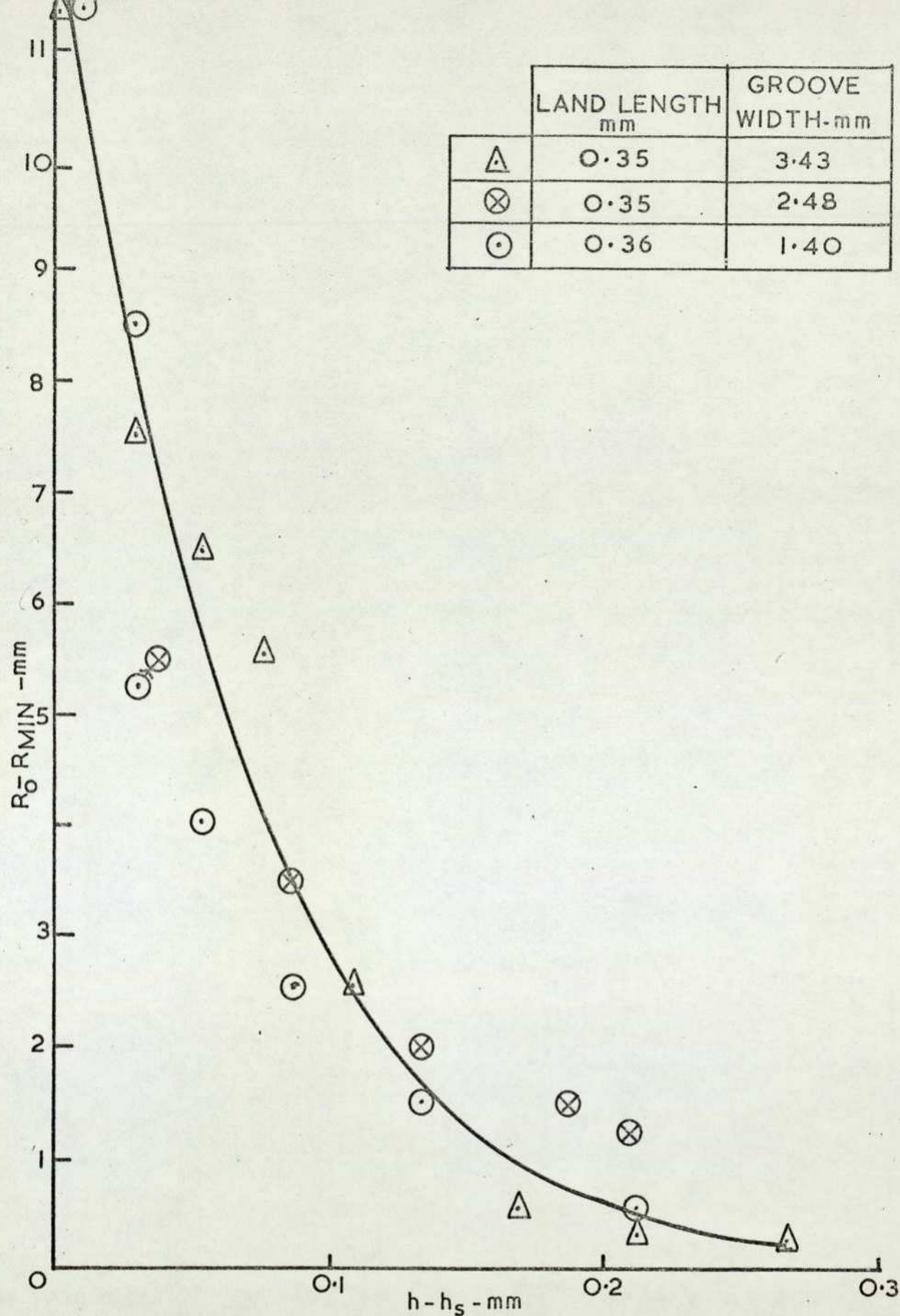
WORKPIECE MATERIAL En 1B CUTTING SPEED 120 m/min

FIG.610b



EXPERIMENTAL RELATIONSHIP BETWEEN $h - h_s$ &
 $R_0 - R_{MIN}$ FOR -15° PRIMARY RAKE ANGLE TOOL

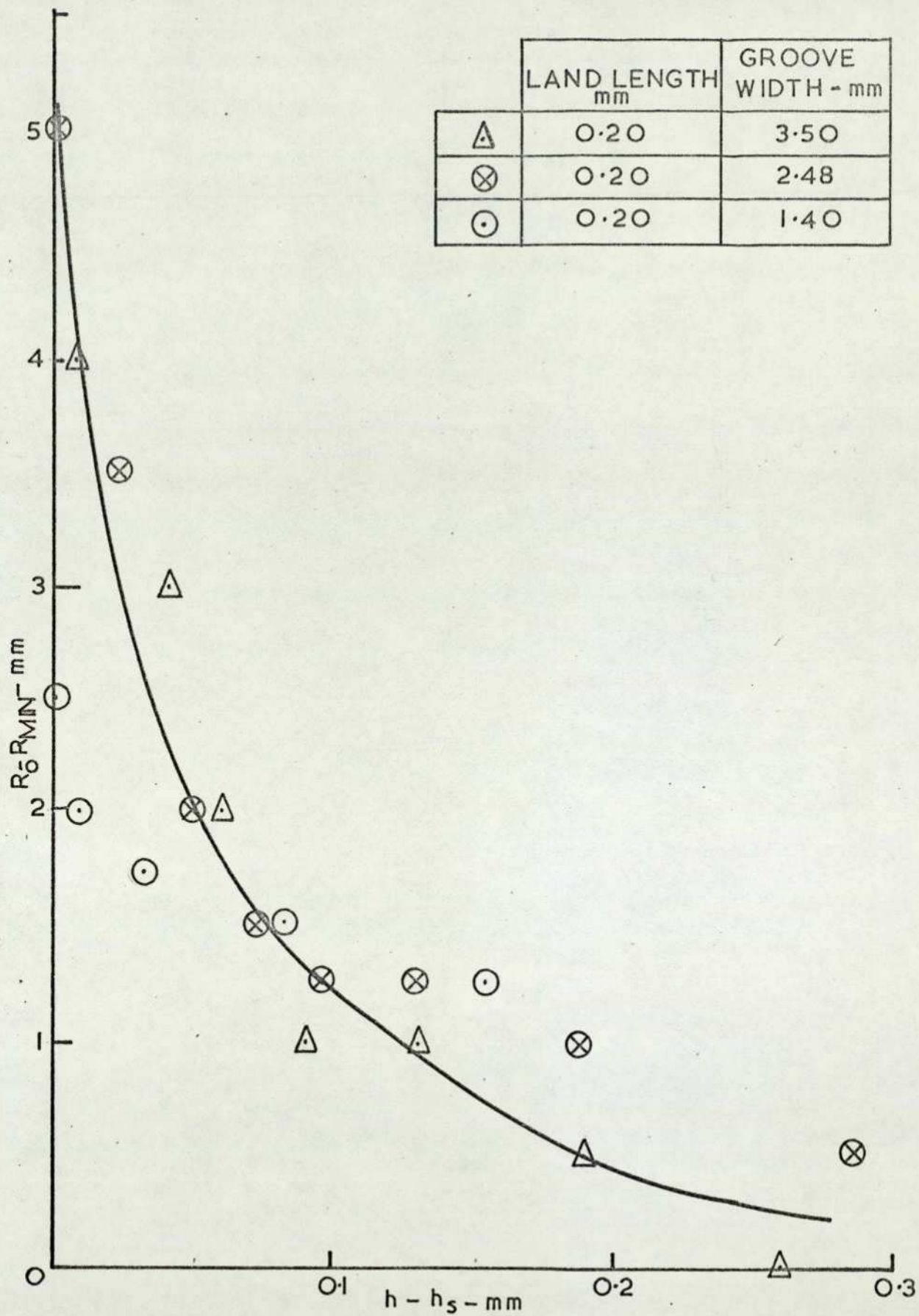
WORKPIECE MATERIAL En 1B CUTTING SPEED 120 m/min



EXPERIMENTAL RELATIONSHIP BETWEEN $h-h_s$ &

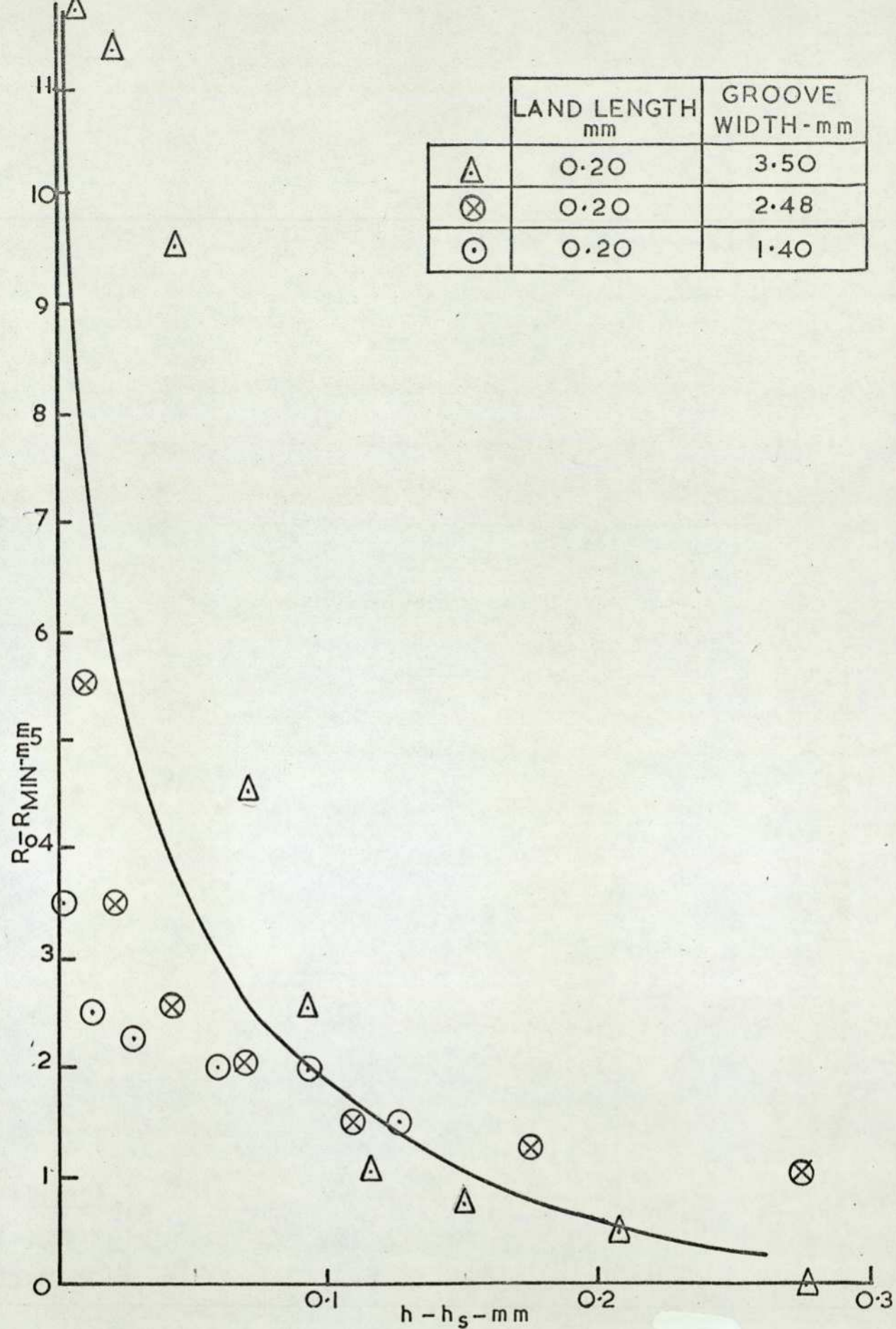
$R_o - R_{min}$ FOR -30° PRIMARY RAKE ANGLE

WORKPIECE MATERIAL En1B CUTTING SPEED 120 m/min



EXPERIMENTAL RELATIONSHIP BETWEEN $h - h_s$ & $R_0 R_{MIN}$
FOR $+7^\circ$ PRIMARY RAKE ANGLE TOOL

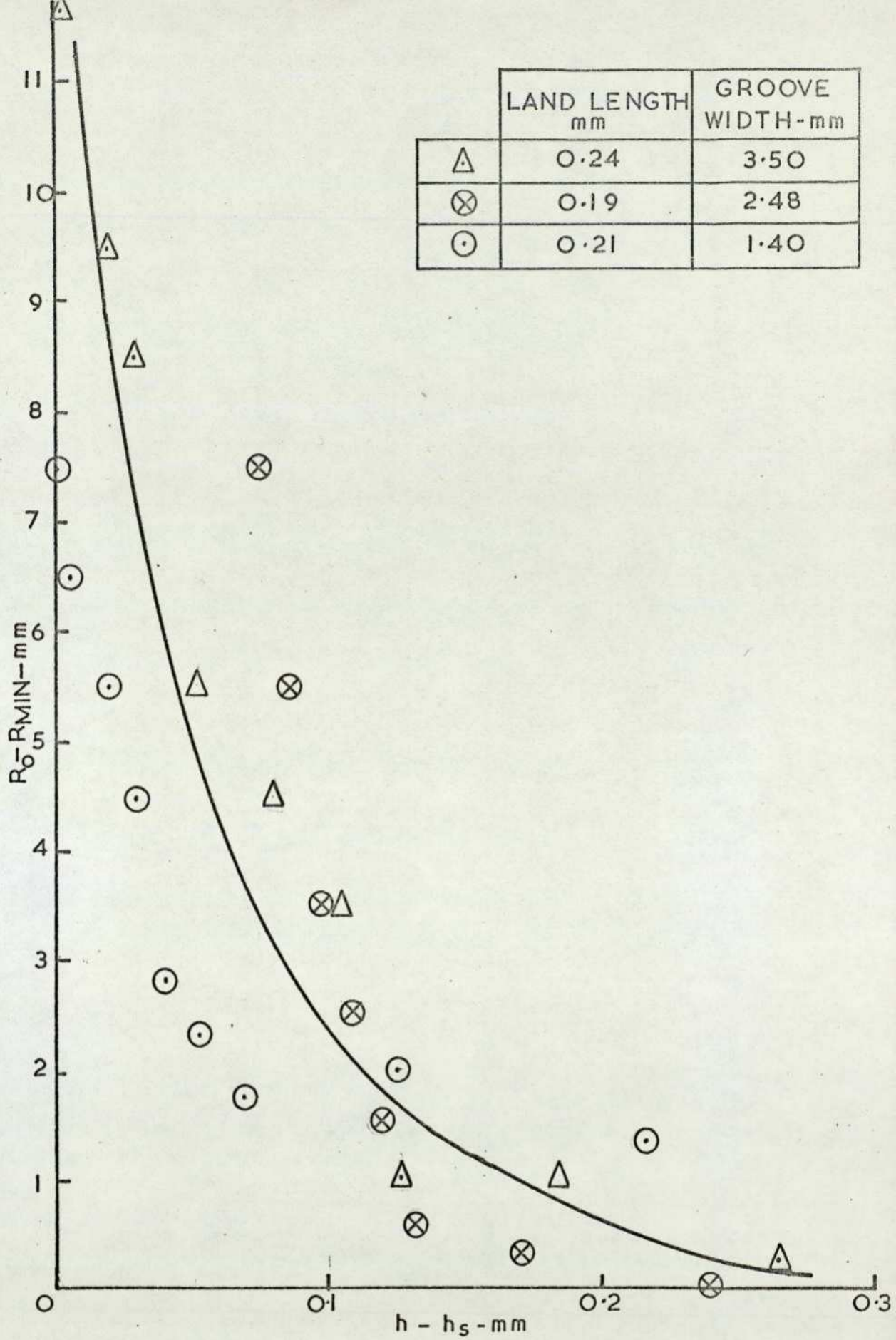
WORKPIECE MATERIAL En1B CUTTING SPEED 120 m/min.



EXPERIMENTAL RELATIONSHIP BETWEEN $h-h_s$ & $R_o R_{MIN}$
FOR 0° PRIMARY RAKE ANGLE

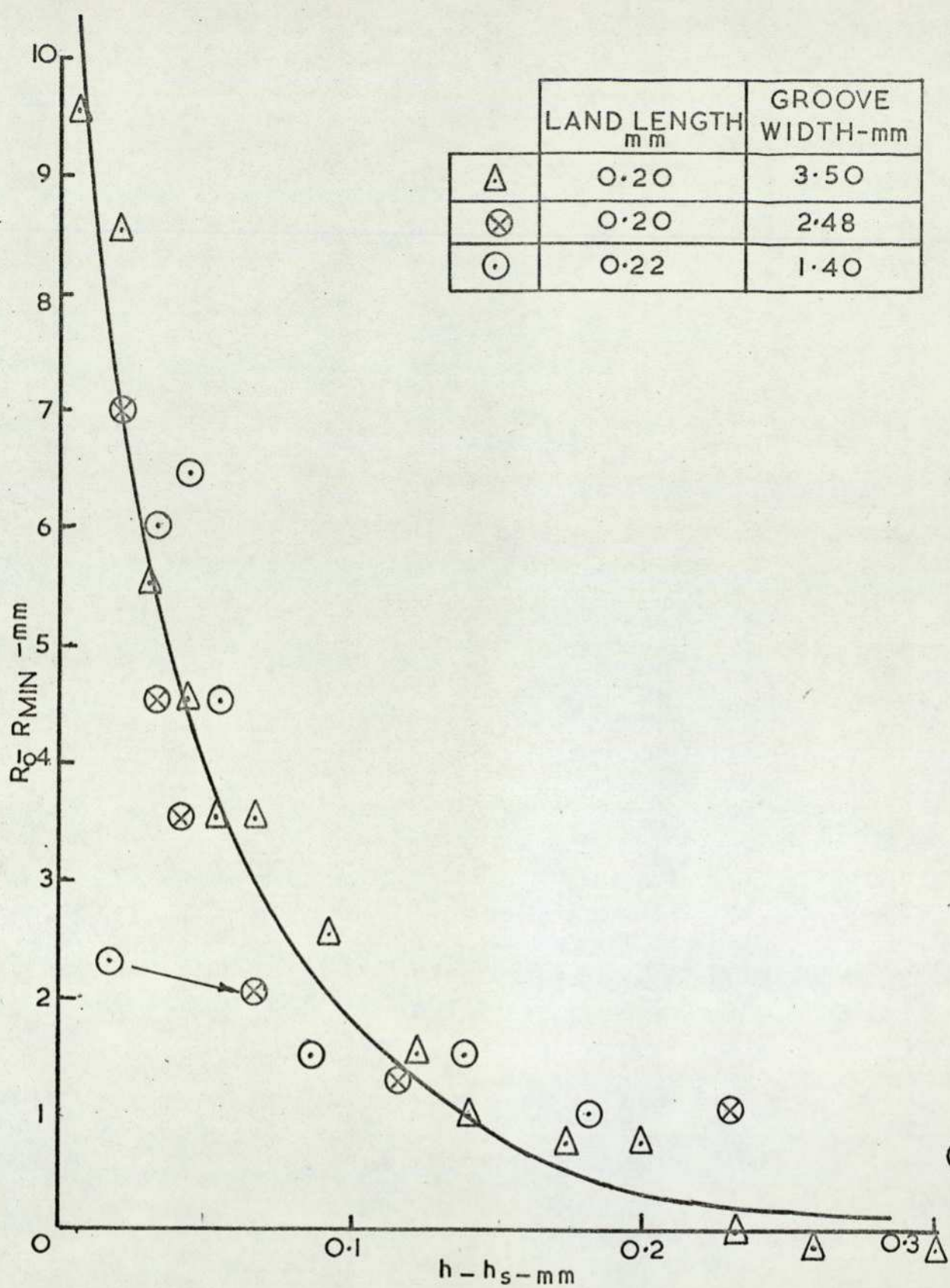
WORKPIECE MATERIAL En 1B CUTTING SPEED 120m/min

FIG.6.11

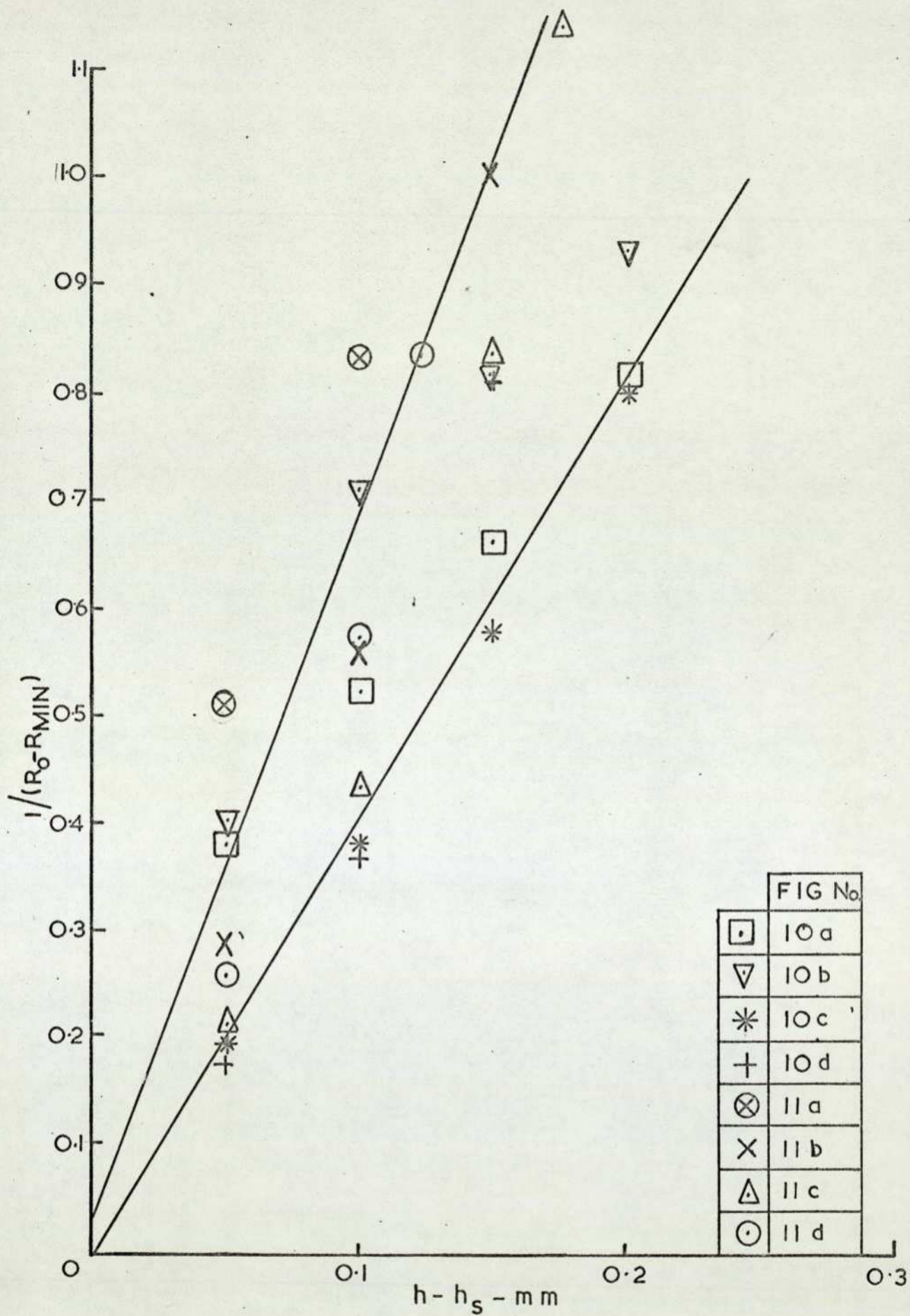


EXPERIMENTAL RELATIONSHIP BETWEEN $h-h_s$ & $R_o - R_{min}$
FOR -15° PRIMARY RAKE TOOL

WORKPIECE MATERIAL E 1B CUTTING SPEED 120 m/min



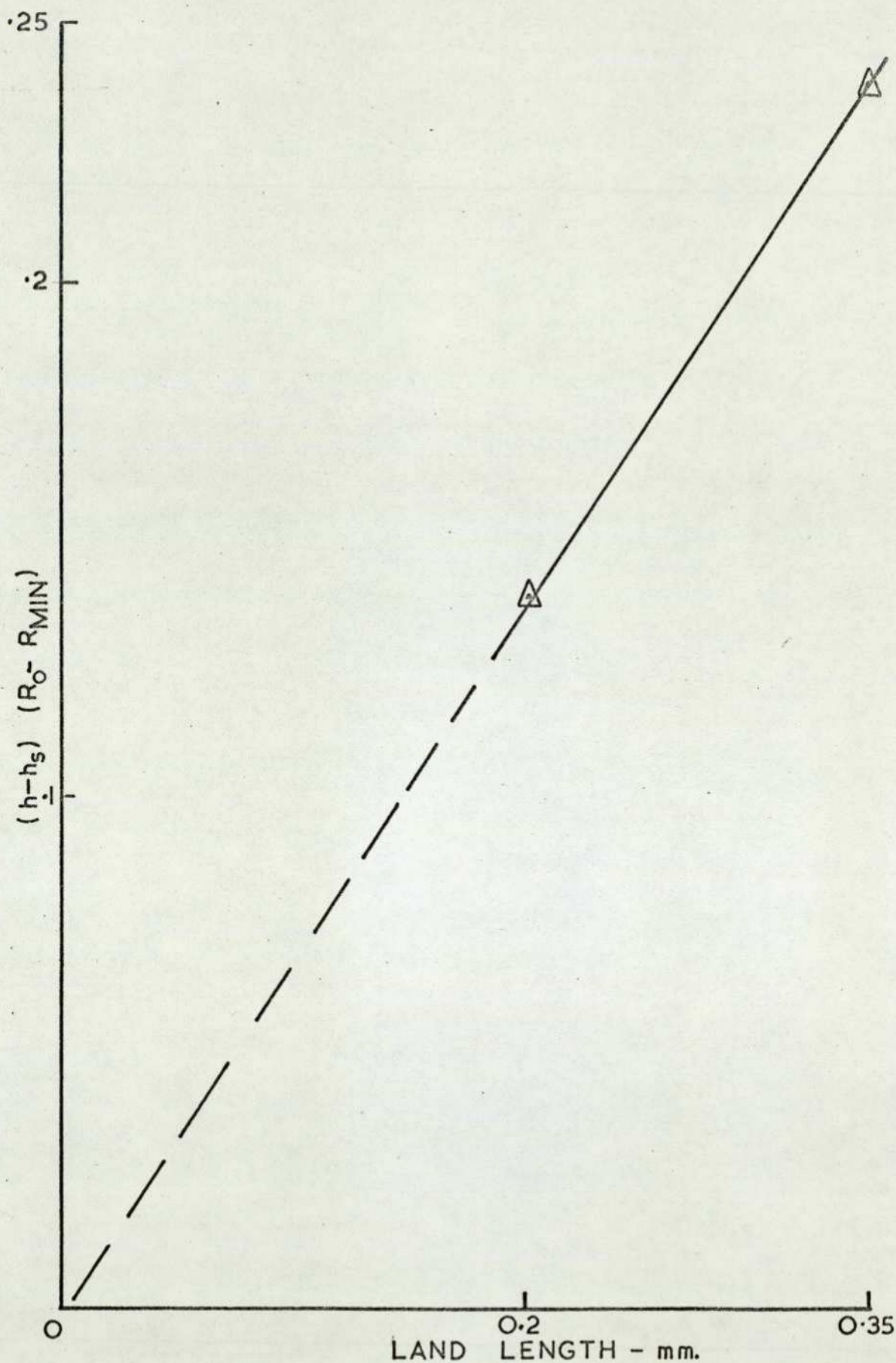
EXPERIMENTAL RELATIONSHIP BETWEEN $h - h_s$ & $R_o - R_{MIN}$
FOR A -30° PRIMARY RAKE ANGLE TOOL.



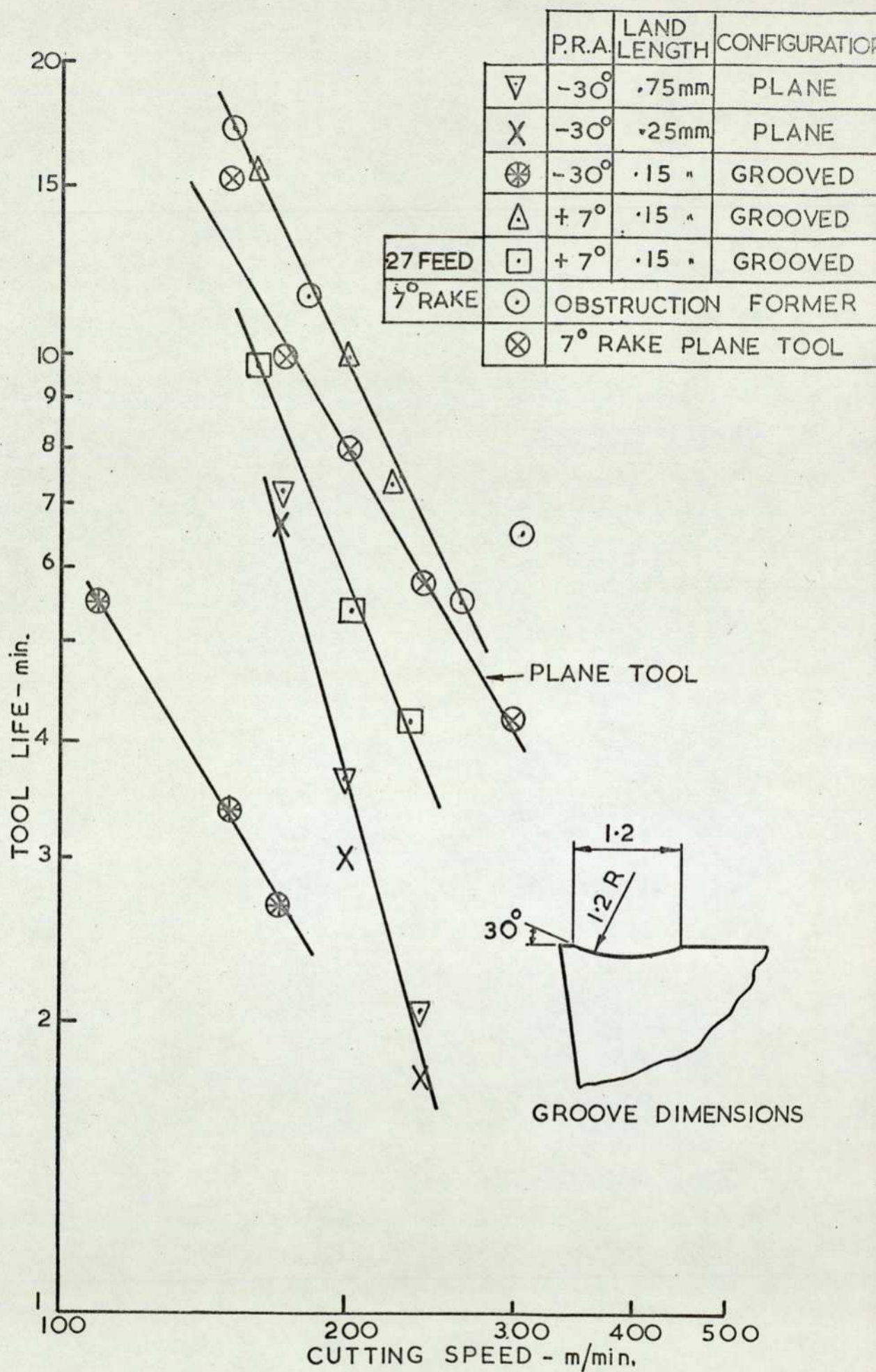
THE RELATIONSHIPS OBTAINED FROM FIGURES
6.10. & 6.11. SHOWN IN STRAIGHT LINE FORM

WORKPIECE MATERIAL En1B. CUTTING SPEED 120m/min.

FIG 6.12



THE SLOPES OF THE EXPERIMENTAL RELATIONSHIPS
OBTAINED FROM FIG.6.12.VERSUS LAND LENGTH



EXPERIMENTAL RELATIONSHIP BETWEEN TOOL LIFE
& CUTTING SPEED FOR VARIOUS TOOL
CONFIGURATIONS