TOOL WEAR IN END MILLING SLOTS

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ABSTRACT

This thesis records an investigation of tool wear in milling slots with carbide-tipped and high speed steel end milling cutters as well as the development of the equipment used. The study is limited to one conventional material (mild steel) and one difficult-to-machine alloy (multimet) only.

The first four chapters present a general review of machinability of materials, description of tool materials and various mechanisms of tool failure. Discussion of problems related to the machinability of heat resistant alloys as well as a discussion on machining under interrupted cutting conditions are included. The theories described are used in interpreting the experimental results.

The fifth chapter describes the development of a Quick-Stop Device. This device is used in metal cutting research to rapidly reduce the velocity of the cutting tool relative to the workpiece to zero. The device enables investigations to be made of the geometrical and metallurgical behaviour of the chip as it is born.

In Chapter VI the effect of various cutting conditions on the development of the tool wear while end milling steel as well as multimet is analyzed and optimum cutting conditions for end milling the two materials are recommended.

In order to try to explain some of the phenomena observed, Turning experiments simulating previous milling operations were carried out and are described in Chapter VII. Here it was possible to separate the aspects of thin and thick chips from the aspects of interrupted cutting. The results of these tests indicate that the thin portion of the chip obtained at the entry and exit of end milling cutter affects tool life much less than the thick part of the chip. However, even these tests did not explain why it was rather the total number of cut interruptions than the actual cutting time which influenced tool life. Further research will be necessary in looking into both the mechanical and thermal shock aspects.

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TABLE OF CONTENTS

TABLE OF CONTENTS

(cont'd)

LIST OF SYMBOLS

a	depth of cut
b	width of cut
c	velocity of wave propagation = $\sqrt{E/\rho}$
C	Taylor Constant
E	Modulus of Elasticity
F_f	Feed Force
F_t	Thrust Force
F_v	Main Cutting Force
KB	Crater width
KT	Crater depth
KT_{max}	Maximum crater depth
N	Revolutions per minute
n	Slope of the log T - log V plot
R	Ratio of the free running time to the actual cutting time
r	Tool Nose Radius
s	Feed per revolution
S_t	Feed per tooth
T	Tool life in minutes
V	Cutting speed
VB	width of flank wear land

VB_{av}	Average width of the flank wear land
VB_{max}	Maximum width of flank wear land
VC	width of the corner wear land
VN	Length of the notch in the major flank
α	Tool clearance angle
γ	Tool rake angle
χ	Tool approach angle
ρ	Density
σ_o	Contact stress

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CHAPTER I

INTRODUCTION

1.1 Machinability of Metals

Machinability is a complex term and the objectives vary from one application to another. Practically all empirical methods of machinability evaluation are concerned with tool life, tool forces, surface finish, chip form and power consumption, but modifications in machining variables such as cutting speed, feed, tool geometry, and cutting fluids generally result in altered values for tool life and order of merit of the cutting stock. The main reason for the complexity of this subject lies in the fact that machinability is not a property that can be measured in terms of absolute units and, therefore, it can mean many things to many people. This complicated situation limits any standard machinability tests to rather narrow areas, and although previous work has produced a few guiding principles, no general theory has emerged. The statement is often made that the only reliable assessment is that made in the machine shop under a given set of conditions, and that scientific tests in the laboratory are rarely amenable to interpretations in terms of practical machining.

In order to arrive at an understanding of this subject it is necessary to take into account not only the metallurgy of the workpiece, but also that of cutting tool. In addition to this, such major factors as the chemistry of the action of cutting fluids, the vibratory nature of the action of the cutting tool, and all the other engineering factors associated with the machine tool itself, have certain modifying effects on this property.

Most production engineers would agree that tool wear is of crucial importance in metal machining. During the nineteenth century the productivity of machining operations was largely determined by the properties of the tool material which placed definite limitations on the rate of cutting. With the introduction, first of high-speed steel tools and then of sintered hard metal, the maximum possible rate of cutting has increased many times and the tool material properties may no longer be the critical factor limiting productivity. Machine shop layout, ease of loading, disposal of swarf, are some of the many factors, which in addition to tool wear, affect the rate of production.

Nevertheless, the wear resistant properties of the cutting tool still decide the rate of machining in most cases, and hence the search for still harder and faster cutting materials continues.

Machinability is generally thought of as a property of the workpiece material. Research in the field of manufacturing processes is aimed continuously at finding ways to improve the machinability of all materials. A number of different tests have been devised to determine the machinability of metals. The machinability rating will depend on the particular definition used and the test employed for its evaluation . These factors should be considered before applying such ratings.

1.2 Specification of Machinability

As mentioned earlier, the term "machinability" means different things to different people. There is no quantitative definition that will cover all shop operations. This is because there are a number of reasons for using machining operations, and different properties of the workpiece are appropriate for each. For example, the machinability of a part that is being machined only to obtain a lustrous finish depends on its ability to be machined at high speed with little tendency to form built up edges. At another set-up, where machining operations are employed to mass produce parts at minimum cost, the machinability of workpiece would be thought of in terms of its effect on tool life at high speeds and feeds.

Lorenz (4) takes a realistic viewpoint and separates machinability from finishability. He has shown that six steels can be ranked in the same order whether conventional or quick tool-life facing tests are used, and that drastic changes in tool geometry do not disturb the ranking.

The word "machinability" implies its own definition - the ability of the material to be machined. Materials which may be cut with ease are said to possess good (or high) machinability. Those which do not respond well to cutting are listed as poor (or low) machinability metals.

While machinability is known to consist of a number of differing requirements, it is common to express it in terms of the cutting speed for a given tool life in minutes. In order to compare and rank materials, a common material is taken as a reference or standard. The machinability of any other material may be compared to the standard by determining the V_{60} (or V_{90}) and the ratio (V_{60} material/

V_{60} standard) and expressing it as a percentage. This ratio is called RELATIVE MACHINABILITY.[1] Clearly, a material with a high cutting speed for a 60-minute tool life will be considered to have a high machinability, which is desirable. Handbooks[5] and manuals[6] contain data on relative machinability for the convenience of users. Thus, when assessed in this way, machinability is essentially equivalent to tool life with particular reference to the effect of work material.

There are a number of factors which affect the ease with which a metal can be cut. One is the cutting tool form and material. The set-up conditions of the machine, which include speed, feed, and depth of cut, also affect the ease of cutting. Some materials may not machine well under dry cutting conditions, but are reasonably machinable when a good cutting fluid is properly applied. The nature of tool-workpiece engagement, the workpiece dimensions, and the condition of the machine tool and its fixtures all affect the ease with which the workpiece may be cut. None of these variables relates to actual properties of the workpiece material, yet a machinability rating is desired for each material according to its characteristics alone. Therefore, machinability is usually thought of as the ease with which a material can be machined under average conditions (or under a prescribed set of conditions).

A number of properties of the metal affect its machinability. The most important of these are chemical composition, microstructure, and general mechanical properties such as hardness, tensile strength, and strain hardening ability.

Since the goal of any machining operation is to produce the desired number of parts to specifications at minimum cost, the machinability of the workpiece may be related to this objective.(1) For example, the machinability of the metal could be rated according to the cost of producing a certain "average" part which combines the usual machining operations used in the particular shop under consideration. Such ratings would have little universal application. Factors readily determined from actual machining tests and useful for broad application are desired as indices of machinability. Three such factors, tool life, surface finish, and power consumption, have come to be accepted as indicators of general machinability. The weight given to each of these depends on application, usually according to their effects on overall machining costs. Various concepts and factors representing or affecting the machinability are summarized in Fig. 1-1.

Tool Life:

Tool life is usually the most important of the three main machinability criteria, from the standpoint of machining costs. For this reason, most machinability ratings of materials are based on tool-life values only. Metals which can be cut without rapid tool wear are generally thought of as being well machinable, and vice versa.

A workpiece material with many small hard inclusions may appear to have the same mechanical properties as less abrasive metal. It may require no greater power consumption during cutting. Yet, the machinability of this material would be lower because its abrasive properties are responsible for rapid wear on the tool, resulting in higher machining costs.

One problem arising from the use of tool life as a machinability index is its sensitivity to the other machining variables. Of particular importance is the effect of tool material. Machinability ratings based on tool life cannot be compared if a high speed steel tool is used in one case and a sintered carbide tool in another. The superior life of carbide tool would cause the machinability of the metal cut with the steel tool to appear unfavourable. If identical types of tool materials are used in evaluating the workpiece materials, meaningless ratings may still result. For example, cast-iron-cutting grades of carbide will not hold up when cutting steel because of excessive cratering, and steel-cutting grades of carbide are not hard enough to give sufficient abrasion resistance when cutting cast iron.

The effects of the other machining variables are often considered in the same way as tool material effects. Machinability ratings are obtained using conditions suitable for the individual materials. For example, relatively high rake angles are used for aluminum and lower rake angles for steel.[1]

Tool Forces and Power Consumption:

The use of tool forces or power consumption as a criterion of machinability of the workpiece material comes about for two reasons. First, the concept of machinability as the ease with which a metal is cut implies that metal through which a tool is easily pushed (requiring low cutting force) should have a good machinability rating. Second, the more practical concept of machinability in terms of minimum cost per part machined relates to forces and power consumption through the overhead costs of a machine of proper capacity.

When using tool forces as a machinability rating, either the main cutting force (in the direction of the cutting velocity) or the thrust force (feeding force) may be used. The main cutting force is more popular of the two since it is the force that pushes the tool through the workpiece and determines the power consumed. Although machinability ratings could be listed according to the cutting forces under a set of standard machining conditions, the data is usually presented in terms of specific energy. Workpiece materials having a high specific energy of metal removal are said to be less machinable than those with a lower specific energy.

The use of net power consumption during machining as an index of the machinability of the workpiece is similar to the use of cutting force. Again, the data is most useful in terms of specific energy. One advantage of using specific energy of metal removal as an indication of machinability is that it is mainly a property of the workpiece material itself and is quite insensitive to tool material. By contrast, tool life is strongly dependent on tool material.

The metal removal factor is reciprocal of the specific energy and can be used directly as a machinability rating if forces or power consumption are used to define machinability. That is, metals with a high metal removal factor could be said to have high machinability.

The big drawback to using force, energy, or power terms as machinability indices is that they do not always corelate well with actual machining costs. Cost per piece remains the practical standard of a production process. While it is true that these indices represent power costs very well, the cost of power is usually a negligible part of the total machining cost. The more expensive machines required when forces and power consumption are high do not add to the overhead charges in direct proportion. It should be remembered that forces and power consumption represent one phase of overall machinability, but they should not be used alone.

Surface Finish:

The quality of surface finish left on the workpiece during a cutting operation is sometimes useful in determining the machinability rating of a metal. Some workpieces will not "take a good finish" as well as others. The fundamental reason for surface roughness is the formation and sloughing off of parts of the built-up-edge on the tool. Soft, ductile materials tend to form a built-up edge rather easily. Stainless steels, and other metals with high strain hardening ability also tend to machine with built-up edges. Materials which machine with high shear zone angles tend to minimize built-up edge effects. These include the aluminum alloys, cold worked steels, free machining steels, brass, and titanium alloys.[6] If surface finish alone is chosen as index of machinability, these latter metals would rate higher than those in the first group.

In many cases, surface finish is a meaningless criterion of workpiece machinability.[4] In roughing cuts, for example, no attention to finish is required. In many finishing cuts, the conditions producing the desired dimension on the part will inherently provide a good finish within the engineering specification. There are cases where a poor finish may be a cause for rejection by the inspector. For these cases, surface finish specifications affect the machining costs and hence the machinability rating of the workpiece.

Machinability figures based on surface finish measurements do not always agree with the figures obtained by force or tool life determinations. Stainless steels would have a low rating by any of these standards, while aluminum alloys would be rated high.[5] Titanium alloys would have a high rating by finish measurements, low by tool life tests, and intermediate by force readings.

The machinability ratings of various materials by surface finish are easily determined. Surface finish readings are taken with an appropriate instrument after standard workpieces of various materials are machined under controlled cutting conditions. The machinability rating varies inversely with the instrument reading. A low reading means good finish, and thus high machinability. Relative ratings may be obtained by comparing the observed value of surface finish with that of a material chosen as the reference.

Chip Form:

There have been machinability ratings based on the type of chip that is formed during the machining operation. The machinability might be judged by the ease of handling and disposing of chips. A material that produces long stringy chips would receive a low rating, as would one which produces fine powdry chips. Materials which inherently form nicely broken chips, a half or full turn of the normal chip helix, would receive up rating. Chip handling and disposal can be quite expensive. Stringy chips are a menace to the operator and to the finish on the freshly machined surface. However, chip formation is a function of the machine variables as well as the workpiece material, and the ratings obtained by this method could be changed by provision of a suitable chip breaker.

Ratings based on the ease of chip disposal are basically qualitative, and would be judged by an individual who might assign letter grading of some kind. Wide use is not made of this method of interpreting machinability. It finds some application in drilling, where good chip formation action is necessary to keep the chips running up the flutes. However, the whipping action of long coils once they are clear of the hole is undesirable.

The factors controlling the machinability of metals have been discussed in the order of their relative importance. Tool life is the most important machining variable affecting actual cost per part in the majority of cases. Therefore, it is the best single indication of workpiece machinability.

whenever possible, all variables discussed should be taken into account. Published values of machinability are usually based on tool life data alone because no suitable formula combining all of the factors that contribute to machinability has been devised.

1.3 Tool Life Testing

A tool that no longer performs the desired function is said to have failed and hence reached the end of its useful life. At such an endpoint the tool is not necessarily unable to cut the workpiece but is merely unsatisfactory for the purpose required. The tool may, therefore, be resharpened and used again on less restrictive machining operations, or it may be disposed of.

In normal workshop practice, it is necessary to regrind a cutting tool when the shape has been so altered that it can no longer cut efficiently, or is about to fail in this way. The amount of work done by the tool between regrinds is called the life of the tool, and this may be measured in a number of different units, depending on the character of the machining operation.[1]

1.4 Specification of Tool Life and Failure Criteria:

The tool life between tool resharpening or replacement can be specified in the following ways:[1]

1. Actual cutting time to failure.
2. Total time to failure - as in the case of an interrupted cutting process such as milling.
3. Length of the work cut to failure.
4. Volume or weight of the metal removed before the end of tool life.
5. Cutting speed for a given time to failure.
6. Number of components produced to failure.

The criterion of the end of tool life varies even more. This may be reached when:

7. The surface finish of the work deteriorates below some acceptable limit.
8. The work becomes oversized due to wear on the tool.
9. Excessive wear causes chatter or vibration.
10. The tool ceases to cut.
11. The power consumption rises sharply.
12. Some critical amount of wear on the tool has been reached.

13. Chipping or fine cracks develop at the cutting edge.

The problem of tool wear is therefore a complicated one and there is no one clear way of dealing with it. One approach is to simplify the problem by accepting one measurable form of wear, and a definite amount of wear of this type as the criterion of tool life. This is the method adopted in many engineering investigations. This method of approach has the advantage that it gives a quantitative result in terms of a figure which can be entered in equations to achieve the sort of ordering of information characteristic of the engineering approach. G. Barrow[7] has recommended the following values:

<u>Carbide and Ceramic Tools:</u>

<u>Flank Wear:</u>

$VB = 0.015$ in.

$VN = 0.030$ in.

$VB_{max} = 0.030$ in.

where VB, VN and VB_{max} are as shown in Fig. 1-2.

When applying these criteria it is suggested that tool life be defined as when the wear reaches one of the limiting values stated.

Crater Wear:

$$KT = 0.004 + 0.3S \text{ in. (See Fig. 1-2)}$$

where S = feed in mm/rev

High Speed Steel Tools:

VB_{max} = 0.060 or complete failure

Complete failure of high speed steel is particularly recommended for the cases where material build-up on the tool makes measurement very difficult.

While failure of tools by crater wear does occur, experience has shown that provided the correct tool material is used, failure by flank wear mechanism is usual.[7] In view of this, tool life equations are usually developed using flank wear criterion. G. Barrow[7] has shown that in some cases the thermal deformation of a mild form does not lead to immediate failure, but accelerates the rate of flank wear (see Fig. 1-3).

The quoted values of flank wear for carbide tools are by no means arbitrary. A judicious choice has to be made between values which are too high (high forces and increased chance of premature failure) and values which are too low (low tool lives). An indication of the problems involved can be obtained by consideration of Fig. 1-4 which shows schematically the relationship between flank wear and time. Three stages are identifiable.[7]

(a) An initial rapid wear rate.

(b) An approximate constant wear rate.

(c) Another zone of rapid wear which leads to eventual failure.

It can be seen from Fig. 1-4 that there is considerable advantages in utilizing the linear portion of the curve as much as possible. The value of flank wear level reached before the second (linear) stage is reached varies considerably for different tool and workpiece combinations. There is, however, a general trend depending upon the type of carbide as shown in Fig. 1-4.

The choice of tool life criterion has a considerable influence on the form of tool life equation as shown in Fig. 1-5. It is, therefore, difficult to compare tool life data if different criteria are used to define the end point of tool life.

1.5 Tool Life Equations

Taylor Type Equations:

The most well known tool life equation is that of Taylor.

i.e. $VT^n = C$ (1-1)

where V is the cutting speed, T is the tool life, n the slope of the logT-logV plot and C is the so-called Taylor Constant, i.e. cutting speed for a one minute tool life.

This formula indicates a linear relationship between log T and log V, i.e. n is a Constant. Experience has shown that in general a curve results from a logT-logV plot and that Constant n is a special case which occurs under certain conditions. Fig. 1-6 shows linear Taylor plots obtained at University of Manchester Institute of Science and Technology while Fig. 1-7 and 1-8 show non-linear Taylor plots obtained by other workers.

According to G. Barrow[7], Taylor equation appears to be reasonably valid when machining carbon and low alloy steels with all types of tool material under semi-roughing conditions (depth of cut 0.050 to 0.15 in. and feeds of less than 0.020 in.) while cutting with speeds to give a tool life between 10 and 50 minutes. Fortunately, when using carbide throw-away tools, one is mainly interested in tool lives of 10 to 50 minutes since it is in this region that one approaches optimum economic conditions. An exception to this is in the case of transfer lines where it is usual to change tools at half or full shift intervals (i.e. tool lives of 240 minutes and above). This is usually the region of maximum curvature and extrapolation of a Taylor curve into this region can create considerable errors.

Equation (1-1) only relates to tool life for a particular tool-workpiece combination, no account being taken of other cutting variables and tool geometry. To connect tool life with several variables, Taylor derived the equation:[7]

$$V_T = \frac{C_1\left(1 - \frac{8}{7(32r)^2}\right)}{S^{2/5} + \frac{2.12}{5+32r}\left(\frac{48a}{32r}\right)^{2/15} + 0.06\sqrt{32r + \frac{0.8(32)r}{6(32r)+48a}}} \qquad (1\text{-}2)$$

where V_T is the cutting speed for tool life T;

S is the feed;

a is the depth of cut;

r is the tool nose radius;

and C_1 is a constant.

While this equation includes the important variables, feed and depth of cut, it is too complex and limited to be of any practical use. Taylor considered that feed and depth of cut could not be combined into a single variable. However, Kronenberg[14] used the data obtained by Taylor and found that in most cases the area of cut (Sa) could be used as a single variable. By plotting data in the form of log V_T - log A he developed the relationship.

$$V_T = \frac{C_2}{(1000A)^Z} \qquad (1-3)$$

Where C_2 is a constant, i.e. cutting speed for an area of cut of 0.001 in.^{2}, A is the area of cut and Z the slope of the log V_T - log A plot.

Combined with Taylor's relationship $VT^n = C$, equation (1-3) becomes

$$VT^n = \frac{60^n C_2}{(1000A)^Z} \qquad (1-4)$$

A shape effect was introduced by considering the slenderness ratio $G = \frac{a}{s}$, so that

$$VT^n = \frac{C_2\left(\frac{G}{5}\right)^U 60^n}{(1000A)^Z} \qquad (1-5)$$

where U is a constant and the term $\frac{G}{5}$ relates G to an average value of G which Kronenberg[14] considered to be 5.

While equation (1-5) considers both feed and depth of cut the nose radius is not taken into account. While Taylor connected tool life with cutting speed, feed and depth of cut in separate equations he never attempted to combine them together. This is now done regularly and is known as the "Extended Taylor Equation".[7]

$$T = \frac{C_3}{V^{1/\alpha}\, S^{1/\beta}\, a^{1/\gamma}} \tag{1-6}$$

C_3, α, β & γ are constant.

While this equation is used fairly extensively it still omits tool geometry and assumes that the exponents α, β, γ are constant. As in simple Taylor equation this is not generally so and large errors can occur. The general trend of tool life with the cutting speed, feed and depth of cut is shown schematically in Fig. 1-9. The amount of curvature in a particular case will depend upon the tool and workpiece combination and the cutting conditions.

Provided α, β and γ are reasonably constant, equation (1-6) is quite useful, the evaluation of α, β, γ and C_3 is, however, quite laborious since at least three sets of tests involving fifteen tool life values are required as follows:

(a) Evaluate α by plotting log T against log V(S and a Constant)

(b) Evaluate β by plotting log T against log S(V and a Constant)

(c) Evaluate γ by plotting log T against log a(V and S Constant)

(d) Evaluate C_3 by substitution of α, β and γ and cutting conditions in equation (1-6)

In general

$$\frac{1}{\alpha} > \frac{1}{\beta} > \frac{1}{\gamma}$$

Extended Taylor Equation which takes the tool geometry also into account is:

$$T = \frac{C_4}{V^{1/\alpha} \; S^{1/\beta} \; a^{1/\gamma} \; \chi^{1/\delta} \; ..} \qquad (1-7)$$

where χ is the tool approach angle and δ is a constant.

Konig-Depiereux Equation:

König and Dépiereux[15] have developed an analysis which accommodates non-linearities in the logT-logV and logT-logS curves. Typical curves of this type are shown in Fig. 1-8. From Fig. 1-8 it can be seen that the slope of both the logT-logV and logT-logS graphs vary considerably.

The slopes of the logT-logV curve ($-k = \tan \delta T_v$) can be measured at any point (say at a particular value of feed) and then plotted against V. The same procedure can be repeated for the slope of the logT-logS graph. The results of this procedure are shown in Fig. 1-10.

From Fig. 1-10:

$$k = k_V V^m \quad (1\text{-}8)$$

$$i = i_S S^n \quad (1\text{-}9)$$

or

$$-k = \left(\frac{\partial \log T}{\partial \log V}\right)_S \quad (1\text{-}10)$$

$$-i = \left(\frac{\partial \log T}{\partial \log S}\right)_V \quad (1\text{-}11)$$

From (1-8)

$$-k = \left(\frac{\partial \log T}{\partial T} \quad \frac{\partial T}{\partial V} \quad \frac{\partial V}{\partial \log V}\right)_S \quad (1\text{-}12)$$

which gives

$$\left(\frac{\partial T}{\partial V}\right)_S = -T \quad k_V V^{m-1} \quad (1\text{-}13)$$

and

$$\left(\frac{\partial T}{\partial S}\right)_V = -T \quad i_S S^{n-1} \quad (1\text{-}14)$$

now

$$dT = \frac{\partial T}{\partial V} \, dv + \frac{\partial T}{\partial S} \, ds \quad (1\text{-}15)$$

which leads to

$$\int \frac{dT}{T} = \int -k_V V^{m-1} \, dv + \int -i_S S^{n-1} \, ds \quad (1\text{-}16)$$

$$T = e^{\left(-\frac{k_v}{m} V^m - \frac{i_s}{n} S^n + C\right)} \tag{1-17}$$

If the slope of the logT-logV curve is constant

$$T = e^{\left(-\frac{i_s}{n} S^n + C\right)} V^{-k} \tag{1-18}$$

König and Depiereux have developed a computational technique to evaluate the various constants and predict the tool life curves from only five wear tests.

CHAPTER II

TOOL MATERIALS AND WEAR OF CUTTING TOOLS

2.1 Classification of Tool Materials

The several tool materials in use today may be classified as follows:(24)

1. Carbon Steels
2. Medium Alloy Steels
3. High Speed Steels
4. Cast Tool Alloys
5. Cemented Carbides
6. Minerals
   a. Silicon Carbide
   b. Aluminum Oxide
   c. Diamond

While the first three groups of materials are really steels in as much as their major constituent is iron, the latter three groups contain iron as an impurity.

Carbon Tool Steels:

Tools in use before 1900 were all of this type. Their chief characteristics are low hot hardeners and poor hardenability. They are usually quenched into brine and even then only a thin layer can be fully hardened with the attendant risk of developing quenching cracks. The carbon steels are limited in use to tools of small section which operate at relatively low speed (and hence low temperature). A representative plain carbon steel would have the following range of analysis:

C,%	Si,%	Mn,%
0.8-1.3	0.1-0.4	0.1-0.4

The higher the carbon content, the greater will be the wear resistance of the tool.

Medium Alloy Steels:

These steels differ from the plain carbon steels by the presence of elements designed to improve hardenability. Small amounts of chromium and molybdenum are frequently used for this purpose. Representative compositions of some of medium alloy steels are given below:

C	S	Mn	Cr	Mo	W	Fe
1.2	0.3	0.6	0.5	--	--	Bal.
1.2	0.3	0.7	0.5	0.5	--	
1.2	0.3	0.3	0.7	0.3	1.5	
1.3	0.3	0.3	0.7	--	4.0	

Up to about 4% of tungsten is sometimes added to these steels in order to improve their wear resistance. While these steels are widely used for drills, taps and reamers, their hot hardness is about the same as that of carbon steels, and they are not satisfactory for high speed turning or milling.

High Speed Steels:

This material was first used for turning tools by Taylor and White about the turn of the century. Its introduction made possible a significant increase in machining speeds, which accounts for its name. However, today high speed steel is misnamed since it is now the general-purpose material for use in machining operations performed at low or moderate speeds. The chief characteristics of these steels is superior hot hardness and wear resistance. The compositions of three popular high speed steels are given below:

Designation	Type	W	Cr	V	Mo	C	Fe
T-1	W	18	4	1	--	0.7	Bal.
M-1	Mo	1.5	4	1	8.5	0.8	
M-2	W-Mo	6	4	2	5	0.8	

High speed steels have wide applications but in many operations (particularly single point) they have been superseded by carbides.

Cast Alloy Tools:

A number of nonferrous alloys high in cobalt have been developed for use as cutting tools. These materials which are known as stellites cannot be heat treated and are used as cast from a temperature of about 2300° F. A representative range of analyses for materials of this sort is as follows:

Co, %	Cr, %	W, %	C, %
40 to 50	27 to 32	14 to 29	2 to 4

Cast alloys are not quite as hard as tool steels at room temperature, but retain their hardness to higher temperatures. They are not in wide use. This is due to their fragile nature. Like all cast materials these alloys are relatively weak in tension and hence tend to shatter when subjected to a shock load or if not properly supported.

Cemented Carbides:

Carbides can be classified into two types:

1. The C grade (straight carbides) consisting of tungsten carbide with cobalt as a binder for use in machining

cast irons and nonferrous metals.

2. The S grade (steel cutting carbides) consisting of tungsten, titanium, and tanlabim carbides with a cobalt binder, for use in machining steels.

Cemented carbides are unusual in several respects:

1. They have high hardness over a wide range of temperatures.
2. They are very stiff (Young's modulus is nearly three times that for steel).
3. They exhibit no plastic flow (yield point) even to stresses as high as 5×10^5 psi.
4. They have low thermal expansion compared with steel.
5. They have relatively high thermal conductivity.
6. They have strong tendency to form pressure welds at low cutting speeds.

Diamond Tools:

Diamond tipped tools are sometimes used for special applications such as production of surfaces of high finish on soft materials that are normally difficult to machine. The general properties of diamond may be summarized as follows:

1. Hardest known substance (Brinell hardness = 7000).
2. Lowest thermal expansion of any pure substance (about,

12% that for steel).

3. High heat conductivity (twice that for steel).

4. Poor electrical conductor.

5. Burns to CO_2 when heated to about 1500° F in air.

6. Very low coefficient of friction against metals.

Since very high hardness is always accompanied by brittleness, a diamond tool must be cautiously used to avoid rupturing the point. This usually limits the use of diamond tools to light continuous cuts in relatively soft metals, and low values of rake angle are normally used to provide a stronger cutting edge.

2.2 Types of Tool Failure

The failure of cutting tools may be classified in three general types:(24)

1. Temperature Failure:

The hardness (and strength) of a tool varies with temperature. When the rate of energy input to the tip of a tool becomes too large, the tool becomes too soft to function properly and failure ensues. This type of failure occurs quite rapidly, is frequently accompanied by sparking, and is easily recognized.

2. Rupture of Tool Point:

Because of high hardness required, the tip of a cutting tool is mechanically weak and brittle. This is particularly true of carbide and diamond tipped tools. Whenever the cutting forces exceed a critical value for a given tool, small portions of the cutting edge begin to chip off, or the entire tip may break away in one piece. The high forces which produce this type of failure are not generally associated with steady state cutting, but rather with variations in the cutting process, such as might obtain in a milling operation or when cutting with excessive vibration (chatter). For a given tool material, the tendency toward a rupture failure can be diminished either by reducing the casual forces, redirecting them, or redesigning the tool to withstand them. The forces can frequently be diminished by increasing the rigidity of the tool and work holders.

3. Gradual Wear at the Tool Point:

When a tool has been in use for some time, wear may become evident in two regions as indicated in Fig. 2-1 (i.e. on the flank and rake faces of the cutting tool). In some cases the flank wear is by no means uniform as indicated in Fig. 2-1(b). Nose grooving is a common form of wear during high speed finishing operations, while notching occurs when machining high strength material, particularly heavily work hardening material such as stainless steel, Ni and Co base alloys. Both crater and flank wear (including nose grooving and notch) are progressive with time as indicated in Fig. 2-2(a) and 2-2(b). At high metal removal rates nose grooving and notch wear may be severely modified due to oxidation.

2.3 Basic Wear Mechanisms

Several mechanisms of tool wear have been proposed. Under certain conditions all these mechanisms may act simultaneously as indicated in Fig. 2-3, after Vierege.[25] A brief description of the various mechanisms is given below:

Adhesion wear mechanism:

When surfaces rub together, particularly in the absence of lubricant films, some adhesion occurs at the points of rubbing contact. The friction is primarily the force required to shear the junction so formed. The simple mechanism of friction and wear proposed by Bowden and Tabor[27] is based on the concept of the formation of welded junctions and the subsequent destruction of these. When the destruction is by shearing below the interface, a wear particle is transferred.

The plucked fragments may initially be attached to one surface but may subsequently be back-transferred onto the other. However, in machining operations this process is probably of very minor importance since fragments plucked either from the tool or work are rapidly carried away from the rubbing region.

For this reason, adhesive wear in machining operations is a relatively straightforward concept. The tool is invariably chosen to be harder than work. If a junction is formed at the metal/work interface it will generally pluck out a fragment from the work. The process of plucking-out will have the fragment in a very work-hardened condition and it may well be hard enough to score or groove the work. The accumulation of the transferred material from the work to the tip of the tool is, of course, the origin of the built-up-edge. This nose acts as an extension of the tool, and to some extent protects the tool from wear. However, the built-up-edge may occasionally break away with a small portion of the tool itself. This is particularly likely if the tool is heterogeneous in structure so that local regions may be appreciably weaker in tension or shear than the overall strength. Adhesive wear of the tool is therefore likely to be most marked if the tool is of non-uniform strength.[8]

Clearly the best way of minimizing adhesive wear is by reducing the amount of adhesion. The commonest method is by using a lubricant. However, it is still not clear whether the lubricant acts mainly as a coolant or as a means of reducing friction and adhesion. If it acts as a true lubricant it is highly desirable to know how the lubricant gets into the work/tool interface and how quickly it can interact to be effective. Another approach is to allow adhesion to occur but to ensure that transferred film is very easy to shear. The easiest way of doing this is to incorporate suitable materials on small quantities in the work material itself. It may be that free-machining steel, which contains small quantities of lead, function, to some extent, in this way. Another idea is to make the work relatively brittle so that the removed chip easily fragments and breaks away from the tool face. Silicates in the work probably function in this way, although at higher speeds it is possible that a smeared glass-like film acts, in some measure, as a lubricant between work and tool.

This mechanism cannot be the complete explanation of the wear process, since it implies that one surface will become covered with a layer of metal from the other surface and it does not explain how loose wear particles are produced.

Abrasive wear mechanism:

Probably the earliest concept of wear was one of abrasion of high spots on one surface through material of the other surface. The abrasion process involves cutting and, as such, it depends on the hardness, the elastic properties and the geometry of the two mating surfaces. Abrasive wear occurs if a hard particle cuts or grooves one of the rubbing surfaces. The first criterion for appreciable abrasive wear is that the particle should be harder than the surface being abraded. If the Vickers hardness of the particle is, say, 1.5 times that of the surface, abrasion can occur fairly readily. If the particle is smooth, most of the abrasion will be in the form of plastic grooves (with very little material removed) or in the form of chips and flakes if the surface is brittle. If the particle has sharp corners or edges and it is appropriately oriented, it will cut the surface. Abrasion then resembles microcutting and the abrasion rates are relatively high.

Tool wear by abrasion is most likely to occur with work materials containing hard inclusions. According to

D. Tabor[8] if the inclusions are spherical they are more likely to groove the tool face and flank and the rate of removal of material will be very small. If on the other hand, the inclusions are sharp they may produce microcutting and relatively high rates of abrasion. Clearly the best way of avoiding such wear is to use work materials that do not contain hard inclusions or at least to arrange for the inclusions to be smooth. Another approach is to use a tool material that is harder than the inclusions. Alternatively, a softer tool material may be used provided it workhardens under repeated abrasion to give a hard surface layer capable of resisting further deformation or cutting by abrasive particles. The same effect may be achieved by coating the tool with a very hard skin either by plating or by chemical treatment, e.g. nitriding.

Diffusion wear mechanisms:

Holm [26] thought of wear as a process of atomic transfer at contacting asperities, i.e., wear purely by diffusion. More recent concepts of wear consider diffusion to be an integral part of other wear processes. As pointed out by Bowden and Tabor,[27] some diffusion must occur in the adhesion of contacting asperities; the diffusion and alloying processes at the interface junctions will control the size and nature of the wear particles.

Diffusion may be classified as part of the abrasion wear mechanism under certain circumstances. One of the well-known examples of this is in the wear of tungsten carbide tools used in cutting steels. The chemical affinity between the steel of the work material and the cobalt binder in the tungsten carbide leads to diffusion of the cobalt out of the tool. This, in turn, causes the formation of a weakened surface layer on the tool, which is manifested by severe cratering of tungsten carbide when cutting steels. It can be controlled by addition of titanium and tantalum alloying elements.

The diffusion rate is a temperature-dependent phenomenon, i.e., a direct function of the rubbing speed. However, the amount of material transferred by diffusion is dependent on the time of contact of the mating surfaces - an inverse function of speed. The relationship between sliding speed and wear rate as influenced by diffusion is thus a complex one.

This type of wear may be reduced in three ways:

(a) by running at lower speeds so that the surface temperatures are lower.

(b) by cooling the system so that the interfacial temperatures are diminished.

(c) by using tools that are not soluble in the work even at elevated temperatures, e.g., by the use of titanium carbide with ferrous materials.

Chemical wear mechanism:

There is another kind of wear which may involve both adhesion and abrasion. It occurs if the rubbing surfaces are attacked by the environment to form a removable surface film. For example, in the presence of a sulphurized lubricant a sulphide film may be formed on the metal surface; in the presence of a fatty acid a soap film. More generally, oxide or hydroxide films will be formed in the presence of air.[8] These films may be removed by the sliding process to expose fresh underlying metal which is highly labile and can readily react with the environment to reform the surface film. This type of wear is often slow and generally is to be preferred to the wear that would occur if no surface films were present. However, if extremely reactive lubricants are used, chemical wear or even direct corrosion may become significant.

Fatigue wear mechanism:

Although fatigue wear can always occur between sliding surfaces it is usually swamped by adhesive or abrasive wear. Consequently, fatigue wear becomes important only when adhesive and abrasive wear are relatively small. For example, in well lubricated systems adhesive wear may be negligible. If hard particles are excluded from the system (this may be difficult because dust can often act in this way) abrasive wear may be small. If then the surfaces are continuously subjected to loading or unloading they may gradually fatigue and pieces of the surface may easily be detached. This occurs in sliding systems where asperities on one surface continuously transmit stresses onto the other even though they are completely separated by a lubricant film. A similar effect may occur in rolling bearings. Fatigue failure is often initiated at a surface flaw or crack. According to D. Tabor [8] an applied stress may open the crack a little; in the presence of a contaminating atmosphere the crack does not 'heal' on removal of the stress. Repeated cycling of the stress will thus gradually produce spalling of a fragment out of the surface. Sometimes fatigue cracks can be initiated at defects which lie below the surface.

In this case repeated stressing gradually work hardens the subsurface material. This may be followed by shear or tensile failure.

Fatigue does not usually occur if the applied stress is below a certain limit. To minimize fatigue wear in tools it is desirable to use tools that are considerably harder than work. The contact pressures which are determined by the yield properties of the work may then be below the limit at which rapid fatigue occurs. It is also desirable to avoid flaws in the surface of the tool and inhomogeneities in its structure.

2.4 Factors Involved in Tool Life

Although the shapes of metal-cutting tools used in turning, milling, drilling, etc., vary widely, the basic form is that of a wedge forced asymmetrically into the work material. It is now accepted that in general the workpiece material is deformed as indicated in Fig. 2-4.[7] The secondary deformation zone is caused by the chip adhering to the tool over a portion of the total contact length between chip and tool. This form is dictated by the objective of the operation, which is to remove a thin layer from a more rigid body. The layer moved in the form of fragment or a continuous ribbon bears on the rake face of the tool and passes over it, while the more rigid body of the work material bears against the passes over the flank or clearance face of the tool. To avoid excessive friction between the tool and workpiece a clearance angle (which may be from about 1^{o} to 20^{o}) on the flank of the tool ensures that the work surface is in contact with only a narrow band very close to the tool edge. Because of the rigidity of the work this normally remains narrow until a new surface, more or less parallel to the work surface, is formed by wear. Such a worn surface is called the flank wear or land and is the most typical form of tool wear.

The layer removed from the work surface (the swarf or chip), being thinner and more flexible, can conform more readily to the tool shape and normally makes contact with the rake face of the tool along a considerably longer path, a distance several times the thickness of the undeformed chip. Wear also takes place on the rake face of the tool although not so universally as on the flank.

Flank wear:

This often takes the form of an even band of wear (Fig. 1-2), the width of which can be measured with reasonable accuracy. Wear-land formation is not always uniform along the side and end cutting edges of the tool. Often localized wear at one or more positions along the edge is several times greater than the average. Two positions at which accelerated wear commonly occurs are where the work surface intersects the cutting edge of the tool and near the nose of the tool. At the former position the surface condition of the work and the atmosphere may influence the wear process.

Flank wear occurs under almost all conditions of cutting, but metallographic evidence shows that more than one wear process is involved so that simple laws relating the rate of wear to variables such as speed, feed, tool geometry, etc., can be expected only under conditions where the wear process remains substantially unaltered. Cutting tools are generally used most efficiently when the only form of wear is an even land on the tool flank, but factors other than flank wear influence the life of carbide tools in practice.

The surface finish produced in a machining operation usually deteriorates as the flank-land wear increases - although there are circumstances in which a wear land may burnish the workpiece and produce a good finish. Cutting forces are normally increased by flank wear of the tool. Flank wear also influences the plan geometry of a tool. This may affect the dimensions of components produced in a machine with set cutting tool positions, or it may influence the shape of components produced in an operation utilizing a form tool.

Vibration or chatter is another aspect of the cutting process which may be influenced by tool wear. A wear land increases the tendency of a tool to dynamic instability. A cutting operation which is quite free of vibration when the tool is sharp, may be subjected to an unacceptable chatter mode when the tool wears.

Crater wear:

On the rake face a cavity or crater frequently forms a short distance from the cutting edge, as shown in Fig. 1-2. Once the crater is established, its depth KT grows more rapidly than its top width KB. The edge of the crater approaches the cutting edge, both by wear of the crater and by clearance-face wear. This weakens the tool close to the cutting edge and a major failure may occur by fracture from the crater through to the clearance face. This is more likely under discontinuous cutting conditions. Cutting forces are normally increased by wear of the tool. Crater wear may, however, under certain circumstances, reduce forces by effectively increasing the rake angle of the tool.

Built-up edge:

According to E.M. Trent,[9] in steel cutting, the pressures locally on the rake face may be greater than 100,000 lb/in.^{2}. The surface temperatures may be several hundred degrees C, and clean metal surfaces are constantly being generated. It is not surprising therefore, that when the tool is withdrawn from the cut a fragment of the work material is often found firmly adhering at the edge. The built-up-edge is not formed during the act of disengaging the tool, but represents a body of metal present throughout the cutting process. Size and shape of the built-up-edge vary with the cutting speed and feed. Fig. 2-5 shows an idealized picture of built-up-edge. As cutting speed increases, the shape often changes from a large wedge to a flattened lump and then with further increase in speed it disappears almost entirely leaving only smears of metal on the tool surfaces.

The presence of built-up-edge is important in relation to tool life and surface finish. It may either be harmful or beneficial to the tool, depending on the conditions. E.M. Trent [9] has suggested that when cutting cast iron B.U.E. is usually beneficial and cast iron is frequently cut under conditions where built-up-edge is formed. This largely protects the rake surface of the tool from wear and the rate of flank wear is low.

When cutting steel with carbide tools, the built-up-edge is most frequently harmful.[9] Not only does surface finish of the work become poor, but the built-up-edge is often broken away, bringing with it small fragments of the tool edge and leading to rapid breakdown of the tool. Without dissolving the metal adhering to the tool, the cause of breakdown may not be obvious and failure may appear to be due to rapid flank wear.

Unlike flank wear, which occurs under almost all conditions of cutting, the built-up-edge is a factor affecting tool life mainly at low cutting speeds and feeds. To predict tool life, surface finish, etc., it is important to know the conditions under which built-up-edge occurs for the tool and work material concerned.

Tool deformation:

There is a constant trend in metal cutting to increase metal removal rate by increasing cutting speed and feed rate. With increased speed the temperature at the edge of the tool is raised, while both temperature and the stress near the cutting edge are increased with increments of feed rate. A limit is eventually reached at which the tool material can no longer resist the combination of stress and temperature, and begins to deform permanently. The resistance of the tool to deformation may be the property on which depends the upper limit to the cutting speed and feed which can be used. The development of tool materials from carbon steel through high-speed steel and cast co-based alloys to cemented carbides represents a series with increasing resistance to deformation under compressive stress at high temperature.

Deformation is a factor in tool life quite distinct from normal flank wear. Where the tool tip is not stressed above its elastic limit the wear rate is not related to the resistance to deformation. As cutting speed and feed are raised, the elastic limit is exceeded and the tool begins to deform. At first this may have no effect on the wear rate then, rather suddenly, the limit may be reached of the strain which the tool can withstand, and it may fail suddenly as a result of local fracture. Such failure may be attributed to flank wear or to mechanical chipping, unless the tool is carefully examined under the microscope, but it is necessary to diagnose the failure correctly in order to apply the correct remedy. Tool failure by mechanical chipping may require the use of a tougher tool material, while to overcome deformation a harder though less tough tool may be needed. Deformation occurs most frequently at the nose radius of a tool and may be minimized by attention to tool design. A tool with a small nose radius will deform at much lower speed and feed than one with a large radius.

It is useful to know under what conditions deformation of the tool occurs. To calculate this would require knowledge of the temperature and stress distribution near the cutting edge of the tool, knowledge not at present available. Fortunately, much useful information can be obtained at relatively simple laboratory tests. The flank surface of a tool tip is lapped optically flat and the tip is then clamped in a tool holder and used for cutting under controlled conditions. After cutting, any deformation of the tool tip can be observed and measured by placing the flank surface of the tip on a flat glass plate and examining it under monochromatic light.

By testing different tool and work material in this way, with varying tool geometry, it is possible to build up a body of knowledge concerning conditions under which deformation of the tool is a factor of importance in tool life, and the relative resistance of tool material to deformation.

Mechanical chipping:

Chipping of the tool, as the name implies, involves removal of relatively large discrete particles of tool material. Tools subjected to discontinuous cutting conditions are particularly prone to chipping. Built-up-edge formation also has a tendency to promote tool chipping. A built-up-edge is never completely stable, but it periodically breaks off. Each time some of the built-up material is removed it may take with it a lump of tool edge, to which it has adhered. This leaves a chipped cutting edge.

Chipping results most frequently from impact of the swarf on part of the cutting edge not engaged in the cutting, or when starting or stopping the cut, or from careless handling.[9] It can be greatly reduced by measures taken to control the formation of swarf by chip curlers, etc., and by efficient methods of swarf disposal. In many cases honing, or the formation of a small radius or chamfer on the cutting edge of the tool, will prevent this form of damage, or it may be necessary to use a tougher grade of cemented carbide. In such ways mechanical chipping can be minimized but its general effect is to cause scatter in the data for tool life, and often so much scatter as to render workshop test results meaningless.

Again it is important to be able to distinguish correctly between failure due to mechanical chipping and other causes. To do this with certainty usually requires microscopical examination of tools treated in acid to remove adhering metal.

Thermal cracking:

At the cutting edge of the tool very steep temperature gradients exist, and in interrupted cutting frequent and rapid changes of temperature occur. It is, therefore, not surprising to find, particularly in milling operations, that cracks may be formed across the cutting edge which can be attributed to the stresses associated with local thermal expansion and contraction. They may shorten tool life in two ways. If many cracks form close together, fragments of the tool edge may break away between them. If the tool is subjected to major stresses in service, the stress concentration at the root of the thermal cracks may result in failure of the tool by larger scale fracture, but a small number of short thermal cracks does not appreciably affect the tool life.

There are other factors and causes of wear involved in particular metal-cutting processes, but most of these, e.g. oxidation of the tip, or failure due to brazing and grinding stresses, are avoided by taking reasonable precautions well known to those 'skilled in the art of metal cutting', or are rarely encountered.

CHAPTER III

MACHINING OF HEAT RESISTANT ALLOYS

3.1 General Concept

With the advent of supersonic aircraft and rockets, thermal-resistant alloys have replaced the traditional magnesium and aluminum for many applications in aerospace industry. These alloys are hard, tough and often abrasive. Their machinability is low. End milling is difficult. Current trend in the aircraft industry has increased demand for materials that are:

1. of great strength,
2. of lighter weight,
3. resistant to oxidation, particularly at high temperatures,
4. exhibit small deformations at high temperatures,
5. are not brittle at low temperatures.

The materials that meet these requirements are generally difficult to machine. In many cases these alloys are so new that no machining information is available for use in setting up production machining operations.

Three major factors are the sources of much of the difficulty encountered in machining high-strength and thermal-resistant alloys. These are:[17]

1. Abrasive character of metal - determined by the nature and distribution of the microconstituents.
2. High temperature at the edge of the cutting tool.
3. Tendency of the metal to work harden.

While an ever-increasing quantity of ordinary structural materials will be machined in our mass production industries in the future, an increasing percentage of our productive efforts will involve the processing of less conventional materials. This work is concerned with some of the basic principles associated with the end milling of one of the conventional materials, namely PDS 10105AP (mild steel) and one of the less conventional materials, namely PDS 10710KA (Multimet) that might be classified as difficult to machine. Multimet is an iron base corrosion and heat resistant alloy with a high Ni content in it. Therefore, its machinability characteristics are very much similar to those of nickel-based alloys. To efficiently machine such a material is obviously a very challenging problem which has not been completely solved today.

The Cutting Process:

To understand the difficulty of metal removal with respect to Multimet and nickel-based alloys a close look at the cutting process is necessary. When a sharp tool engages with the workpiece in a machining operation a complex dynamic relationship is established, and although it may be customary to talk of discrete values of tool forces these will, in fact, vary continuously over a wide range. During cutting the material at the tool point reaches a yield criterion and fails; the volume of metal attains values of stress which will vary with the tool sharpness. A rounded tool will produce a large volume of near-yield material, and branching cracks may result. P. Warburton[9] has found that the material immediately in the region of the tool absorbs a large amount of energy and is likely to be highly stressed both hydrostatically and in shear; it is therefore likely that most metal cutting operations will promote a brittle type of fracture of the branching crack variety, as this dissipates more energy than a single crack failure.

3.2 General Machining Characteristics

The principal machining characteristics of heat resistant alloys are also encountered when machining ordinary materials, but usually to a lesser degree. Each class of materials has its particular combination of difficulties.

Heat resistant alloys have low thermal conductivity and low specific heat, both of which give rise to higher cutting temperatures. A high coefficient of thermal expansion makes it difficult to maintain dimensional accuracy. These materials also tend to strain harden appreciably and may even transform to martensite while being cut. This results in relatively high values of cutting force unless the strain in the chip can be reduced. Tools of relatively large rake angle and low tool-chip friction are called for. Going hand in hand with large strain hardening is built-up-edge formation and poor finish.

Another problem associated with heat resistant alloys is the tendency to leave a disturbed surface layer and residual stresses in the finished surface.(16) If a second cut must be taken it is then necessary to deform previously strain hardened material. In order that weakest portion of the tool (the tip) will not have to engage strain hardened material, it is important that the undeformed chip thickness exceeds the depth of the disturbed layer. The chips produced when machining heat resistant alloys are ductile and chip disposal or chip breaking is apt to be a problem. The large thermal coefficient of expansion and the dimensional change with phase-transformation makes it difficult to machine to close tolerances. An increased rake angle helps both of these problems.

Best results are, therefore, obtained with heat resistant alloys when they are machined at moderate values of feed using tools of high rake angle (due to the strong tendency for strain hardening) and having a low tendency to weld to the workpiece material.[16] Ceramic tools are not well suited to these materials. Cast iron (straight tungsten carbide) grades of carbide give best results and tool hardness should be as high as possible, consistent with edge chipping, in order to decrease the tendency for weld formation. Therefore, cast iron grade carbide inserts SPU-422- H13 were selected for testing purposes.

The iron base high temperature alloys are not as effective as the nickel and cobalt base alloys with respect to oxidation stability and high temperature strength, but are more easily machined and less expensive.

Since larger rake angles may generally be used with High Speed Steel (H.S.S.) tools than with carbide, H.S.S. tools frequently give the best results when machining high temperature alloys. Therefore, H.S.S. tools were also used in the investigation.

In addition, low values of speed and feed should be used and machine tools should be as rigid as possible. Cutting fluids containing active chlorine and sulphur generally aid in the machining of high temperature alloys. As the maximum operating temperature of a high temperature alloy rises, the difficulty of machining increases. The strong tendency to strain harden gives rise to deep grooves at both edges of a chip.(16)

The high temperature alloys should not be machined with tools having flank wear values that are as high as those normally employed in cutting steel. Tools should be taken from service when flank wear reaches 10 to 15 thou instead of the usual 30 thou.

3.3 Classification of Problems Associated with Difficult-to-Machine Materials

Practically all the problems associated with difficult-to-machine materials may be classified as follows:

1. Problems of tool life.
2. Problems of surface finish.
3. Problems of tool forces and power.
4. Problems of chip disposal.

3.3.1 Tool Life

Tools usually fail in one of the following ways:-[16]

Due to plastic deformation of cutting edge -

Since cutting temperatures frequently tend to be high when machining high temperature alloys this can be the source of failure for both H.S.S. and carbide tools. Since this type of failure requires the removal of large amount of the tool when regrinding, tools should be more frequently inspected when this form of failure is apt to occur, so that plastic flow of the cutting edge may be detected at an early stage in its development.

Due to attritious wear -

This type of wear occurs as a result of the shear failure of local regions on the tool surfaces. It may result from ploughing action of hard particles in the chip or workpiece. The item of interest here is the hardness of the highly worked chip and workpiece constituents relative to the softest phase of the tool. In this sense the heat resistant alloys frequently behave in an abrasive manner. The establishment of microwelds between chip and tool is another source of attritious wear. The amount of wear resulting from weld formation depends on the relative strength of materials in the vicinity of the weld. If the weakest region is in the chip then a built-up-edge results. This is usually the case with heat resistant alloys. When the weld interface is weakest there will be no transfer. However, when the points of greatest weakness lie within the tool, wear particles are developed. Since many of the heat resistant alloys both tend to weld and to strain harden they may be viewed as abrasive in this sense too. A change in the chemical composition of the tool face (thin layer) due to diffusion into the chip may reduce the strength of the tool face and cause an increase in attitious wear. However, as Opitz[18] has shown, a boundary layer may form at the chip-tool interface due to chemical action there which has a protective action. The promotion of this type of protective action is particularly important for the difficult-to-machine materials and deserves further study.

Due to groove formation -

When cutting high temperature alloys (especially nickel or cobalt high temperature alloys) there is a tendency for grooves to form at either edge of the chip. Sometimes multiple grooves having a spacing equal to the feed are found on the secondary edge of the tool. These are obviously produced by uncut material escaping the cutting edge at the point where the first groove forms on the secondary cutting edge.

Groove wear has been attributed to a strain hardened layer on the work surface at points corresponding to the chip edges. Material of hardness 63 Rc has been found in these regions.

Due to gross chipping -

Larger pieces of tool material may also be lost due to brittle fracture. In such cases high internal tool stresses induced by shock are of greatest interest. To avoid shock, continuous chip formation should be promoted. Thermally induced stresses caused by temperature gradients in the tool can also cause gross chipping.

For efficient machining of high temperature alloys, tools should be refractory to avoid plastic flow, have high wear resistance to avoid attritious wear, and have good brittle fracture resistance to avoid gross chipping. Unfortunately, the first two of these requirements do not occur naturally with the third and frequently a compromise solution must be sought.

The correction of tool failures should follow the procedure used for ordinary materials. First determine the cause of tool failure. This is particularly important since a remedy for one type of failure frequently promotes another. For example, an increase in cutting temperature is harmful from the point of view of first two types of failure, but may be beneficial in decreasing gross chipping. However, use of a coolant may sometimes promote gross chipping.

3.3.2 Surface Finish

The roughness of machined surfaces is due mainly to the following two items:[19, 20]

(i) Geometric factors.

(ii) Point of separation of chip from workpiece.

The first includes feed marks, the depth of which may easily be calculated for a given feed and tool geometry.

Built-up-edge (B-U-E) leaves behind strain hardened debris on the finished surface. Certain high temperature alloys are particularly troublesome from the point of view of B-U-E. To avoid B-U-E, the following steps may be taken:[21]

(a) Increase the chip tool interface temperature to the point where the chip material re-crystallizes. This may be difficult to achieve without destroying the tool in case of high temperature alloys which have very high re-crystallization temperatures.

(b) Use a cutting fluid that prevents chip-tool adhesion.

(c) Increase the rake angle to about 30°.

(d) Change machining conditions to promote discontinuous chip formation.

3.3.3 Cutting Forces and Power

Some of the heat resistant alloys require high cutting forces and higher power. The power above is no problem except that it results in higher cutting temperatures, for the same speed. High forces may be troublesome and cause tool breakage and poor accuracy, particularly if the part is slender and has a low Young's Modulus of elasticity. It should be noted that:

(i) Hardness which is essentially a static room temperature test is not capable of expressing the relative tendency of materials to strain harden in cutting, particularly when ordinary steels and high temperature alloys are involved in the comparison.

(ii) The strain hardening that takes place in cutting occurs at high temperatures and high strain rates. This results in a much higher degree of strain hardening for a high temperature alloy than for an ordinary material of the same hardness.

Thus, it is very important to note that the strain hardening that occurs when cutting high temperature alloys is special and cannot be measured by a hardness test or by compression or torsion test, but only at a combination of high temperature and high strain rate.

3.3.4 Chip Disposal

In milling, space for chip flow is limited and a long stiff chip may result in tool damage. It should be noted that a thin chip may be broken by a small force but requires a large deflection.[22] Since most chip breakers provide a fixed deflection, thicker chips are more easily broken than thin ones but require more force. Thick chips are produced by an increase in undeformed chip thickness or a decrease in shear angle.

While milling heat resistant alloys, chipping of cutting edge is the most important problem encountered. This is due not only to thermal and mechanical shock and fatigue, but also to chips which become welded to the tools. Climb (or down) milling is helpful in avoiding this difficulty, since the chip thickness and tool-chip contact area are small at the end of each cut. This type of milling also decreases attritious wear since it reduces the rubbing that precedes cutting, and this is particularly important for materials that strain harden greatly. Because of the intermittent nature of the milling process, and the fact that climb milling is advocated for difficult-to-machine materials, it is important that the milling system be unusually rigid and stable.

CHAPTER IV

MACHINING UNDER INTERRUPTED CUTTING CONDITIONS

The term "interrupted cutting" is used to describe a variety of cutting operations in which, after intervals of time, measurable in seconds or fractions of a second, the cutting alternates with the free running of the tool. The interrupted cutting operation is frequently encountered in production engineering. It is conditioned by the kinematic properties of a number of processes like milling and planing. In interrupted cutting several specific phenomena are encountered, by virtue of which the change in the life and efficiency of a tool is subjected to rules which are different from those in continuous cutting.

By specially conducted experiments Zorev[28] established that the life of a high speed cutting tool in interrupted cutting is the same or even greater than in continuous cutting. For the convenience of comparison he determined the tool life as the total time of actual cutting (free-running time was not taken into account). Zorev[28] also showed that the life of a carbide-tipped cutting tool in interrupted cutting can be several times shorter than in continuous cutting.

By the analysis of experimental data, obtained under different conditions of cutting, Braiden and Dugdale[8] have shown that a reduction in the life and efficiency of a cutting tool on changing over from the continuous to interrupted cutting may depend not only on the properties of the tool material, but also on the shape of the blank being machined and so on.

Fig. 4-1[28] compares the life of T5k10 carbide tipped cutting tools for the continuous turning and face milling of steel having a hardness of 190 HB when t = 6mm and s = 1.1 mm/rev (mm/tooth). To obviate the effect of the vibration of the teeth on the tool life, single-tooth fly cutters were used. The life of the cutter was based not on the total machining time up to the instant of blunting, but on the actual cutting time. From the graph it is seen that all other conditions being equal, the life of the carbide-tipped cutting tool is almost the same in milling and continuous turning. In other words, for the chosen conditions of milling the interrupted character of operation has practically no effect on the life of the T5k10 carbide-tipped cutting tools. It would be possible to quote other examples which show that the effect of the interruption factor may be very different.[28]

Thus, it seems to be impossible to give any general correction for the life of the cutting tool (or permissible cutting speed) for interrupted cutting. It is also impossible to recommend any type of carbide for interrupted cutting. It is necessary to establish the physical nature of the effect of interruption on the life of the carbide-tipped cutting tool and to find the basic factors which determine the intensity of this effect.

In literature, the point of view is repeatedly expressed that a reduction in the life of a carbide-tipped cutting tool in interrupted cutting is conditioned mainly by the impact action of the material being machined on the cutting edge of the tool. In this connection, for interrupted heavy cutting it was recommended by Braiden[8] that large negative rake and axial rake angles of the tool should be used. Furthermore, it was proposed that the most favourable points of initial contact between the cutting face of the tool and the metal being machined should be secured for the initial cut and even that steps should be taken to decrease the speed of initial entry of the tool.

In the detailed investigation it was shown by Zorev[28] that these recommendations, as well as the conception itself about the decisive role of mechanical impact at the instant of the entry of the tool, were unfounded. As an example, some results from experiments conducted by Zorev[28] for the purpose of clarifying the role of impact on initial entry are shown. The tool-life diagrams in Fig. 4-2 were obtained for two cases of planing using a TT7k12 carbide-tipped cutting tool.

In first case, on a planing machine when s = 2mm/stroke and V = 25 m/min a steel-45 plate having a length of 2000 mm was fixed to slant towards the plane of the table so that the initial entry of the tool into the metal was made at zero cutting depth which gradually increased to 10mm at the exit of the cutting tool.

In the second case the plate was slanted in opposite direction and the entry of the tool into the metal was made at full depth (10mm) which gradually decreased to zero at the exit of the cutting tool. Thus, for the equal amount of metal removed and for the same amount of work done in cutting, in the first case the impact on entry into the metal was non-existent, and in the second case it had the highest value. However, in both cases the life of the cutting tools was shown to be nearly the same. The insignificant difference in the life was smaller than in the variations in the life of individual cutting tools. This brings out the fact that in the given case the impact at the instant of the initial entry of the cutting tool into the metal does not play an effective role.

The study of wear of a carbide-tipped tool by Shinozaki[29] showed that the reduction in its life in interrupted cutting is associated with the formation of micro- or macro-cracks. The cracks represent the areas of wear concentration on the front and rear surfaces. Under adverse conditions the cracks increase rapidly in size, and chipping of the cutting edge or even shearing takes place.

The study of the operations of the face milling cutters showed that all the factors which increase the cooling rate of the cutting edge during its free running aid the formation and extension of cracks and as a result of this reduce the life of the cutting tool. On the other hand, the factors which reduce the temperature during the free running of the milling cutter tooth increase the life.[30] In particular, it was shown that the life of the carbide-tipped milling cutters reduces rapidly when cooled by an emulsion. At the same time the preheating of the milling cutters by gas flame during the free running increased the life.

Thus, the conception emerged that the basic cause for the formation of cracks and reduction in the life of a carbide-tipped cutting tool in interrupted cutting lies in the cyclic cooling of the cutting edge during the free running.

During the cutting period the contact surface layers of the tool are heated to a higher temperature than the sub-surface layers. Under these conditions, owing to the deformations caused by the difference in temperatures, compressive stresses are set up in the surface layers.

During the period of free running the surface layers of the tool cool very rapidly, and their temperature becomes lower than the temperature of the sub-surface layers, under which conditions tensile stresses are set up in the surface layers. Since the compressive strength of carbides is considerably greater than their tensile strength, then the tensile stresses which are set up during free running of the tool play the greatest role in the formation of cracks.

It is obvious that the more vigorously the tool cools during the free running the more severe will be the tensile stresses set up in the surface layers, the cracks form in the cutting edge and develop rapidly, and the life of the tool reduces.(31)

According to what has been said it must be expected that the interruption factor will show itself more strongly the longer the duration of the free running of the tool. From this point of view it is possible to explain quite a different effect of the interruption factor, mentioned above in the consideration of experimental data.

Zorev(28) has shown that the duration of free running of the tool does not completely characterize the effect of the interruption of cutting on the tool life. The tool operating time to, during which heating of the inner layers of the carbide tip takes place, has also a considerable effect. With a short duration the inner layers of the tool do not heat up and, consequently, less severe tensile stresses are set up in the surface layers during the free running. The tool life is, therefore, reduced to a lesser degree. Zorev(28) has shown that with an increase in the duration of the interruptions the life of the cutting tool reduces considerably.

It should be borne in mind that an increase in the duration of free and operating runs of the cutting tool cannot be continuously accompanied by a reduction in the life of the carbide-tipped cutting tools. An increase in the duration of the operating run will continue to reduce the tool life up to the point when maximum possible heating of sub-surface layers of the carbide tip is achieved. In exactly the same way an increase in the duration of the free run will continue to reduce the tool life up to the point when the maximum possible cooling of the surface layers of the carbide tip, relative to its inner layers, is reached. A further increase in the duration of the free run will not cause a reduction in the life of the tool, but on the contrary, the tool life will be increased more, since under these conditions the number of heating and cooling cycles per unit time is reduced. It is obvious that in the interrupted cutting the life of the carbide-tipped tool is determined not only by the amplitude of the change in stresses in the surface layers, but also by the number of these changes.[28]

The most adverse duration of free and operating runs of the cutting tool depends on many factors, in particular on the cutting speed, the feed rate, the thermal conductivity of the carbide, the area of contact between the chip and the front surface, the mechanical properties of the metal being machined, etc. Zorev[28] has found that in interrupted cutting of a plain carbon steel having a hardness of 170 to 180 HB, when s = 1.5 to 2mm/rev, a = 6 to 10mm and v = 30 to 40 m/min, the most adverse duration of the operating and free runs is 3 to 5 seconds.

The determination of general quantitative relationship between the life of the carbide-tipped cutting tools on the one hand, and the duration of free and operating runs of the cutting tool on the other hand, represents a complex problem, since these relationships may change materially under the influence of different conditions.

It is found that the effect of duration of interruptions is the more powerful the weaker the tool material.[31] The investigations showed that, all other conditions being equal, the effect of the duration of interruptions also depends on the hardness of the steel being machined. A reduction in the hardness of steel below 200 HB reinforces the effect of interruptions. Therefore, for those conditions of cutting under which the effect of interruptions has already markedly shown itself, a hump-shaped graph is observed for the relationship between the hardness of the steel being machined and the life of the tool, but for those conditions under which the effect of interruptions does not yet appear, this relationship is uniform in character.

For high-speed cutting tools, which possess very high strength, the uniform relationship between the permissible cutting speed and the hardness of the material being machined remains in force even under the very adverse conditions of interrupted cutting. On the other hand, for very brittle tool materials, for example, the TsM 332 ceramics, the hump-shaped character of the indicated relationship reveals itself even with the very insignificant effect of interruptions. Actually, the life of ceramic tools under the conditions of prolonged turning of plain short parts of steel-45 is greater when turning parts made of mild steel-10 or hard steel V-12.[28]

From what has been said above, it follows that in interrupted cutting of steel with high feed rates the carbide must be chosen by taking into account the effect of a large number of factors. However, in the first approximation it is possible to be guided by taking into account the duration of the free run of the cutting tool only.

It was shown by Braiden and Dugdale[8] that in interrupted cutting the speeds permissible for a carbide-tipped tool may be lower than in continuous cutting. Therefore, for working out the conditions for interrupted cutting for heavy cuts it is impossible to use the existing formula or tables compiled on the basis of the study of continuous cutting.

CHAPTER V

THE DEVELOPMENT OF A QUICK-STOP DEVICE

5.1 Introduction

In order to put the analysis of a metal cutting operation on a qualitative basis, certain observations must be made before, during and after a cut. Some features of the cutting configuration can be determined before any cutting is undertaken - such as the undeformed chip thickness, the tool cutting angles and the strength, hardness and microstructure of the workpiece material. Other features can be determined after cutting - such as the thickness of the chip produced and the strength, hardness and microstructure of the chip material. Certain features however can only be determined by "freezing" the cutting action so that the geometrical and metallurgical behaviour as the chip is born can be investigated.

As a part of the development of the metal cutting research laboratory, a quick-stop device was designed. A quick-stop device is an instrument used in metal cutting research to rapidly reduce the velocity of the cutting tool relative to the workpiece to zero. The device enables investigations to be made of the zones of chip and workpiece surface generation under conditions indicative, to some extent, of the "pseudo-steady-state" commonly encountered in metal cutting. Studies of this form have not been performed before at this University and the development of the device is a very useful contribution towards the development of the metal cutting research laboratory at McMaster.

The material contained within the zones of chip and workpiece surface generation constitutes the "chip root". In order that the chip root should faithfully represent the geometrical and metallurgical configuration that exists under normal cutting conditions, instantaneous separation of the tool and the workpiece should take place. As instantaneous separation requires infinite acceleration (or deceleration) of either the tool or the workpiece, this performance is physically impossible to achieve and some deviation from the ideal must be tolerated.

5.2 Requirements of a Quick-Stop Device

Some desirable features of the action of a quick-stop device are as follows:

1. The separation time of the tool and the workpiece should be small.
2. The distance travelled by the tool relative to the workpiece during the separation process should be small.
3. Geometrical and metallurgical changes in the chip and

the workpiece surface introduced by the action of the device should be minimal.

4. Vibrations introduced into the cutting action by the action of the device should be minimal.
5. The device should have the static and dynamic characteristics of a good tool post.
6. The tool should not be damaged in the separation process.
7. The device should be safe and easy to use, should be reliable and give reproducible results.

It may not be possible in designing a quick stop device to satisfy all these requirements and some compromise may have to be made.

5.3 The Development of the Device

Fig. 5-1 shows the device in its developed form. A Ramset Piston-Set tool (gun) is used to accelerate the tool. With this tool three different types of cartridges to give three different velocities to its piston which strikes the tool holder were used. Velocities of piston obtained with different cartridges are as follows:

Cartridge Type	Velocity of Piston
1-2CR-Grey	75 ft/sec
2-2CR-Brown	150 ft/sec
3-2CR-Green	225 ft/sec

This enables to conduct experiments in which separation time and separation distances can be varied to see the effect of their variation on the chip roots for a given set of machining conditions.

Also the piston-set tool (gun) must be pressed down before it can be fired. This is a safety feature. The yield strength of the piston of this gun is sufficiently high to withstand the contact stress produced as the piston strikes the tool holder.

The tool block is pivoted at the rear end and it rests on the shear pin on the other end. The shear pin is made of high carbon steel (1/4" dia.). The pins are notched down to 1/8" dia. at the appropriate shear sections. The root diameter of the pins was determined such that the force required to shear a pin was greater than the maximum tangential cutting force envisaged. The shear pin and the pivot pin rest in the side plates of the device. Hardened bushes are used for the shear pin. The tool block is secured in its normal position by clamping bolts. The barrel of the gun is held in position by means of two plates and bolts such that the line of action of the gun is exactly in the centre of the tool block and is normal to the shear pins. On the impact of the piston of the gun onto the tool block, the shear pin breaks and the tool block accelerates down and rotates around the axis of the pivot pins. At the end of its travel the motion of the tool block is arrested by plasticine. The device is canted over at 5^{o} to the vertical in the direction away from the workpiece to minimize the interference of the tool with the previously cut surface during the tool retraction stroke. Interference would occur with vertical retraction because the tool cutting edge has a velocity in the feed direction during as well as before, the retraction process.

The acceleration of the tool and its separation distance from the workpiece depends on the velocity of the piston of the gun.

Time of contact between piston and the tool shank:

Theory of wave propagation is applied to determine the time during which the piston will remain in contact with the tool shank. Our case in which the piston strikes the stationary tool with a velocity V can be simplified to the case of colinear impact of two bars of unequal length moving with equal velocity of v/2 (see Fig. 5-3).

Initially the stress in both tool as well as piston is zero and their velocity is v/2.

According to the theory of wave propagation,[23] immediately after the impact as the two wave fronts travel in the two bodies they go on making the velocity of a part of the body equal to zero as they pass through it and stress in that part is:[23]

$$\sigma = \rho C \, v/2$$

where ρ is the density of the material

C is the velocity of wave propagation

$C = \sqrt{E/\rho}$

where E is the modulus of Elasticity of the striking bodies.

Therefore, immediately after the impact equal lengths of each body will have been brought to rest because the elastic wave speed in both is same. A compressive stress $\sigma = \rho C \, v/2$ will have been propagated away from the common plane of impact. The compressive pulse is reflected as a wave of tension from the free end of each body, so that for the period of time $\frac{L_2}{C} < t < \frac{2L_2}{C}$, the tool holder will be unloaded. When $t = \frac{2L_2}{C}$, the tool holder is completely stress free and the particle speed in it will everywhere have been exactly reversed to become $-V$. At this instant the two bodies will separate. Therefore,

$$\text{time of contact } dt \doteq \frac{2L_2}{C}$$

$$L_2 = 0.75 \text{ inches}$$

$$C = \sqrt{E/\rho} = \sqrt{\frac{30\times10^6}{\frac{0.283}{386}}} = 20.227\times10^4 \text{ in/sec}$$

$$dt = \frac{2\times0.75}{20.227\times10^4}$$

$$dt \simeq 7.41\times10^{-6} \text{ Secs.}$$

Fig. 5-4 shows the variation of velocity of the tool holder with time in this idealized case. Since v/2 is more than the normal cutting speed, the separation of the tool will be almost instantaneous. Here, energy required to shear the pin has been neglected.

$$\text{Contact stress} = \sigma_o = \rho C\, v/2$$

$$\rho = \frac{0.283}{386} \frac{\text{lb}}{\text{in}^3} \frac{\text{Sec}^2}{\text{in}}$$

$$C = 20.227 \times 10^4 \text{ in/sec}$$

$$V = \text{Velocity of piston} = 225 \text{ ft/sec (max)}$$

$$V = 2700 \text{ in/sec}$$

Therefore, $$\sigma_o = \frac{0.283}{386}\left(20.227\times10^4\right)\cdot\frac{2700}{2}$$

$$\sigma_o = 200,200 \text{ lb/in}^2$$

But the yield strength of the kennametal tool holder KTAR 163C is approximately 210 x 10^3 lb/in^2 and that of the material of the piston is also approximately the same. Therefore, the materials will be able to withstand this stress without any plastic deformation.

Fig. 5-2 shows the photomicrograph of the formation of a continuous chip (after polishing and etching) obtained by using a quick stop device.

After the first test, slight plastic deformation on the shank of the tool was noticed. Thus, the outer layer of the tool shank was strain hardened after the first firing and no further plastic deformation occurred during the subsequent firings. Also from the photomicrographs no rubbing of the tool with the chip was noticed which showed that the acceleration of the tool was sufficient for the purpose.

CHAPTER VI

STUDIES OF TOOL WEAR IN END MILLING

The first four chapters have provided a rather lengthy review of some of the problems in the area of metal cutting. In presenting this review it was not the intension to emphasize the negative aspects of the state of the art since considerable progress has been made in compiling metal cutting data under various combinations of tool and workpiece material.

A very comprehensive collection of data for metal cutting operations like turning, planing, boring, milling and shaping, etc. is to be found in reference (33).

This present investigation was promoted by a machining operation that was presenting problems to a local industrial firm. The company was involved in manufacturing slots in turbine shrouds and originally was attempting to produce slots by a planing operation. In the considered opinion of the company the process they were employing was uneconomical and Dr. Tlusty was approached regarding an alternative method of manufacture. It appeared that end milling might be a possible solution but some preliminary work in the area carried out by the company was not successful.

The problem was then referred back to Dr. Tlusty and arrangements were made for the author to carry out an investigation into the end milling of the slots aimed at optimizing the cutting conditions. The work involved the milling of two distinctly different materials from which the turbine shrouds were manufactured:

1) PDS 10105 AP (Mild Steel)

2) A difficult-to-machine, heat resistant high Ni, high Cr, iron base alloy having the trade name multimet.

Because of the dissimilar nature of these two materials it was deemed necessary to carry out some fundamental and comparative tests involving the use of different cutting techniques, i.e. cutters made from different materials and cutting under different operating conditions.

Thus the author was involved in finding optimum cutting conditions for end milling narrow slots and had the opportunity to contribute some knowledge in a field where practically there is no data available. Since this was the first investigation of this type, i.e. investigation into tool wear and machinability, to be carried out at McMaster University, the author was obliged to set up the necessary equipment for carrying out the investigations. This also involved consultation and making arrangements for regrinding the tools and supply of the materials with the Westinghouse of Canada, Ltd., purchasing and commissioning of the tools, measuring equipments and set up equipments required.

Properties of the workpiece materials:

(a) PDS 10105 AP (steel):

Condition: Hot rolled steel bars.

Chemical Composition:

Carbon	0.13% - 0.28%
Manganese	0.30% - 1.00%
Phosphorus, Max.	0.040%
Sulphur, Max.	0.050%

Mechanical Properties:

Tensile strength, psi, min.	55,000
Yield strength, psi, min.	35,000

(b) PDS 10710 KA (Multimet):

Corrosion and heat resistant alloy plate.

Condition: Hot rolled, annealed and pickled.

Chemical Composition %:

Carbon	0.08 - 0.16
Manganese	1.00 - 2.00
Silicon, Max.	1.00
Phosphorus, Max.	0.040
Sulphur, Max.	0.030
Chromium	20.00 - 22.50
Nickel	19.00 - 21.00
Cobalt	18.50 - 21.00

Molybdenum	2.50 - 3.50
Tungsten	2.00 - 3.00
Columbium & Tantalum	0.75 - 1.25
Nitrogen	0.10 - 0.20
Iron	Remainder

Mechanical Properties:

Tensile strength, psi, min.	100,000
Yield strength, psi, min.	40,000
Elongation in 2" or 4D, %, min.	40

6.2 Testing Procedure

In view of the nature of operations and the materials used, following cutting tools were selected for the purpose of the tests:

(1) Carbide Cutters:

2.5 inches diameter cutter capable of holding 6 throw-away inserts. Following inserts were selected:

(a) Sandvik SPU-422, S4 (steel grade) for cutting steel.

(b) Sandvik SPU-422, H13 (cast iron grade) for cutting Multimet.

NOTE: During these tests single tooth cutting was done using only one insert at a time. The purpose was to obviate the effect of the vibrations of the teeth on the tool life. In the case where all the 6 inserts cut simultaneously, because of the inevitable run out, the effective feed will be maximum for one particular tooth and for the rest of the teeth it will be less. Therefore, in single tooth cutting the feed represents only an average value of the feed/tooth.

(2) High Speed Steel Cutters:

Clarkson Rippa (ripping cutter) of 1.5" diameter (5% co. high speed steel) with 6 teeth.

Machines used for testing:

A dynamically stiff machine tool is a must for metal cutting experiments. Sturdy spindle bearings, adjusted for heavy cutting loads, are needed, as is adequate torque to carry the flute through the cut. The feed mechanism must have zero backlash. Snug, clean and correctly lubricated gibs and slides are important. The machine must have adequate power to maintain cutting speed and it must be free from vibrations. Following machines were used for testing:

(1) Cincinnati Hydrotel (3 spindle vertical NC milling machine) using mist of coolant.

(Accuracy: $V \pm 0.5\%$ and $S \pm 0.2\%$)

Fig. 6-1 shows the experimental set-up on Cincinnati Hydrotel.

(2) CORREA FSUA (Spanish) milling machine using a flood of coolant. (Accuracy: V±2% and S±1%)

(3) ZBROJOVKA FA4V Nc milling machine using flood of coolant. (Accuracy: V±2% and S±1%)

Cutting Fluid:

The coolant used was a solution 20:1 of TRIM SOL, product of Master Chemical Corporation. The fluid was fed on the circle of the cutter pass through a nozzle.

Measuring Devices Used:

(1) Scanning Electron Microscope, Cambridge S.E.M.

(2) Tool maker's microscope (see Fig. 6-2). (Accuracy: ±.0001i:

(3) Special purpose microscope which can be used to measure wear on the teeth of the milling cutter while the cutter is mounted on the machine (see Fig. 6-3). (Accuracy: ± 0.0001 in.)

Types of Tests:

Following types of tests were performed with and without the use of cutting fluid:

(1) Slotting tests under different cutting conditions.

(2) Half-immersion tests:

These tests differ from the slotting tests in the type of chip obtained. In slotting tests the chip thickness varies from zero to a maximum value and then from maximum to zero again. In the case of half-immersion tests there can be two cases:

(a) Conventional or up milling: In this case the workpiece is fed in the direction opposite to the direction of cutter rotation (see Fig. 6-4 (b)). The chip thickness varies from zero to a maximum value.

(b) Climb or down milling in which case the direction of work feed and cutter rotation is the same (see Fig. 6-4 (a)). Here the chip thickness varies from a maximum value to zero.

The purpose of half-immersion tests was two-fold:

(1) to compare the tool life obtained in up milling and down milling.

(2) When a special milling cutter is used the diameter of which equals the width of the slot, only the "slotting", i.e. full-immersion cut is taken and the slot is machined in one pass. Normally, however, a general purpose cutter is

used with a diameter smaller than the width of cut. In this case it takes one slotting pass and one partial-immersion pass to machine completely the slot. The half-immersion test thus relates to such a second pass and its purpose is to see how the tool lives of the full-immersion and half-immersion cuts differ with respect to only half the time of actual cutting in the latter case as compared with the former one.

Ranges of Cutting Conditions:

	Range of Speed ft/minute	Range of Feed/Tooth in/tooth
Carbide Cutter	164 to 361	0.002 to 0.007
H.S.S. Cutter	35 to 196	0.003 to 0.007

Tables 6-1 to 6-3 give the data of the tests performed.

It may be pointed out that the total number of the tests performed was much greater than those included in the tables 6-1 to 6-3 because of various types of tool or machine malfunctions during some of the tests.

Each tool tested was studied with regard to the flank wear after test intervals of fixed length. The investigations were carried out with light optical microscopes as well as a scanning electron microscope. The two kinds of microscopes have different kinds of depth sharpness characteristics, and thus are complementary to each other in an excellent way.

6.3 Description of Results

To analyse the pattern of the development of wear, the average and the maximum flank wear VB_{av} and VB_{max} was measured at various time intervals. In addition, the type of pattern of tool wear, built-up-edge, if any, types of chips, surface finish obtained, length of cut and other special features, if any, were recorded at those time intervals. Figs. 6-5 to 6-10 show the plots of VB_{max} versus time for various tool and workpiece combinations. The cutting speed in ft/minute, feed per tooth in inches and the test numbers are marked on each individual curve. These test numbers coincide with numbers in Tables 6-1 to 6-3. As can be seen from Fig. 6-5, the development of wear with time while cutting steel with carbide is rather uniform. Wear increases steadily with time. The pattern of wear development for half-immersion and slotting tests is not very different. Fig. 6-6 shows the development of wear of carbide tools while cutting Multimet. It can be seen that up to a certain time the wear develops uniformly but after that time a rapid development of wear results in tool failure. This is because as the wear develops the chips start sticking to the tool. In re-entering the cut the edge breaks off first in small parts and further in bigger parts and soon a large damage is caused. Another item of interest here may be the hardness of the highly worked chip and workpiece constituents relative to the softest phase of the tool. In this sense, multimet behaves in an abrasive manner. The establishment of micro-welds between chip and tool is a source of attritious wear. The amount of wear resulting from weld formations depends on the relative strengths of materials in the vicinity of the weld.

Fig. 6-7 is a plot of VB_{max} versus time for H.S.S. on steel. In this case the development of wear is again uniform. Fig. 6-8 shows the development of VB_{max} with time for H.S.S. on Multimet. It can be seen that cutting speed has a great effect on the tool life. At 35 ft/minute, the wear develops rather uniformly as seen from tests #25 and #27, sometimes with increasing wear rate as in test #29. But when the cutting speed is increased to 49 ft/minute the tool fails very fast as can be seen from tests #26 and #28 and as illustrated further in photograph Fig. 6-13 (b).

The photograph in Fig. 6-13 compares the wear on two H.S.S. tools while cutting Multimet. It can be seen that on the tool with 35 ft/minute cutting speed the wear is normal but on the tool with a speed of 49 ft/minute the first two sections of every tooth are sheared off completely, probably as a result of softening due to high temperature of the tooth tips.

Fig. 6-9 shows the development of VB_{max} with time while cutting steel and Multimet with carbide tools. No coolant was used in these experiments. It can be seen that rate of wear in these cases is very high. Tool failure in these cases occurred quite rapidly, was accompanied by sparking, and was easily recognized. Chips obtained in test #31 were red hot. It is obvious that in tests #30 and #31, temperature failure of the tools occurred.

Fig. 6-10 compares the tool life in up-milling and down-milling. It is seen that in case of both H.S.S. and carbide tools, longer tool life is obtained in down-milling than in up-milling. But the increase in tool life in case of carbide tools is not very much. The reason for obtaining a better tool life in down-milling is that down-milling is helpful in avoiding the formation of microwelds between the chip and the tool. Down-milling also decreases attritious wear since it reduces the rubbing that precedes cutting, and this is particularly important for materials that strain harden greatly. Also, slotting cutters have less tendency to deflect sideways when used in down-milling.(32) In down-milling however, the cutting edge begins to cut on the rough surface of the work and the presence of sand or scale is detrimental to cutter life. In up-milling, the cutting edge engages the workpiece on the surface milled by the previous tooth, and the condition of the outer surface of workpiece has generally no appreciable effect on cutter life.

Photographs in Figs. 6-14 to 6-23 show typical electron micrographs of wear patterns for various combinations of tool and workpiece.

From the foregoing discussion of wear development and of wear modes it is seen that it is possible to accept flank wear VB_{max} = 0.030 inches as tool life criterion. Here, we do not take VB_{av} as criterion because of the rather irregular form of flank wear in those cases where there is an increased wear either on the nose or at the point on the edge which cuts the surface of the workpiece and also because of those cases where chipping and breaking out of the edge starts to accelerate. For the H.S.S. cutters, wear on each of the six teeth was measured and noted down at regular time intervals. For tool life limit the second worst tooth was taken. For the carbide cutters, the only existing edge was measured and it was assumed that it may be taken as representative. This assumption leads to higher tool lives than what will probably be obtained on a real cutter where one of the teeth will be more loaded because of the run-out.

The thus established values of tool life T in minutes for all the investigated cases are assembled in diagram shown in Fig. 6-11. The horizontal co-ordinate of the graph is cutting speed in ft/minute. Feed per tooth in inches is noted at each point or line on the graph. Lines are used to connect points representing the same tool-workpiece combination, same feed per tooth and same mode while they differ in cutting speed. For such tests where only one cutting speed was tested, isolated points only are shown.

We shall now discuss the individual features resulting from this diagram.

In the left hand part, covering the range of cutting speeds up to 200 ft/minute, results of tests with H.S.S. cutter are given. Five cases of machining Multimet are grouped at the left and five cases of machining mild steel on the right. For both groups a very strong effect of cutting speed on tool life is evident. Actually the two cases of Multimet machining at $V = 49$ ft/minute are those in which very fast destruction of the tooth tips occurred as shown in photograph Fig. 6-13(b). On the other hand, feed per tooth, in the range used, from 0.003 to 0.007 inches, does not seem to influence tool life at all. It is also interesting to notice that the full-immersion and the half-immersion tests at $V = 35$ ft/minute and S_t = 0.005 inches on Multimet gave equal tool lives in terms of total time (free running time plus actual cutting time). The same applies to such two tests at $V = 98$ ft/minute and S_t = 0.007 inches, on steel. In terms of the total volume of material removed per tool life, full-immersion tests give better tool life than the partial-immersion tests.

Recommendations of $V = 35$ ft/minute, $S_t = 0.005$ in. for Multimet and $V = 98$ ft/minute, $S_t = 0.007$ in. for steel result clearly of these tests.

In the right hand part of the diagram carbide tool tests results are plotted. The numbers in circles given at some points are test numbers for which photographs of tool wear are included in this thesis.

As regards the effect of cutting speed in this part, contrary to the findings for H.S.S. tool, no systematic influence on tool life is found. For both steel and Multimet machining we find both positive and negative effect of cutting speed on tool life but none of them is strong. In average, we may take ~~this effect~~ effect as negligible. On the other hand, again for both tool materials, a strong influence of feed on tool life is found in a very systematic way. Tool life increases with the decrease in feed per tooth for a given speed.

Further features in this region are: depth of cut has also a strong effect on tool life, however, not as strong as to justify taking two half-depth cuts instead of one full depth. Comparing the two 0.007 in. lines for steel machining we conclude similarly to the case of the H.S.S.

tool that the half-immersion test gives tool life equal to that of full-immersion slotting.

It is necessary to point out that test #7 is a repetition of test #7a. Test #7 gave such an exceptionally long tool life that we disregard ~~it and for the resulting~~ recommendation, conditions of case 7a are applied.

It is usually argued[29] that the reduction in the life of carbide tools in milling is associated with the formation of micro- or macro-cracks and reduction in the life of a carbide-tipped milling cutter lies in the cyclic cooling of the cutting edge during the free running.

Reason for crack formation is explained in detail in Chapter IV.

It is interesting to note that no thermal cracks were observed during our experiments. It shows that the tool operating time t_o, during which heating of the inner layers of the carbide tip takes place, has a considerable effect on crack formation. With a short duration t_o the inner layers of the tool do not heat up and, consequently, less severe tensile stresses are set up in the surface layers during the free running. The tool life is, therefore, reduced to a lesser degree. In our experiments the duration of operating cycle was very short (from 0.054 seconds to 0.11 seconds). Therefore, no thermal cracks were formed. These results, incidently, are in close agreement with experimental results of Zorev.[28]

6.4 Recommendations

The recommendations to be formulated are based on conclusions of the discussion of Fig. 6-11 and on the summary of best results given in Fig. 6-12 where tool lives obtained are expressed in length L of full depth of cut (applies equally to slotting and half-immersion) instead of in time as in Fig. 6-11. Thus, from Fig. 6-12, it is recommended:

For machining Multimet:

With H.S.S. Cutter: $V = 35$ ft/min, $S_t = 0.005$ in.,
$S = 2.7$ in/min, resulting in $L = 60$ in.

With Carbide Cutter: $V = 302$ ft/min, $S_t = 0.002$ in.,
$S = 5.5$ in/min, resulting in $L = 98$ in.

For machining mild steel:

With H.S.S. Cutter: $V = 98$ ft/min, $S_t = 0.007$ in.,
$S = 10.5$ in/min, resulting in $L = 360$ in.

With Carbide Cutter: $V = 361$ ft/min, $S_t = 0.005$ in.,
$S = 16.6$ in/min, resulting in $L = 540$ in.

The findings of Chapter VI are contrary to those of other workers. But it should be noted that end milling of narrow slots is a specialized operation where it is not possible to use large diameter cutters and chip disposal is a serious problem. The following uncommon phenomena were observed:

1) Better tool life is obtained while cutting with carbide cutters using coolant. As mentioned in Chapter VI, other workers have found that the application of coolant on carbide cutters under interrupted cutting condition is detrimental to tool life because of the formation of thermal cracks due to cyclic cooling of the cutting edge during the free running time. Fig. 6-9 shows the development of VB_{max} on carbide cutters without coolant and Fig. 6-6, the development of wear on carbide cutters while coolant is used. By comparing the two graphs we find the obvious difference in tool life. Tool life in cutting with coolant is better because the coolant helps in chip disposal. Also, from the graph in Fig. 6-6 it is possible to specify the time after which the rapid wear on the tool will occur. As can be seen from the graph, VB_{max} = 0.030 inch can be used as an approximate

criterion for carbide tool life. In the case of H.S.S. tools this criterion is justified because if we accept more wear on the tool then the number of regrinds per tool will decrease which will decrease the overall life of the H.S.S. tool.

2) The effect of cutting speed on tool life under the conditions specified in the case of carbide tools is negligible as can be seen from Fig. 6-11.

3) The effect of feed on the tool life under the conditions specified in the case of H.S.S. tools is negligible (see Fig. 6-11).

4) The total number of impacts rather than the actual cutting time governs tool life.

The tests of Chapter VI are quite reliable when the coolant is used. These tests are repeatable to the extent that it was possible to specify the time after which the rapid wear on the tool will occur (see Fig. 6-6). However, under dry cutting conditions the results are extremely scattered (see Fig. 6-9). Since the tool life obtained while milling without coolant is much lower than that obtained with the coolant in all the cases, further investigation including statistical analysis is not justified.

However, it is the belief of the author that he has been able to identify some of the problems encountered in the end milling of slots in both mild steel and multimet turbine shrouds using H.S.S. and Carbide cutters. The company is now in a position to carry out successfully the machining of the turbine shrouds following the specifications laid down by this work.

Table 6-1 Tests with Carbide Cutters (with coolant)

Test Number	Material and Type of Test	Depth of cut in inches a	feed in inches/tooth s_t	feed in inches/Minute s $s = N x s_t x$ no. of teeth on cutter	Spindle RPM N	Cutting speed in ft/Minute V	Length of cut per insert in inches l	Length of cut per tool in inches L	Tool Life in Minutes T
1	Slotting on Steel	0.25	0.005	2.31	462	302.5	73	438	31.6
2				2.76	552	361.42	90	540	32.6
3			0.007	3.234	462	302.5	70	420	21.645
4				3.864	552	361.42	77	462	19.92
5	Half immersion on Steel	0.25	0.007	3.234	462	302.5	78	468	24.118
6				3.864	552	361.42	80	480	20.7039
7	Slotting on Multimet	0.3	0.002	0.924	462	302.5	34	204	36.8
7a				0.924	462	302.5	16.3	97.8	17.6
8				1.104	552	361.42	12	72	10.87
9			0.003	0.753	251	164.34	3	18	3.4
10				0.945	315	206.25	3	18	3.175
11				1.131	377	246.85	4.7	28.2	4.15
12				1.386	462	302.5	11	66	7.936
13				1.656	552	361.42	12	72	7.25
14			0.005	2.310	462	302.5	5.5	33	2.38

Test Number	Material and Type of Test	Depth of cut in inches a	feed in inches/tooth s_t	feed in inches/Minute s $s = N \times s_t \times$ no. of teeth on cutter	Spindle RPM N	Cutting speed in ft/Minute V	Length of cut per insert in inches l	Length of cut per tool in inches L	Tool Life in Minutes T
15	Slotting on Multimet	0.15	0.002	0.924	462	302.5	9.6	57.6	10.4
16			0.003	1.386	462	302.5	22.7	136.2	16.37
17			0.005	1.885	377	246.85	8	48	4.244
18				2.310	462	302.5	32.17	193.02	13.92
18a				2.310	462	302.5	25.00	150	11.2
19			0.007	3.234	462	302.5	8	48	2.47

Table 6-2 Tests with High Speed Steel Cutters (with coolant)

Test Number	Material and Type of Test	Depth of cut in inches a	Feed in inches/tooth s_t	Feed in inches/minute s $s = N \times s_t \times$ no. of teethoncutter	RPM N	cutting speed in ft/minute V	Length of cut per tool in inches L	Tool Life in Minute T
20	Slotting on Steel	0.3	0.003	9.00	500	196.43	144	16
21			0.005	10.65	355	139.5	104	9.765
22			0.007	10.50	250	98.21	360	34.285
23				14.90	355	139.5	192	12.885
24	Half immer-sion on steel	0.3	0.007	10.50	250	98.21	380	36.19
25	Slotting on Multimet	0.3	0.003	1.62	90	35.357	29	17.9
26				2.25	125	49.107	18	8
27			0.005	2.7	90	35.357	60	22.2
28				3.75	125	49.107	9	2.4
29	Half immer-sion on Multimet	0.3	0.005	2.7	90	35.357	60	22.2

Table 6-3

Test Number	Description	Depth of cut in inches a	Feed in inches/ tooth s_t	Feed in inches/minute s s=Nxsx no. of teeth on cutter	Spindle RPM N	Cutting speed in ft/minute	Length of cut per tooth in inches l	Length of cut per tool in inches L	Tool Li[fe] in Minute[s]
30a	Slotting tests on steel with carbide (without coolant).	0.25	0.005	2.5	500	327.35	30	180	12
30b	DO	DO	DO	DO	DO	DO	12	72	4.8
30c	DO	DO	DO	DO	DO	DO	24	144	9.6
30d	DO	DO	DO	DO	DO	DO	25	150	10
31	Slotting test on Multimet with carbide (without coolant)	0.3	0.002	1.0	500	327.35	15	9.0	1.5
32	Half immersion test on steel with carbide using coolant. Up milling	0.25	0.005	2.5	500	327.35	48	288	19.2
33a	Half immersion test on steel with carbide using coolant. Down milling	DO	DO	DO	DO	DO	62	372	24.8
33b	DO	DO	DO	DO	DO	DO	64	384	25.6
34	Half immersion test on steel with H.S.S. using coolant. Down milling	0.3	0.007	10.5	250	98.21		550	52.3
35	Half immersion test on steel with HSS using coolant. Up milling	DO	DO	DO	DO	DO		370	35.2

CHAPTER VII

SIMULATIVE EXPERIMENTS

7.1 Objective

From the milling experiments of Chapter VI it was observed that the tool life in terms of total time (actual cutting time plus free running time) in the case of full-immersion (slotting) tests as well as half-immersion tests is approximately the same. However, in terms of the total volume of material removed per tool life, full immersion tests gave better results than the partial immersion tests. It should be noted that the total number of impacts in both the cases is the same for the same total cutting time. Therefore, it might be the total number of interruptions or impacts during the total cutting time which governs the tool life.

Also it was observed that the tool life obtained in down-milling was better than that obtained in up-milling under same cutting conditions. It should be noted that in up-milling the tool starts cutting from the initial thin portion of the chip and in down-milling it starts cutting from the initial thick portion of the chip. This leads to the doubt that it might be the initial rubbing or the thin portion of the chip that might be detrimental to tool life.

Also in some cases of milling such as slotting test on multimet with feed per tooth = 0.005 in. and speed = 49.107 ft/minute (test #28), complete destruction of the tool occurred. The cause of failure in those cases was not clearly known. It could be either the temperature failure or rupture of the tool point due to the excessive cutting forces.

Above discussion leads to the following questions:

(1) Which part of the chip obtained during slot milling is more detrimental to the tool life (thin portion or the thick portion)?

(2) Which is the type of failure in those cases in which complete destruction of the tool occurs (temperature failure or the rupture of the tool tip)?

In an attempt to answer these questions, turning experiments simulating the previous milling were carried out during which it was possible to separate the aspects of thin and thick chips from the aspects of interrupted cutting. In milling interrupted cutting is accompanied by the continuous variation in chip thickness and the two cannot be separated whereas in simulative experiments it is possible to keep the chip thickness during interrupted cutting constant.

7.2 Testing Procedure

Experiments were performed on a rigid MAZAK 24 lathe fitted with an infinitely variable speed drive. Fig. 7-1 and 7-2 show the experimental set-up. Two special steel workpieces were prepared for the purpose (see Fig. 7-3). The type of steel was very much similar to the steel used in milling tests. The ratio R of non-cutting time to cutting time in one case was one (conditions similar to slotting tests) whereas in the other case it was two (partial-immersion tests). Following tools were used:

Carbide Cutter: Sankvik SPU-422, S4 (steel grade) inserts (same inserts which were used in milling tests).

H.S.S. Cutter: Ultra Capital plus one tool bits (Balfour Darwins Ltd.) which are very similar to the H.S.S. of Clarkson rippa cutters used in milling tests.

The coolant used was again a solution 20:1 of TRIM SOL. (same as in milling tests).

The average and the maximum flank wear VB_{av} and VB_{max} was measured at various time intervals. In this case also the investigations were carried out with Toolmaker's microscope as well as a scanning electron microscope.

Tool forces were continuously recorded during every test, using the ultraviolet recorder (See Fig. 7-2). The main cutting force F_v, the feed force F_f and the thrust force F_t were obtained by means of a three component strain gauge dynamometer.

Two feeds (in/rev) were used during the tests: one the minimum available feed on the lathe i.e. 0.0022 inches (corresponds to thinner portion of the milling chip) and other, the maximum feed used in milling tests i.e. 0.0069 inches (nearest available to 0.007 inches) which corresponds to the central thick portion of the chip in slotting tests.

Tables 7-1 and 7-2 give the data of the tests performed.

7.3 Description of Results

Carbide Cutters:

Figs. 7-4 and 7-5 show the plots of VB_{max} and VB_{av} versus time in the case of carbide tools. The effect of feed on tool life can be clearly seen from these plots. Tool life increases as the feed is decreased. Same effect of feed was observed in the milling experiments with carbide tools (see Fig. 6-11). Since small feed gives better tool life, it can be concluded that the thin chip at the entry and exit of slotting tests is not as detrimental to the tool life as the thick portion of the chip. It can also be seen from Figs. 7-4 and 7-5 that at lower feed rate the tool life in both the cases i.e. R=1 and R=2 is the same, in terms of total time (free running time plus actual cutting time). (R is the ratio of free-running time to actual cutting time). At higher feed rate we tend to get better tool life in terms of total time when R=1 but the difference is not appreciable (Fig. 7-8). In terms of the total volume of metal removed per tool life, R=1 gives better results than R=2. Since the thin portion of the chip is not detrimental to the tool life it can be said that it is total number of impacts rather than actual cutting time which governs the tool life.

Comparison of wear pattern of simulative turning test numbers 1 and 3(b) with milling test numbers 4 and 6 respectively shows that the general pattern of tool wear, in these cases is the same as can be seen from the photographs of the flank wear in respective cases (compare photographs in Fig. 6-17 and 6-19 with those in Figs. 7-16 and 7-17 respectively).

High Speed Steel Cutter:

Figs. 7-16 to 7-23 show the typical electronmicrographs of the flank and crater wear on carbide tools under different cutting conditions at various magnifications. No thermal cracks are seen.

Figs. 7-6 and 7-7 show the plots of VB_{max} and VB_{av} versus time in the case of H.S.S. cutter. It can be seen that as the feed is decreased from 0.0069 in/rev to 0.0022 in/rev, the tool life increases from 105 minutes to 300 minutes in slotting tests (R=1). Same is true for R=2 also in which case tool life increases from 180 minutes to 360 minutes as the feed is reduced from 0.0069 in/rev to 0.0022 in/rev. This again shows that the thin portion of the chip in slot milling is not detrimental to the tool life.

In the case of H.S.S. cutters we find that in terms of the total time, R=2 gives better tool life than that in the case of R=1 (R is the ratio of noncutting time to the actual cutting time) but tool life for R=1 is more than that for R=2 in terms of the total volume of the material removed. The same trend was observed in the case of carbide tools also.

Figs. 7-24 and 7-25 show the photographs of the flank wear.

Typical ultraviolet (UV) records of the three components of the cutting forces are shown in Figs. 7-11 to 7-15. In Figs. 7-9 and 7-10, the main cutting force F_v, the feed force F_f and the thrust force Ft (due to the nose radius of the tool) for carbide and H.S.S. cutters respectively, are plotted against time. It can be seen that increase in the cutting forces with time is not much. Fluctuations in the components of cutting force in the case of H.S.S. tools are because of the formation and disappearance of the built-up-edge.

Since there is no drastic increase in cutting forces with time, the possibility of rupture of the tool point because of the excessive cutting forces is ruled out and in those cases in which complete destruction of the tool occurred, the temperature failure of the tool took place.

7.4 Conclusions

From the foregoing discussion it can be concluded that:

1. The thin portion of the chip obtained at the entry and exit of end milling cutter affects tool life much less than the thick portion of the chip.

2. In terms of total volume of the material removed, longer tool life is obtained in full-immersion (slotting) than in partial-immersion milling.

However, even these tests did not explain why it was rather the total number of cut interruptions than the actual cutting time which influenced tool life. Further research will be necessary in looking into both the mechanical and thermal shock aspects.

3. Complete destruction of the tool in some of the tests like test #28, Chapter V (cutting multimet with H.S.S. tool with a speed of 49.1 ft/min. and a feed of 0.005 inches/tooth) was due to the high temperature development in the cut and consequent fast development of the tool wear leading to a further increase in temperature and

ultimately to the melting of the tool.

The simulative experiments were performed because we hoped that these tests might explain some of the unusual phenomena which occurred during milling tests. However, the author does not feel that he has been really able to give a satisfactory explanation for those unusual findings. Further research looking into both the mechanical and thermal shock aspects might explain these unusual facts. This would involve further cutting tests and a comprehensive metallurgical studies aimed at identifying the interaction of the workpiece and tool materials under a set of given cutting conditions. Any metal cutting operation involves a complicated interplay of temperature, strain rate, heat transfer, interactions of tool and workpiece material, perhaps involving chemical interaction between dissimilar materials in the presence of different lubricants.

In short it is a very difficult problem which is not readily amenable to analysis. However, it is only by fundamental studies, as mentioned above, that some light might be thrown on this operation.

Table 7-1. Simulative Tests With Carbide Cutters

Test Number	Ratio R R=Noncutting time / Cutting time	Depth of cut in inches (a)	Feed in in/rev (s)	Cutting speed in ft/min (V)	Tool life in minutes (T)
1	1	0.15	0.0069	361.42	17
2	1	0.15	0.0022	361.42	25
3 (a)	2	0.15	0.0069	361.42	1
3 (b)	2	0.15	0.0069	361.42	10
3 (c)	2	0.15	0.0069	361.42	10
4	2	0.15	0.0022	361.42	25

Table 7-2. Simulative Tests With H.S.S. Cutters

Test Number	Ratio R R=Noncutting time / Cutting time	Depth of cut in inches (a)	Feed in in/rev (s)	Cutting speed in ft/min (V)	Tool life in minutes (T)
5	1	0.15	0.0069	98.21	105
6	1	0.15	0.0022	98.21	300
7	2	0.15	0.0069	98.21	180
8	2	0.15	0.0022	98.21	360

CHAPTER VIII

CONCLUSIONS

A local industrial firm experienced difficulties in manufacturing slots in turbine shrouds made of mild steel and multimet. As a result, milling experiments were carried out using carbide and H.S.S. cutters on the above-mentioned materials and optimum cutting conditions were determined. Simulative turning experiments were also performed in order to explain some unusual phenomena observed during milling experiments. As a result of these investigations the following can be concluded:

1. While milling slots in mild steel and multimet using carbide and H.S.S. cutters it is necessary to use coolant in order to obtain a better tool life. The use of coolant helps in the disposal of the chips which otherwise causes serious problems.
2. With a short duration of actual cutting time the sub-layer of a carbide cutting tool is not heated up and less tensile stresses are formed during the free running time. Therefore, no thermal cracks are formed if the cutting speed is high.

3. The end milling experiments indicate that VB_{max} = 0.030 in. can be used as a tool life criterion while end milling mild steel and multimet with carbide and H.S.S. cutters. This is the most commonly used tool life criterion.

4. For the same volume of the material removed, longer tool life is obtained in full-immersion (slotting) than in partial-immersion milling. This is because the tool life is governed by the total number of impacts on the tool during the total cutting time rather than the actual cutting time.

5. Turning experiments simulating milling show that the thin portion of the chip obtained at the entry and exit of end milling cutter affects the tool life much less than the thick portion of the chip.

6. Better tool life of carbide cutters while using coolant and dependence of tool life on the total number of impacts rather than the actual cutting time are some of the unusual facts found out as a result of these investigations. In order to explain these facts, further research in the area of end milling narrow slots looking into the mechanical and thermal shock aspects is recommended.

F I G U R E S

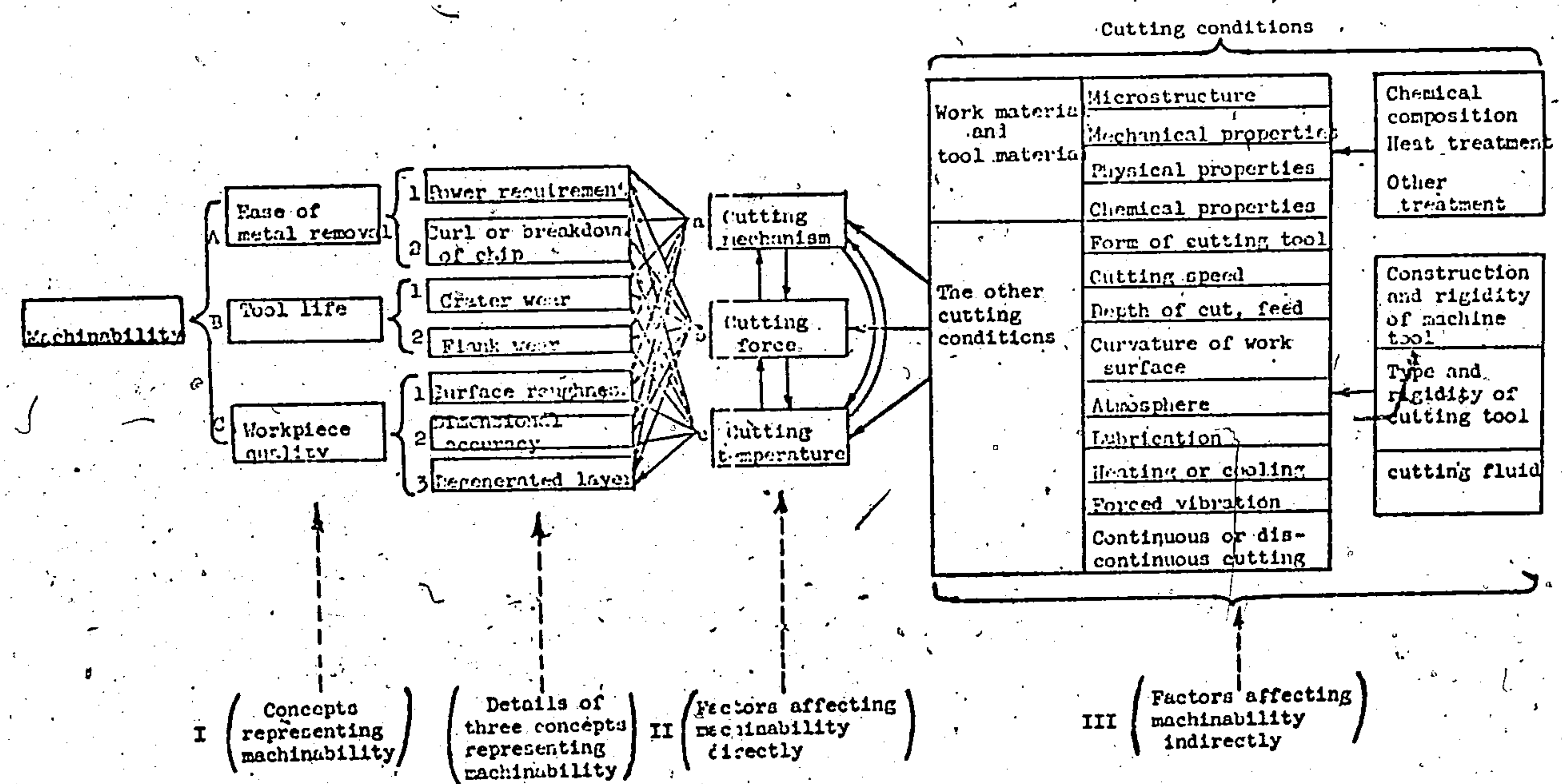


Fig.1-1 A schema showing various concepts and factors representing or affecting the machinability

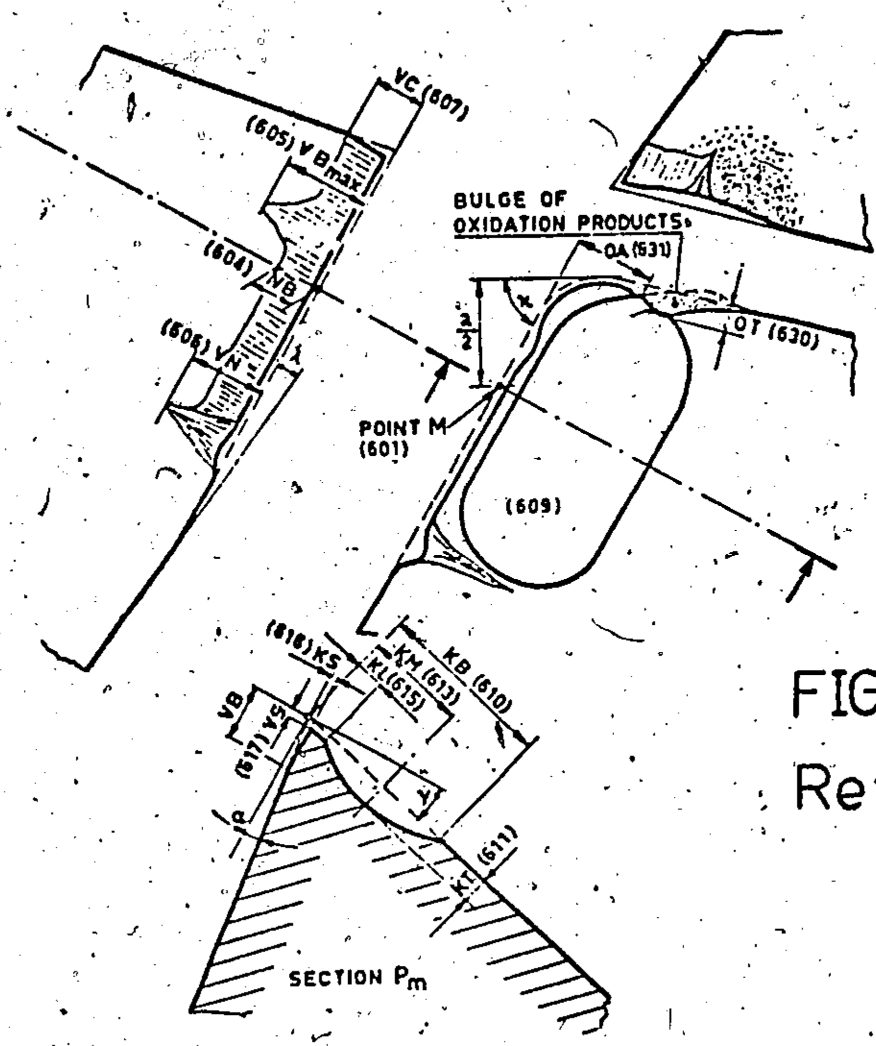
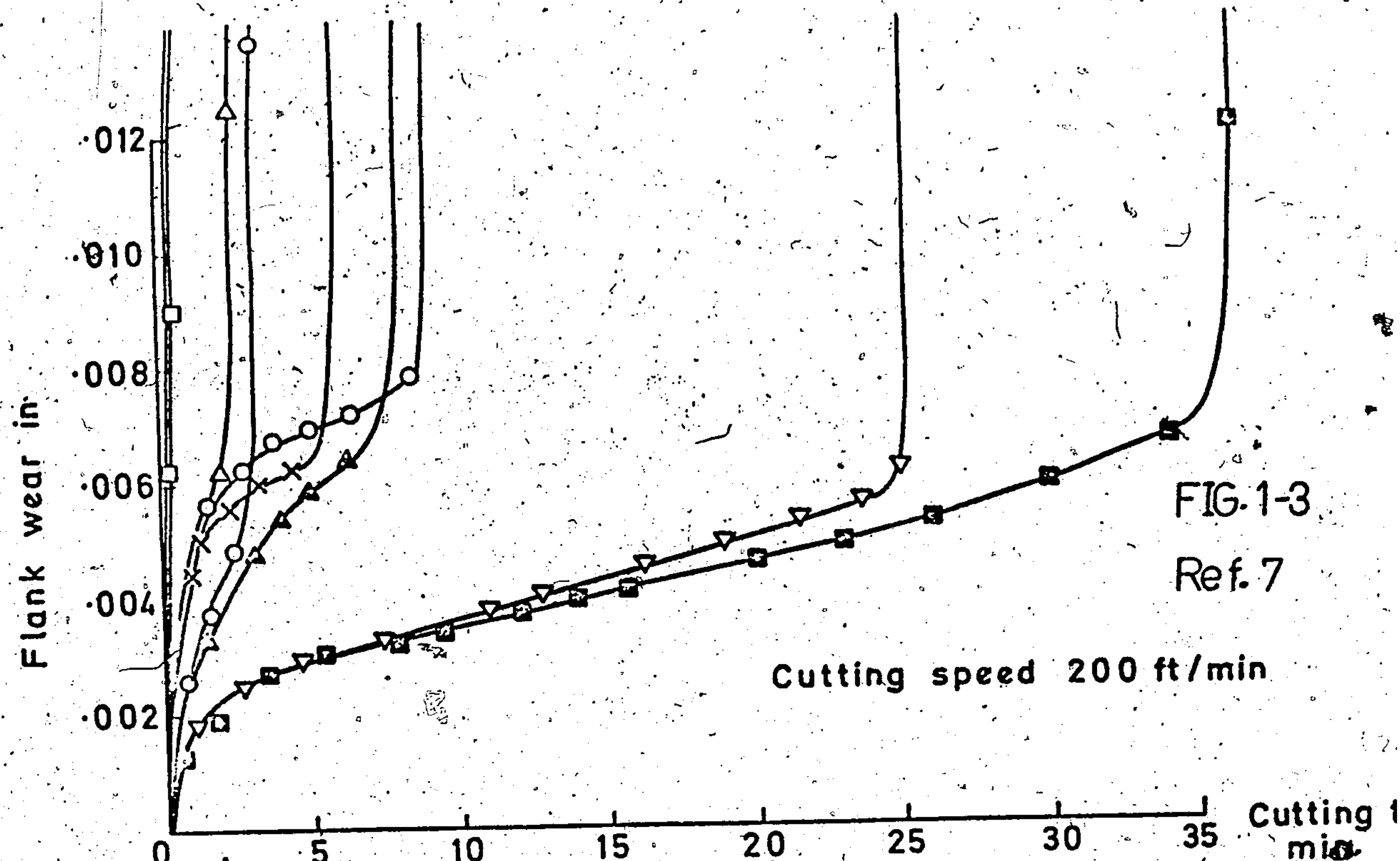
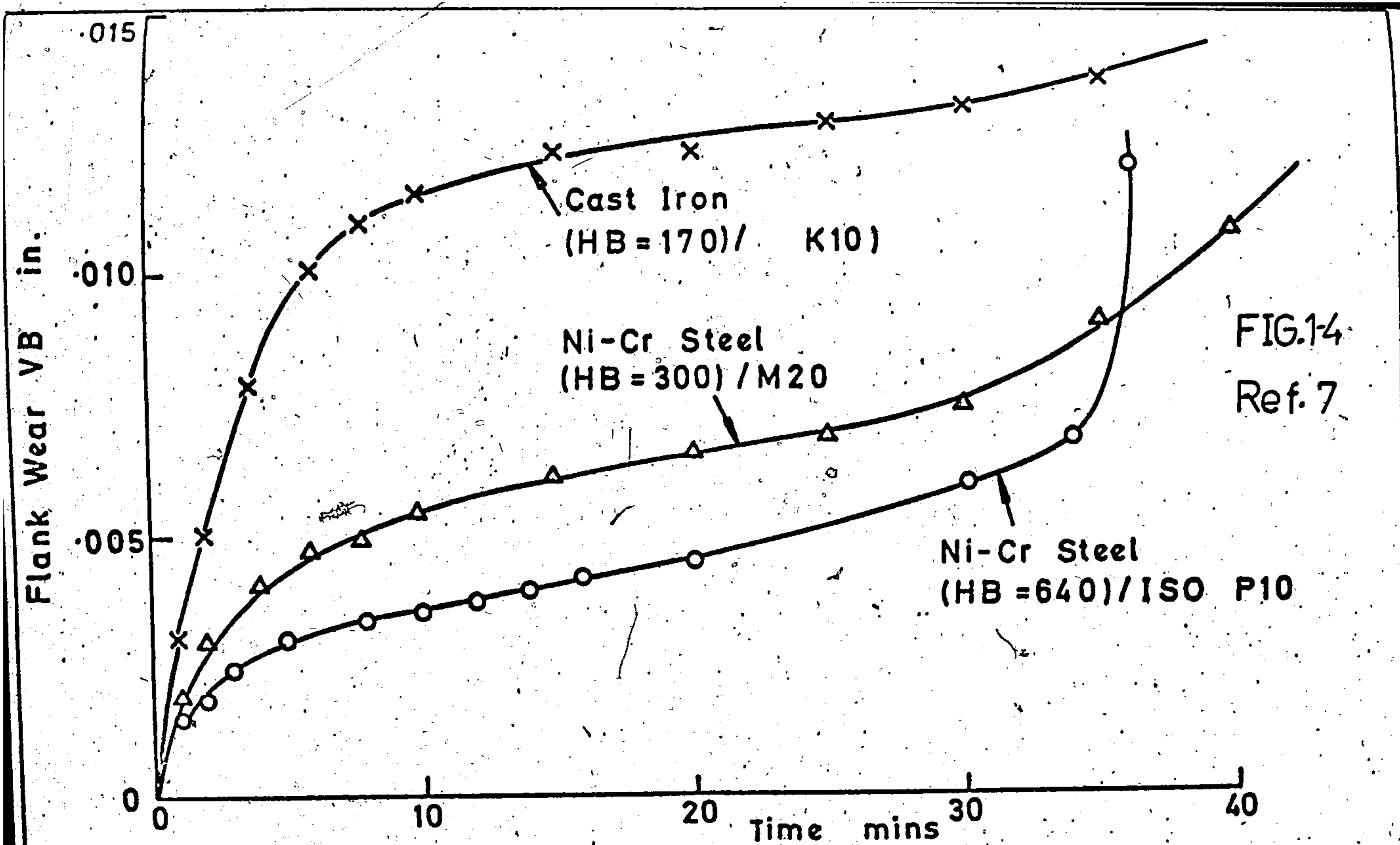


FIG. 1-2
Ref. 10

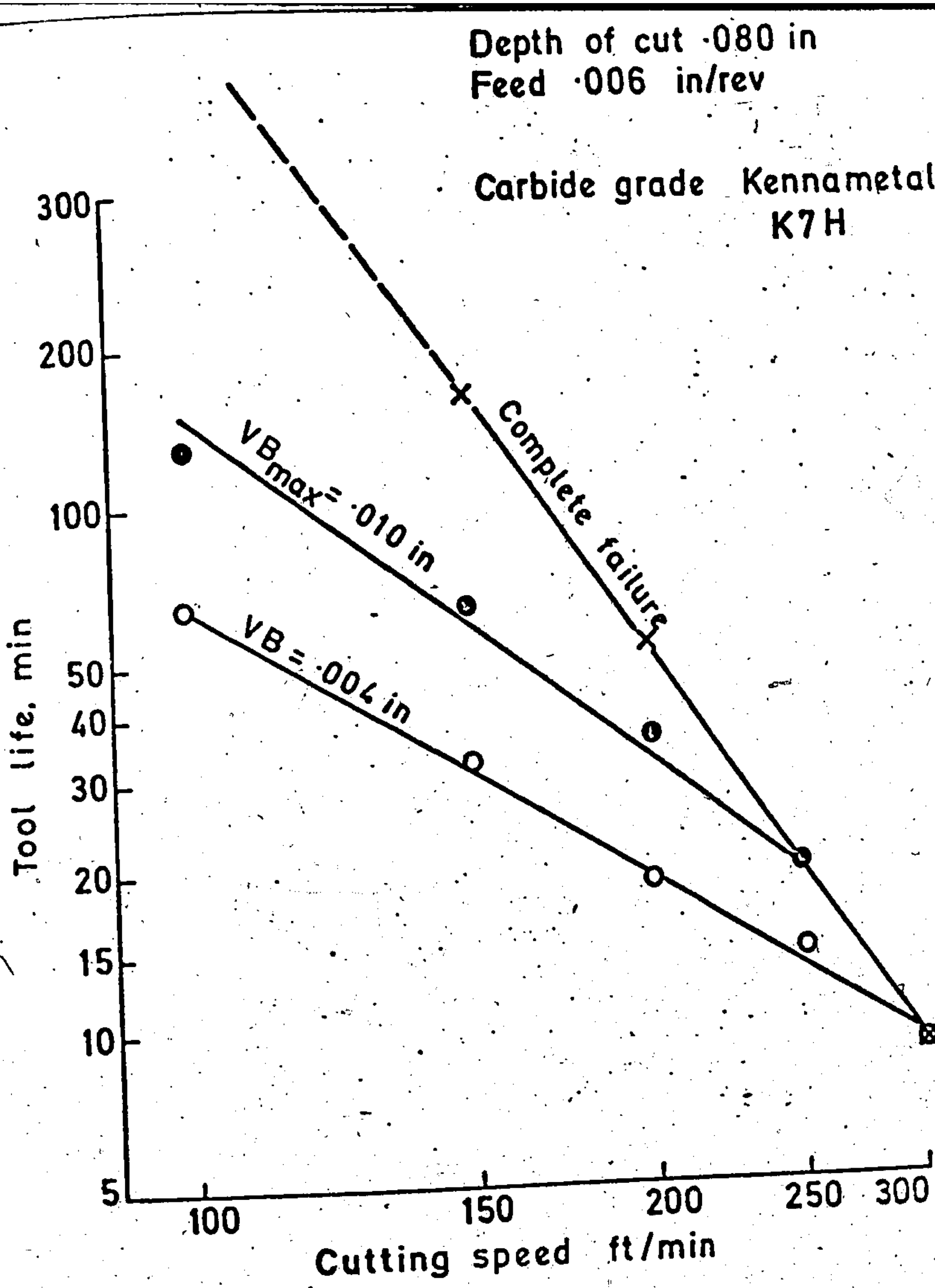
WEAR OF ROUGH TURNING TOOLS



Flank Wear Curves for Carbide Grade K5H Cutting En 26z of Hardness 639 - 648 DPN

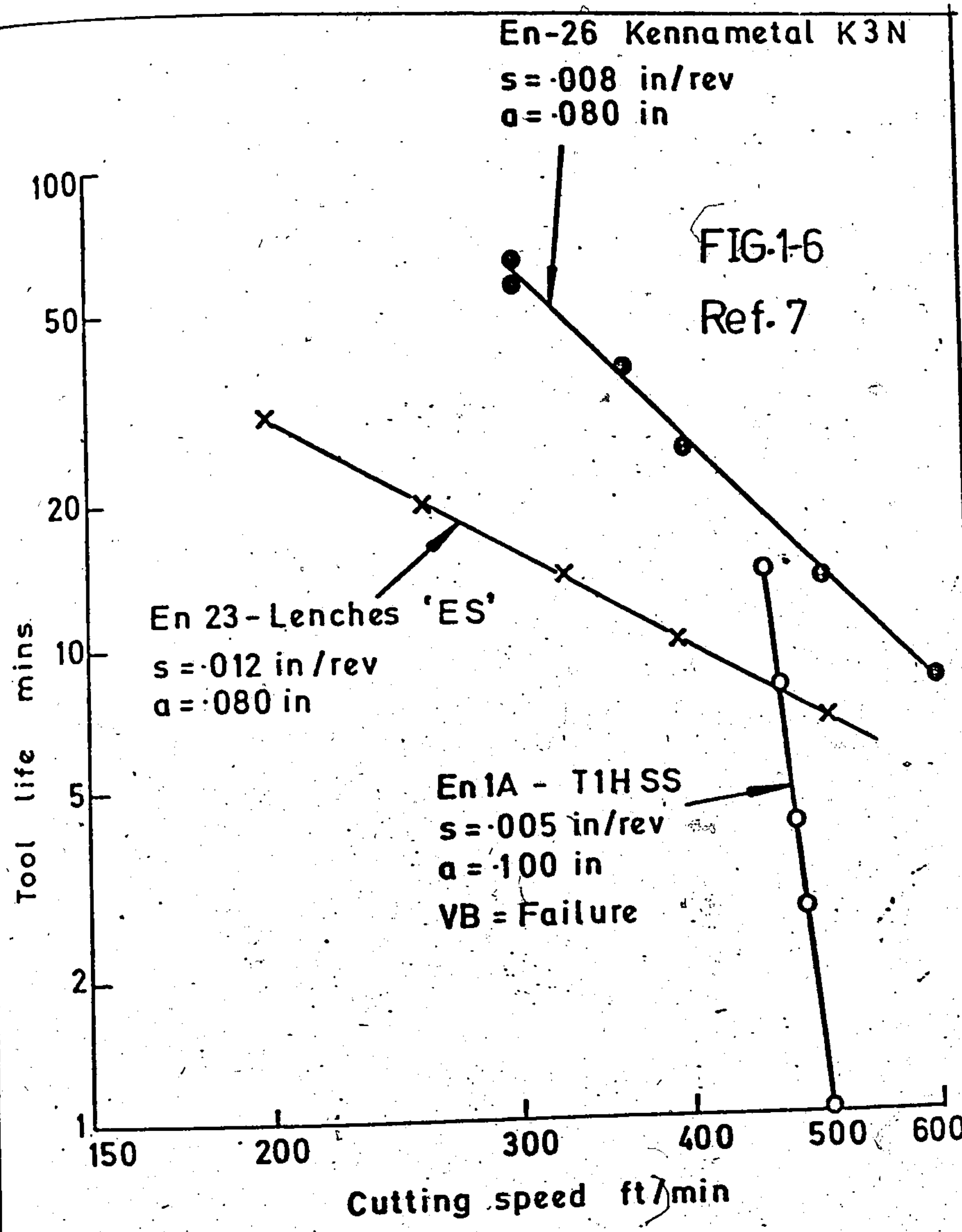


Specimen Flank Wear - Time Characteristics

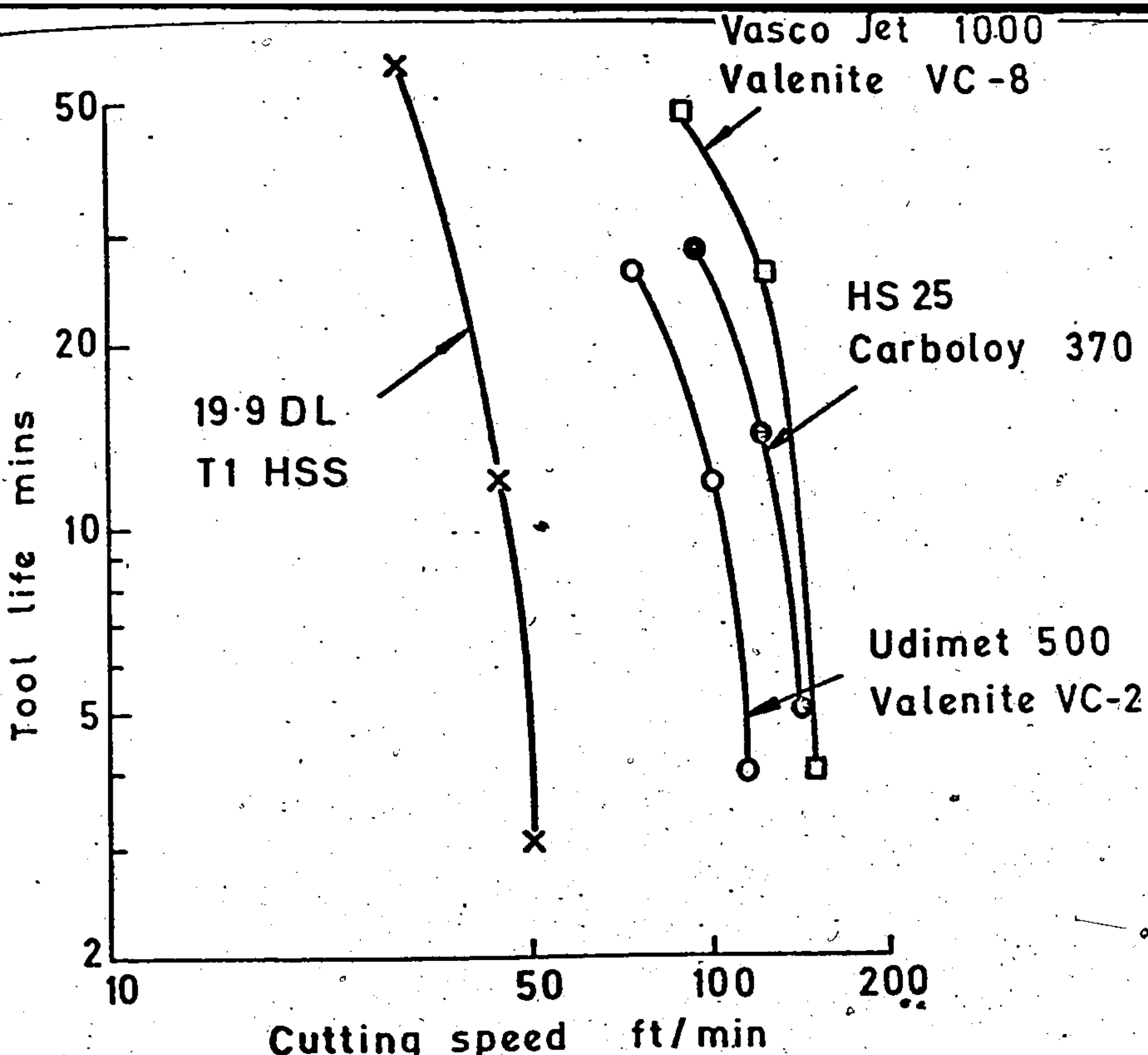


Comparison of Tool Life Criteria for RS 141 Steel
(U.T.S. 115 ton/in^2 BHN 470)

FIG 1-5 Ref-11



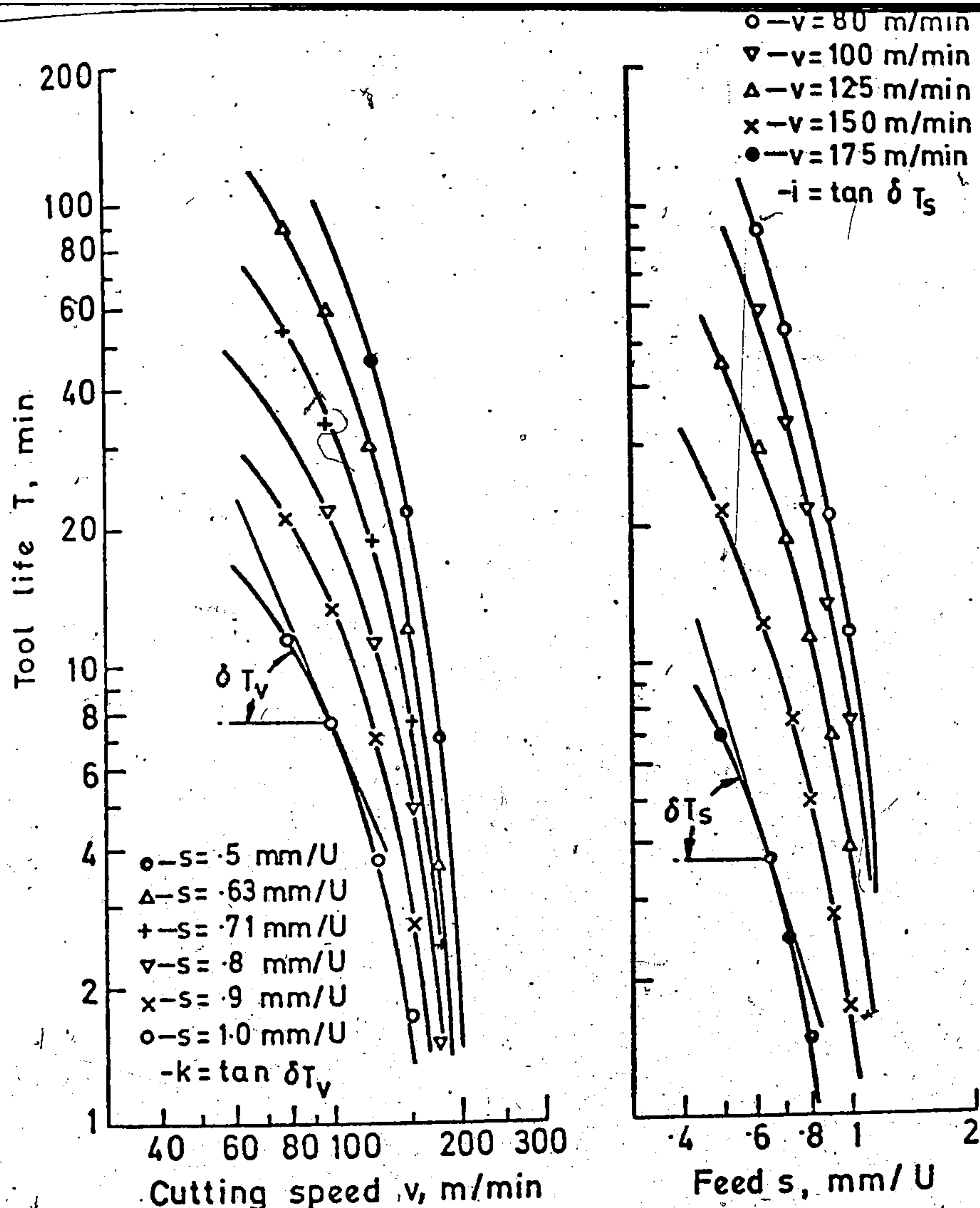
Tool Life Curves for Various Tool & Workpiece Combinations



Vasco Jet 1000 (Hot Work Die Steel) s = ·009 in/rev, a = ·100 in
19·9 DL (Austenitic Stainless Steel) s = ·009 in/rev, a = ·002 in
Udimet 500 (Nickel Base Alloy) s = ·009 in/rev, a = ·100 in
HS 25 (Cobalt Base Alloy) s = ·009 in/rev, a = ·100 in
Tool Life Criteria, Carbide VB = ·015, HSS VB = ·060

Tool Life Curves for Thermal Resistant Materials

FIG 1-7 Ref-12



Workpiece material: Cm 55 N

Tool material: Carbide P 15

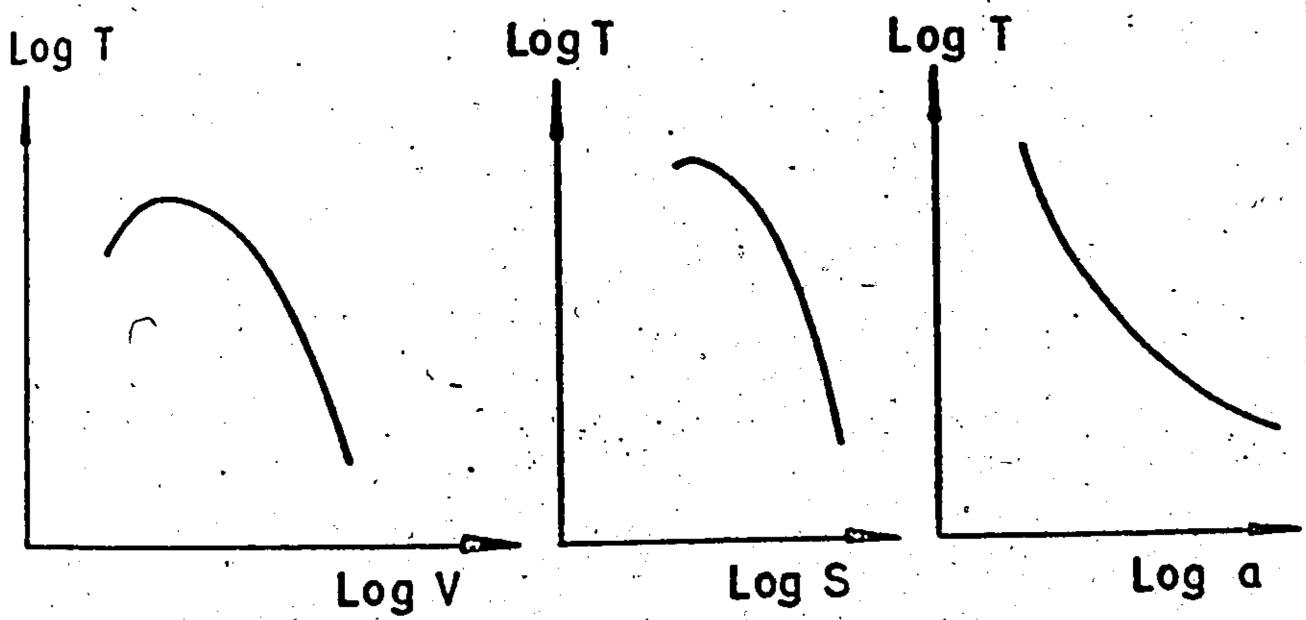
Depth of cut: a = 3 mm

Tool geometry:

α	γ	λ	ϰ	ξ	r
6°	-6°	-6°	70°	90°	1·2 mm

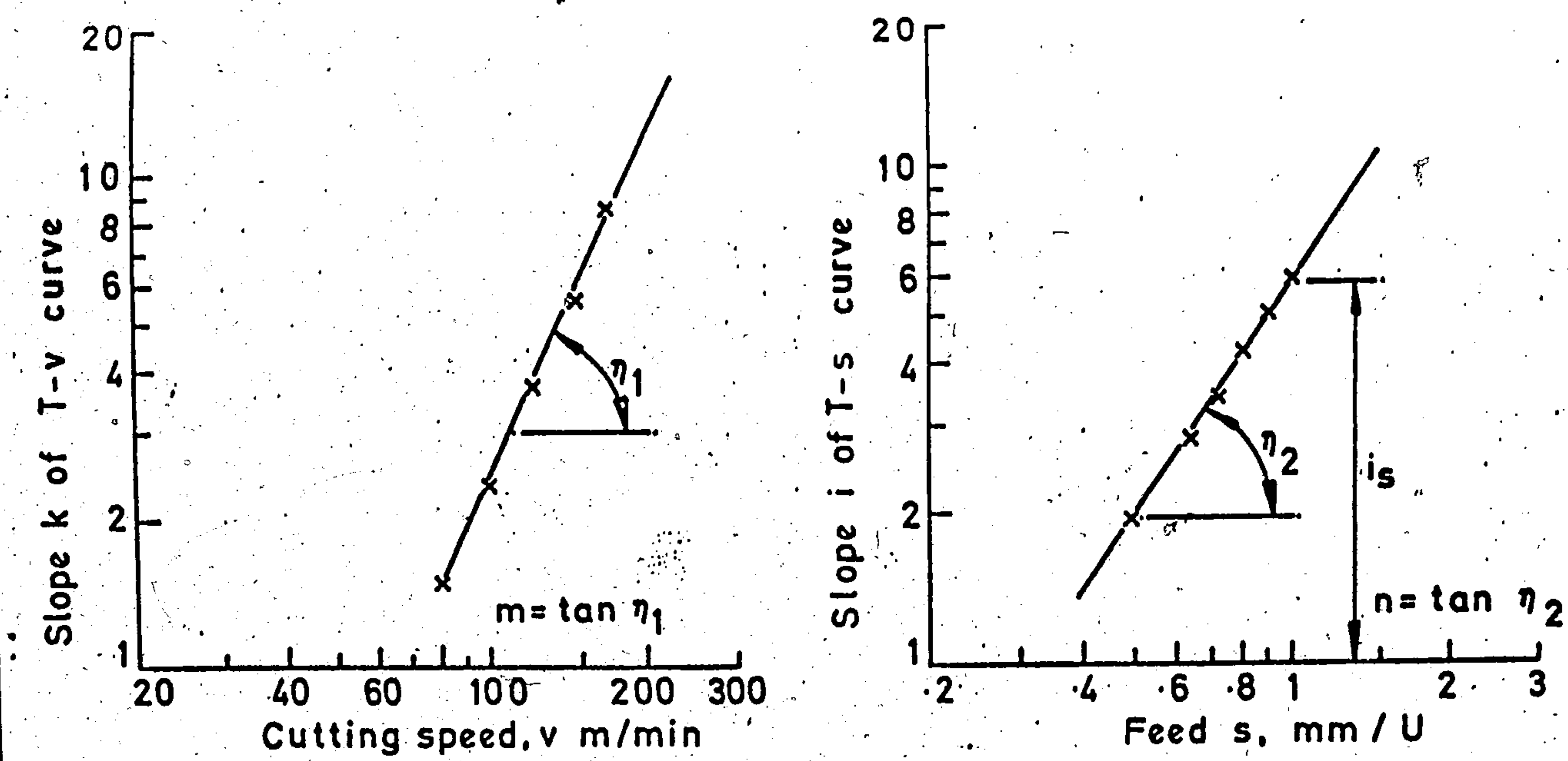
Typical Tool Life Curves with Varying Slopes

FIG-18 (ref. 13)



General Trend of Tool Life with Speed, Feed and Depth of Cut

FIG 1-9 Ref. 7



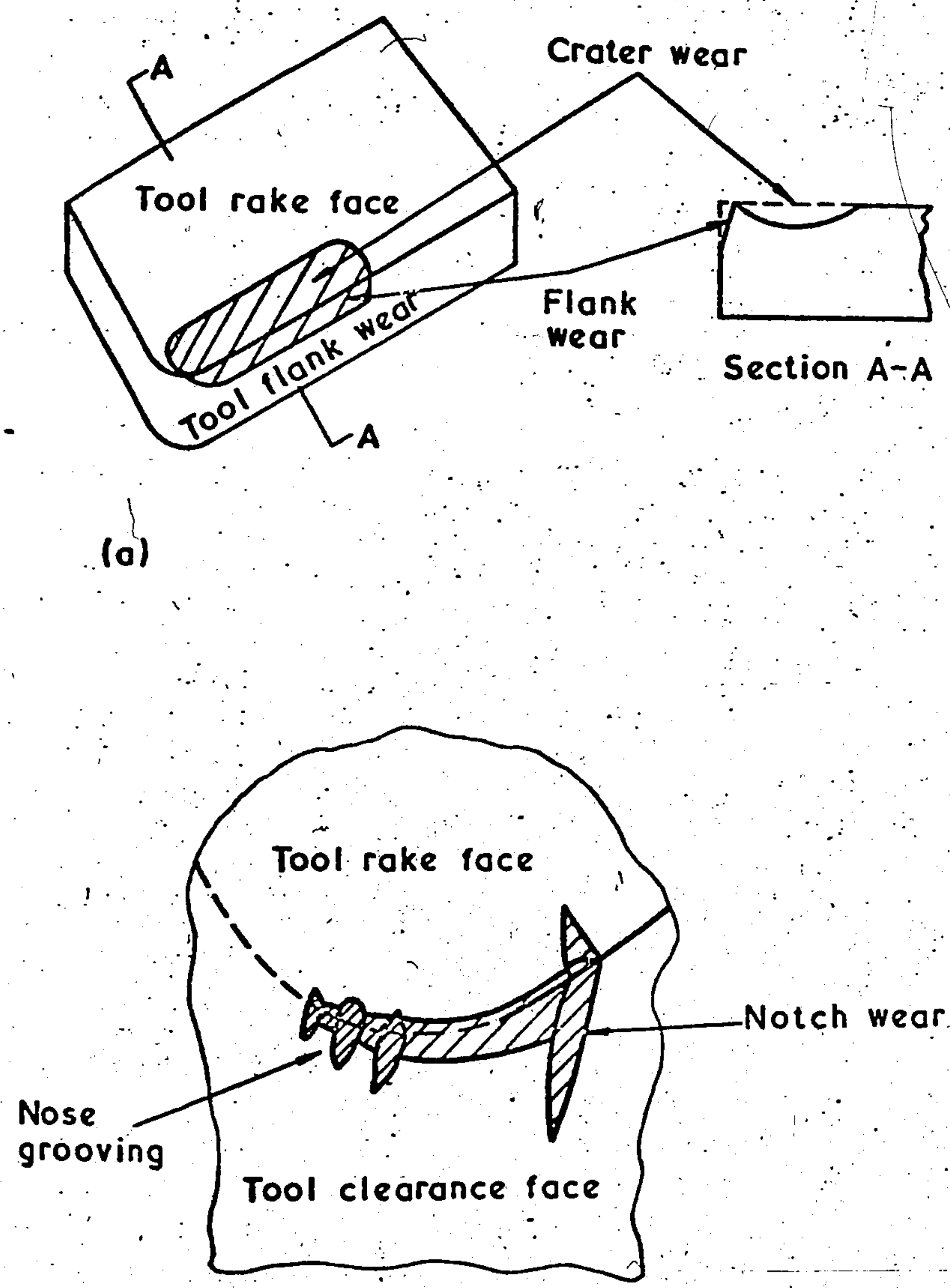
Workpiece material Cm 55N
Tool material: Carbide P15
Depth of cut : a = 3 mm

Tool geometry

a	γ	λ	ϰ	ε	r
6°	6°	6°	70°	90°	1·2 mm

FIG.1-10 Ref.7

Graph Showing Variations in the Slope of the T-v & T-s Curves



(b) FIG-2-1 Ref-24

GENERAL CONFIGURATION OF TOOL WEAR

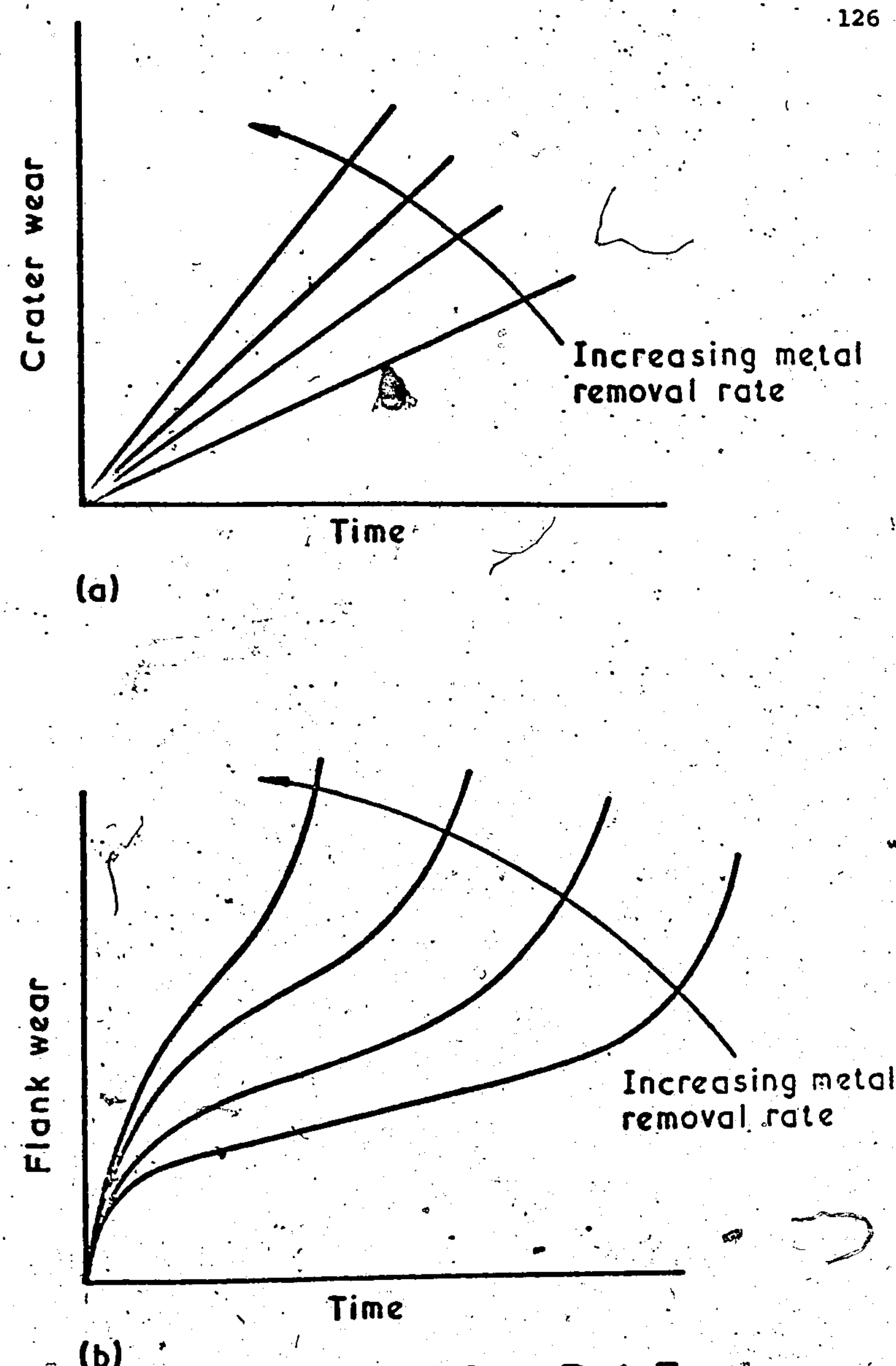


FIG-2-2 Ref. 7

SCHEMATIC REPRESENTATION OF CRATER AND FLANK WEAR PROGRESION

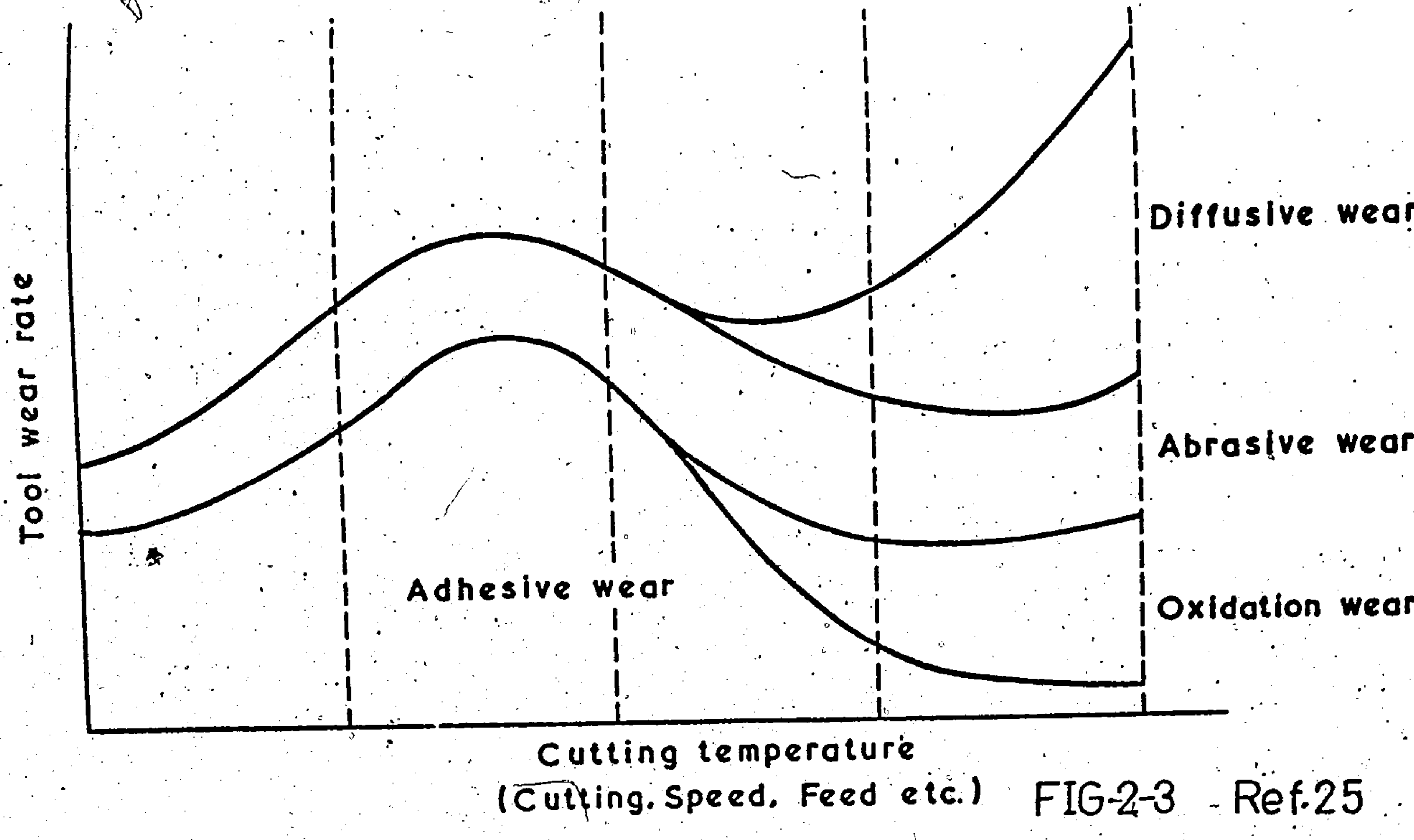
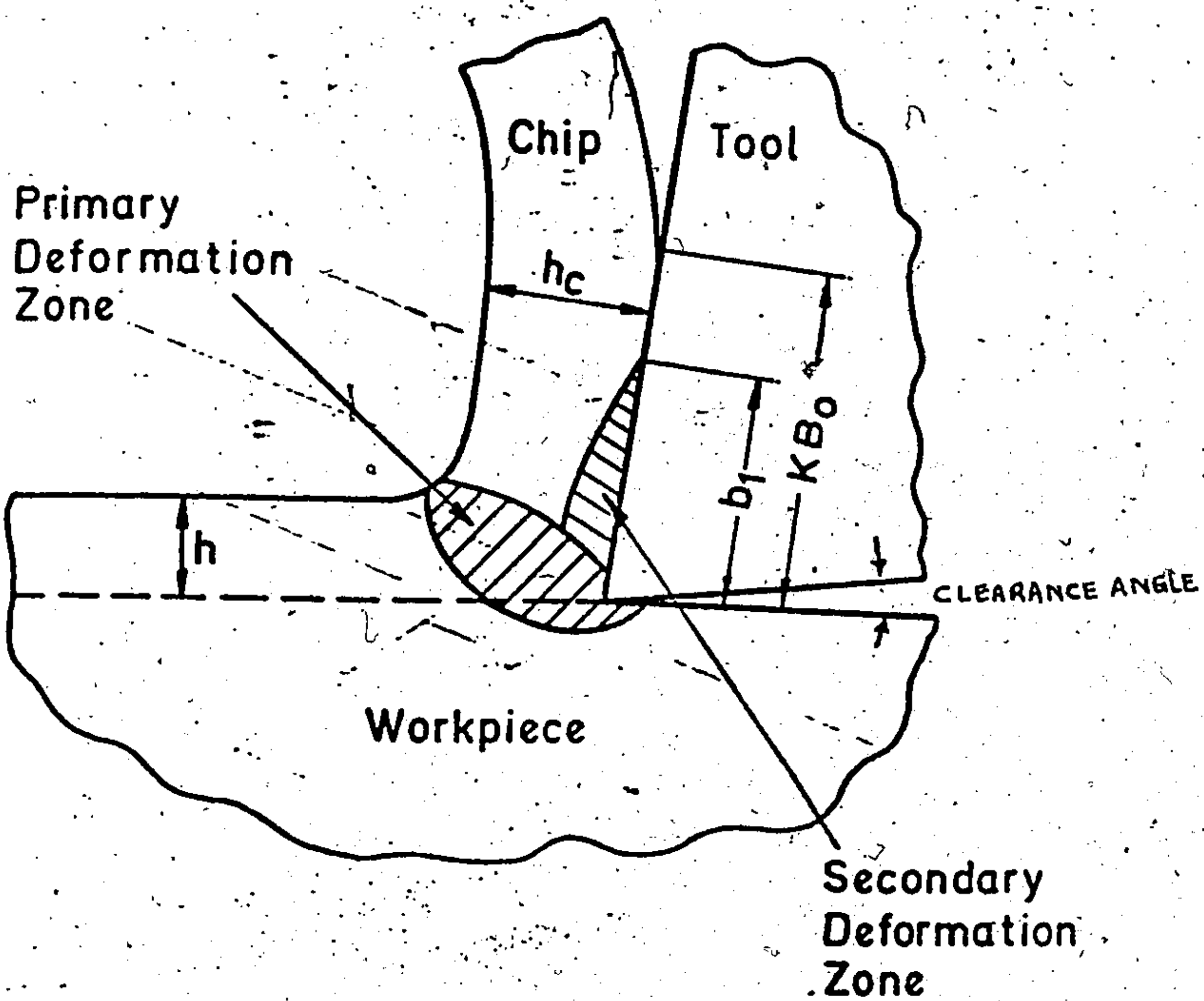


FIG-2-3 - Ref-25

CONTRIBUTIONS OF THE TOOL WEAR MECHANISM



KB_o Contact length between chip and tool

b_1 "Sticking" length

h Undeformed chip thickness

h_c Deformed chip thickness

FIG.2-4 Ref. 7

Deformation Zones In Orthogonal Cutting

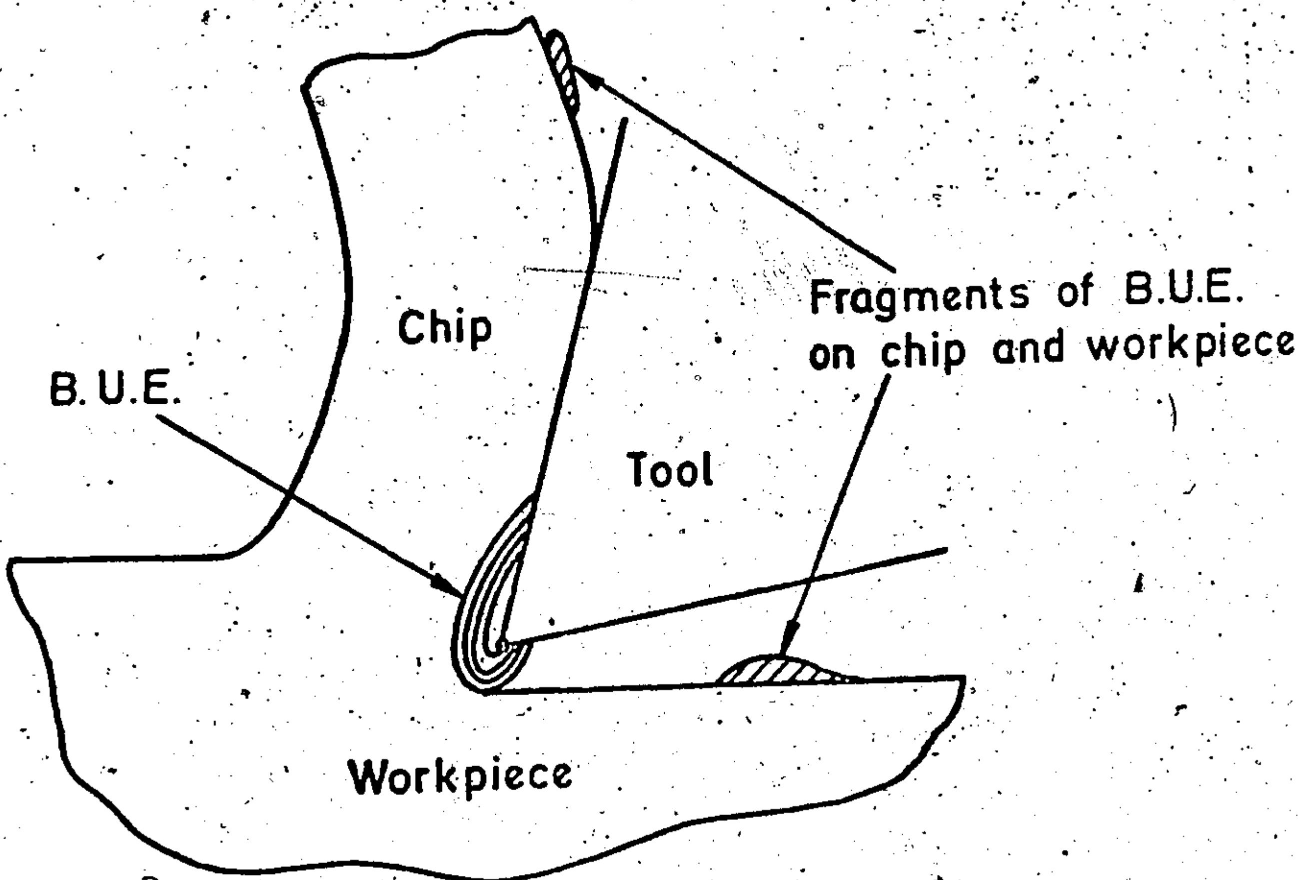


FIG-2-5 Ref-7

Idealized Picture Of Built Up Edge
Formation

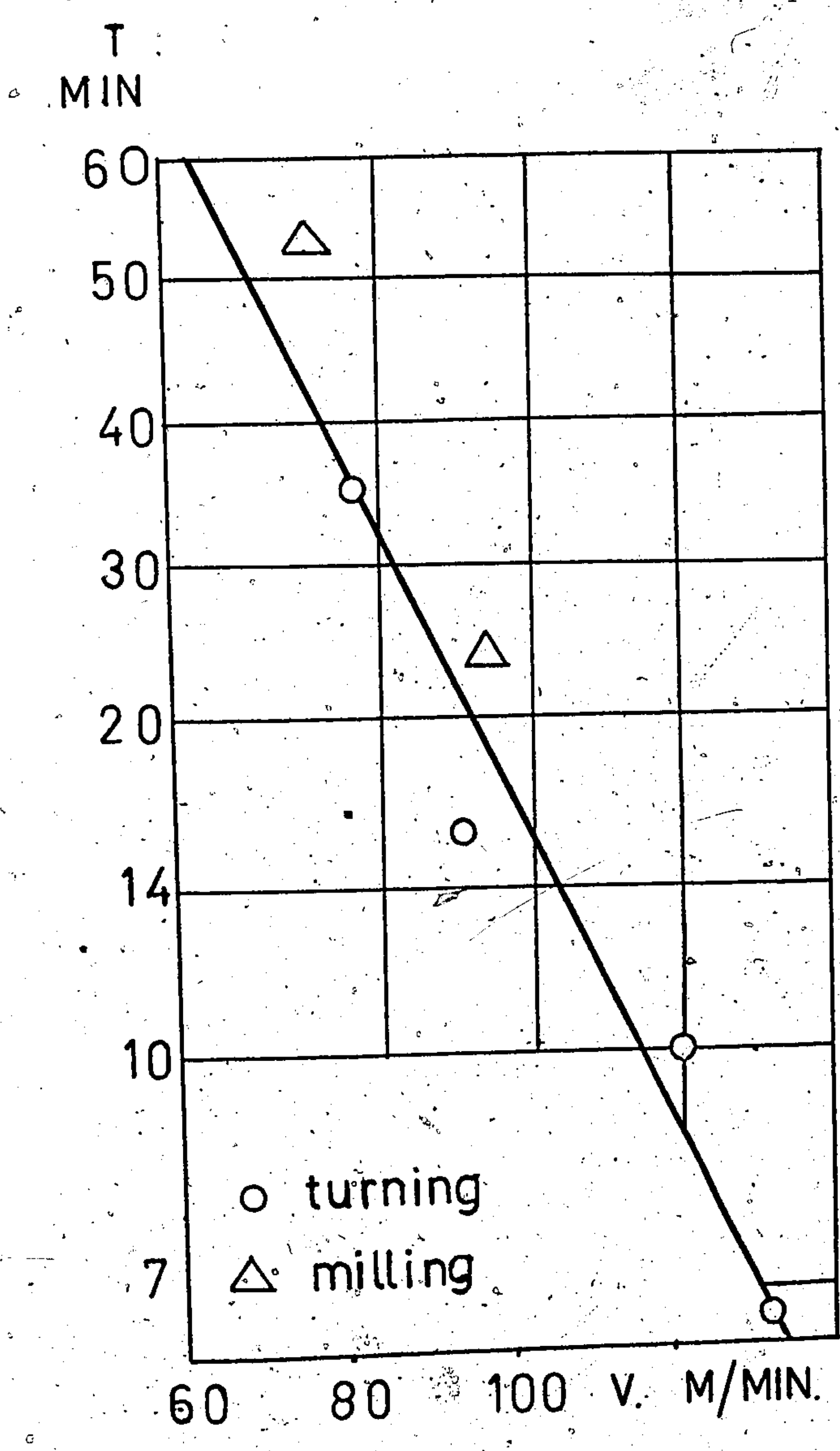


Fig 4·1 Ref 28.

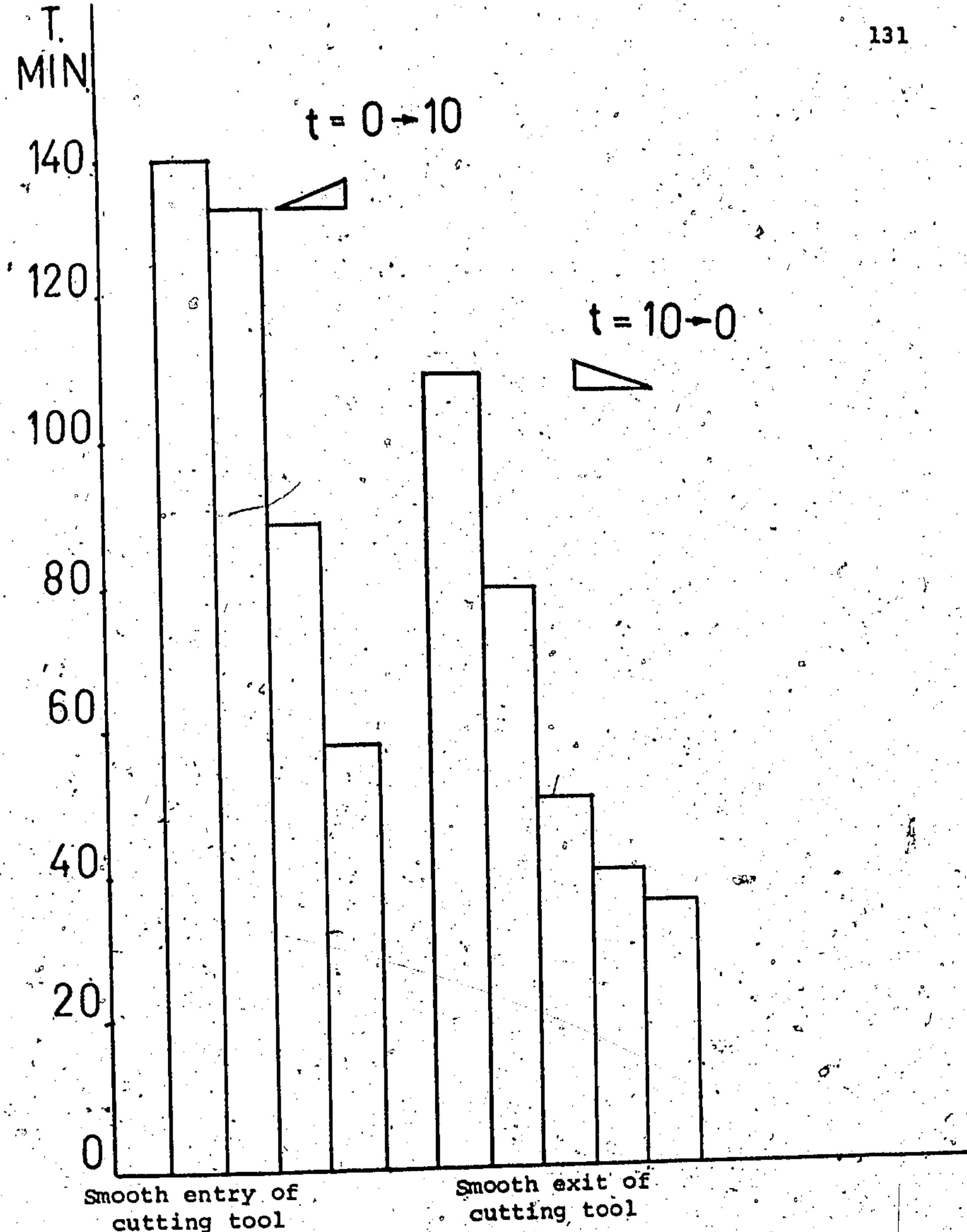

T.
MIN
140
120
100
80
60
40
20
0
t = 0 → 10
t = 10 → 0
Smooth entry of cutting tool
Smooth exit of cutting tool

Fig. 4.2 Ref. 2 8.

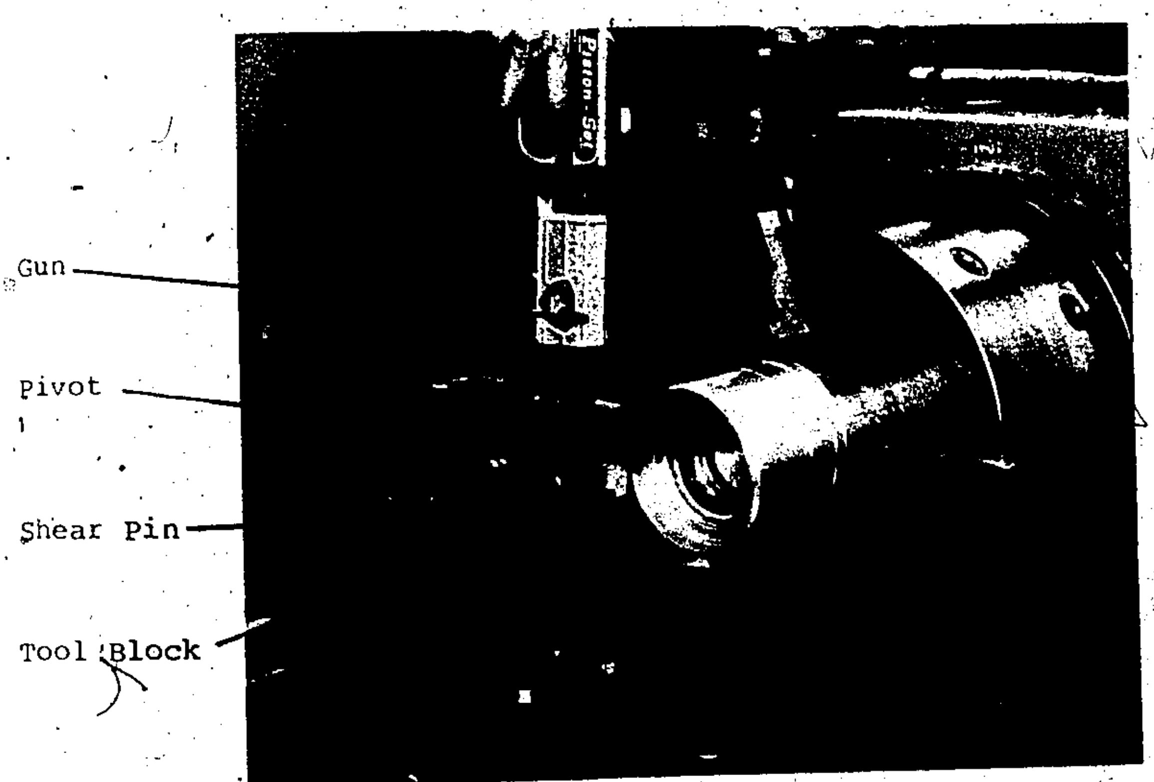


Fig. 5-1. General View of Quick-Stop Device

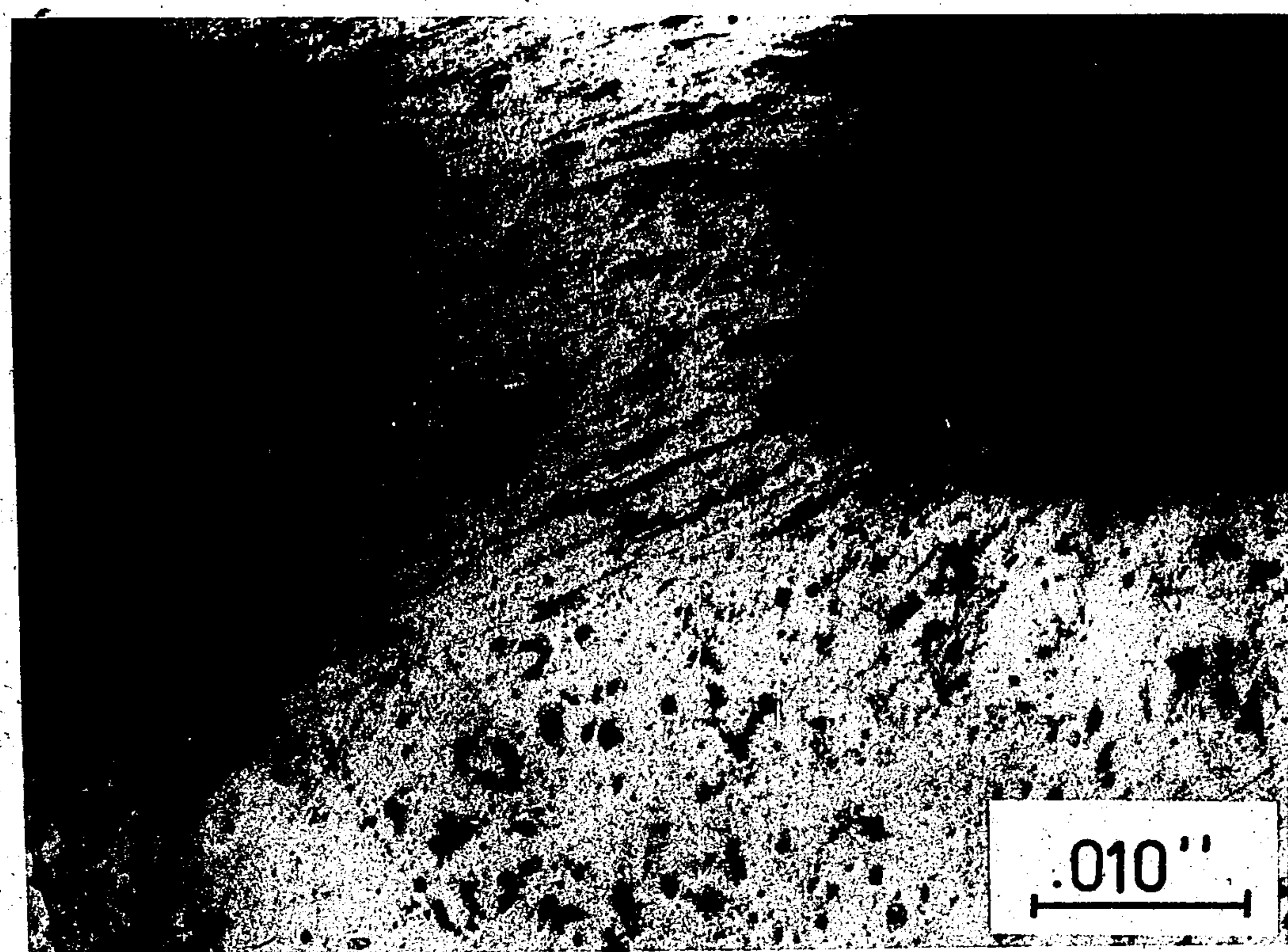


Fig. 5-2. Photomicrograph of the Formation of a Continuous Chip Obtained by Using Quick-Stop Device

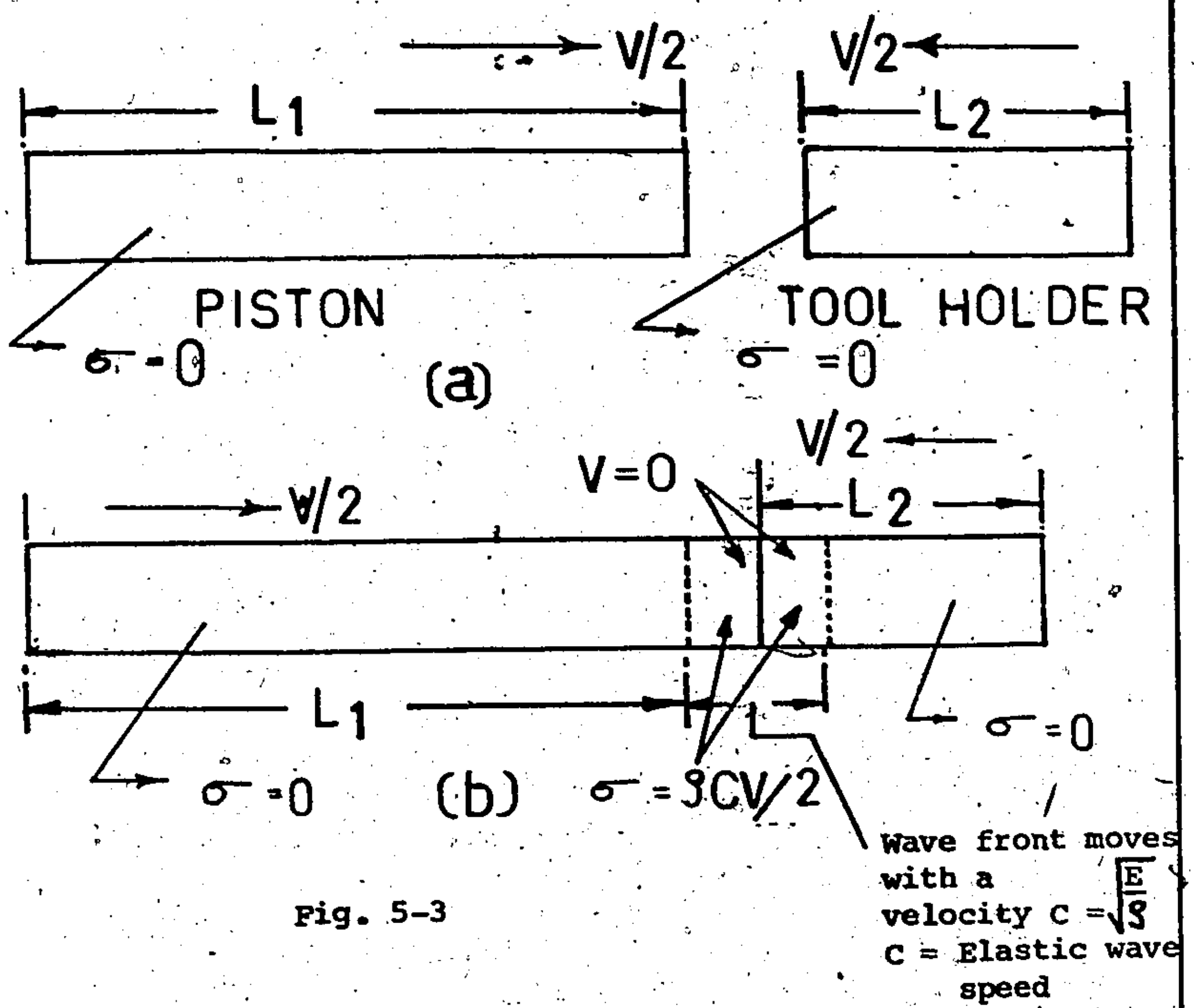

V/2
V/2
L1
L2
PISTON
TOOL HOLDER
σ =0
σ =0
(a)
V/2
V=0
V/2
L2
L1
σ =0
σ =0
(b)
σ = ρCV/2
Wave front moves with a velocity C = √(E/ρ)
C = Elastic wave speed

Fig. 5-3

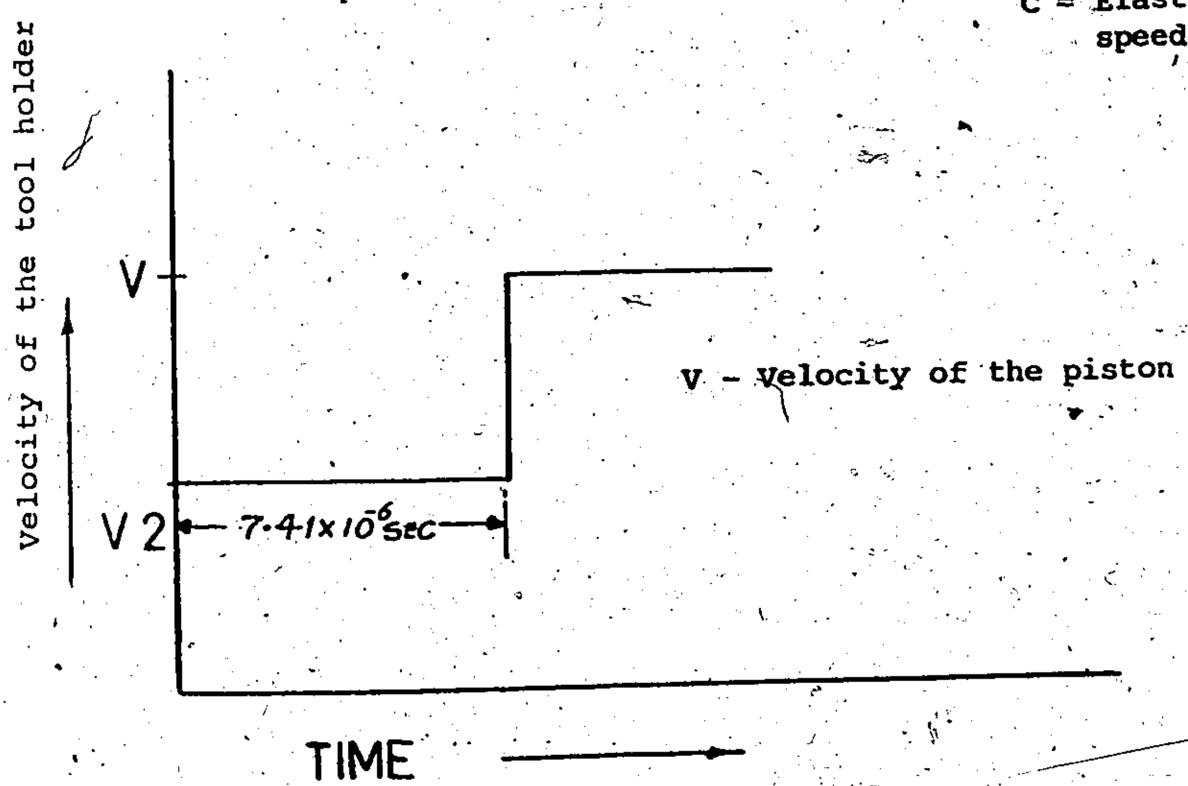

Velocity of the tool holder
V
V 2
7·41×10⁻⁶ sec
V - Velocity of the piston
TIME

Fig. 5-4

Fig. 6-1. Experimental Set-Up for Milling Tests

Fig. 6-3. Measurement of Flank Wear on a Milling Cutter Mounted on the Machine.

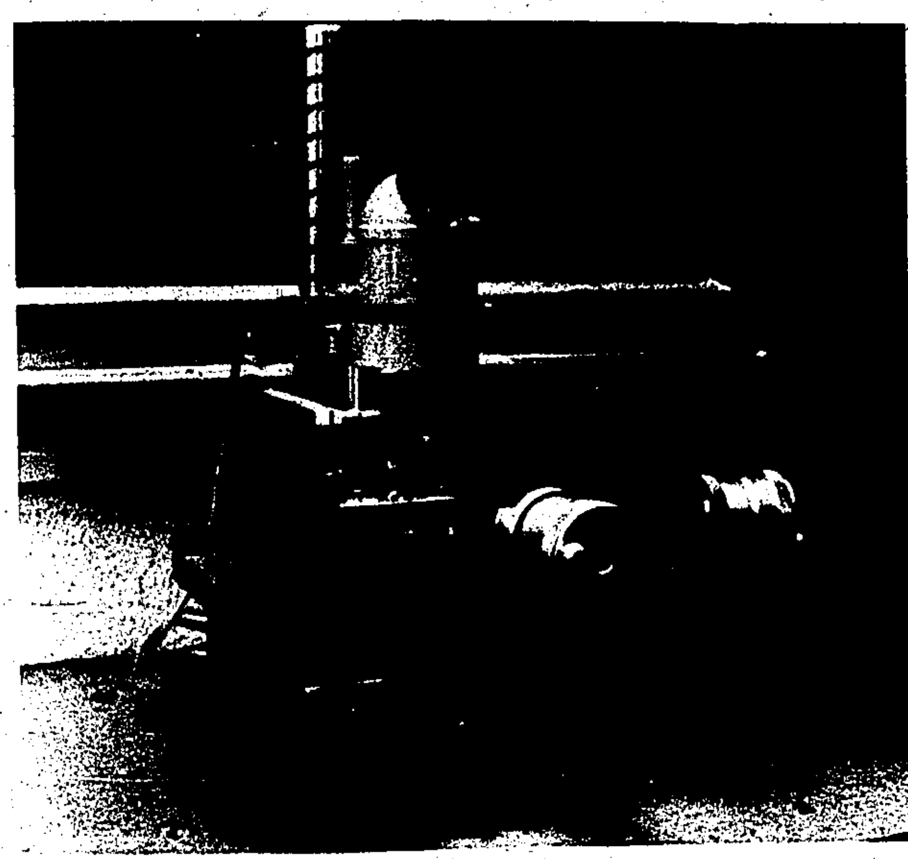
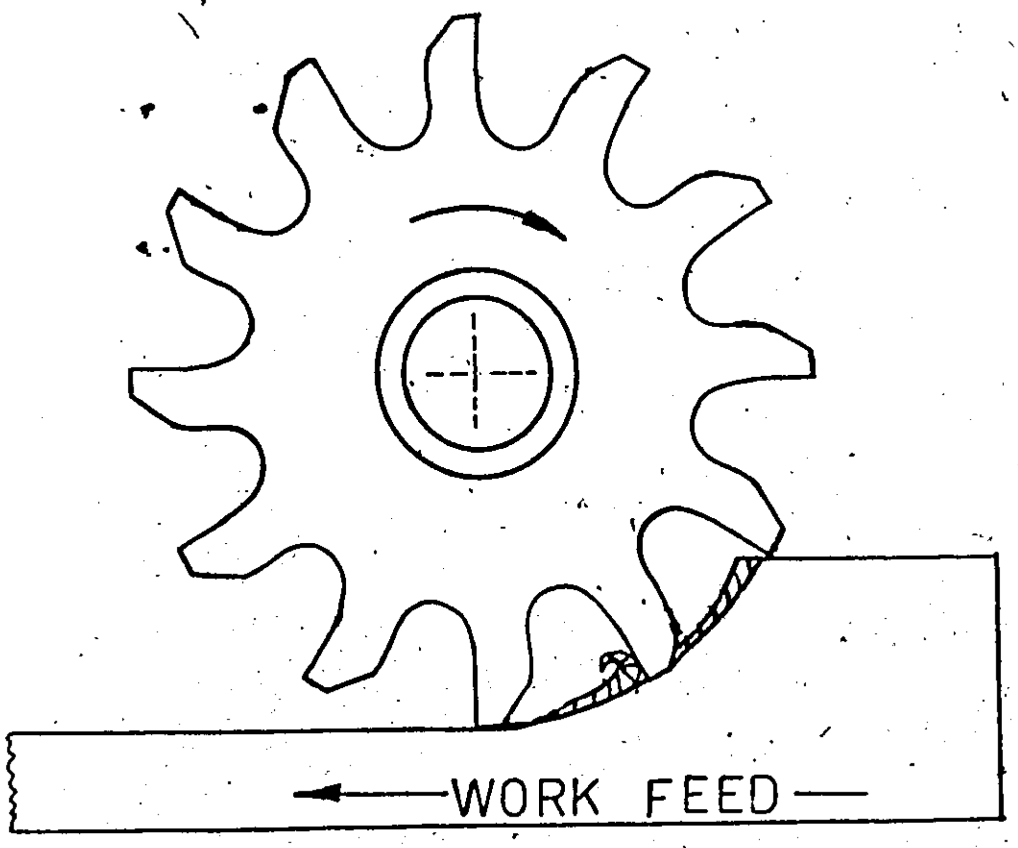


Fig. 6-2. Tool Maker's Microscope



(a) CLIMB OR DOWN MILLING.

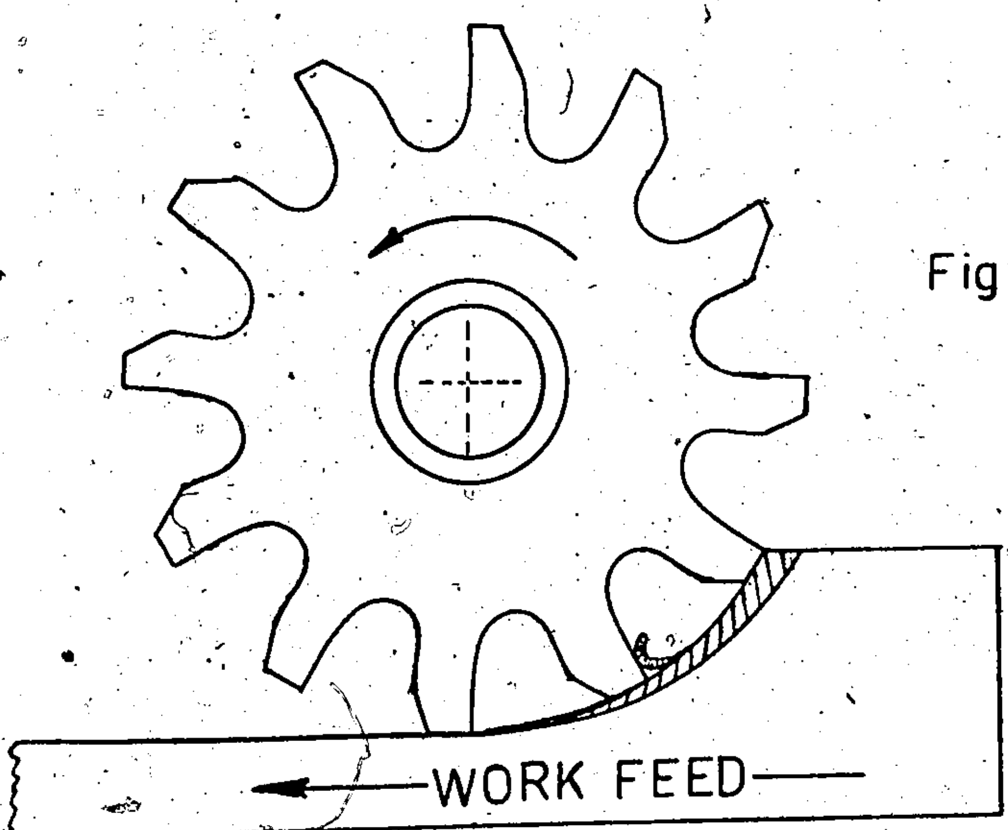


Fig 6-4

(b) CONVENTIONAL OR UP MILLING

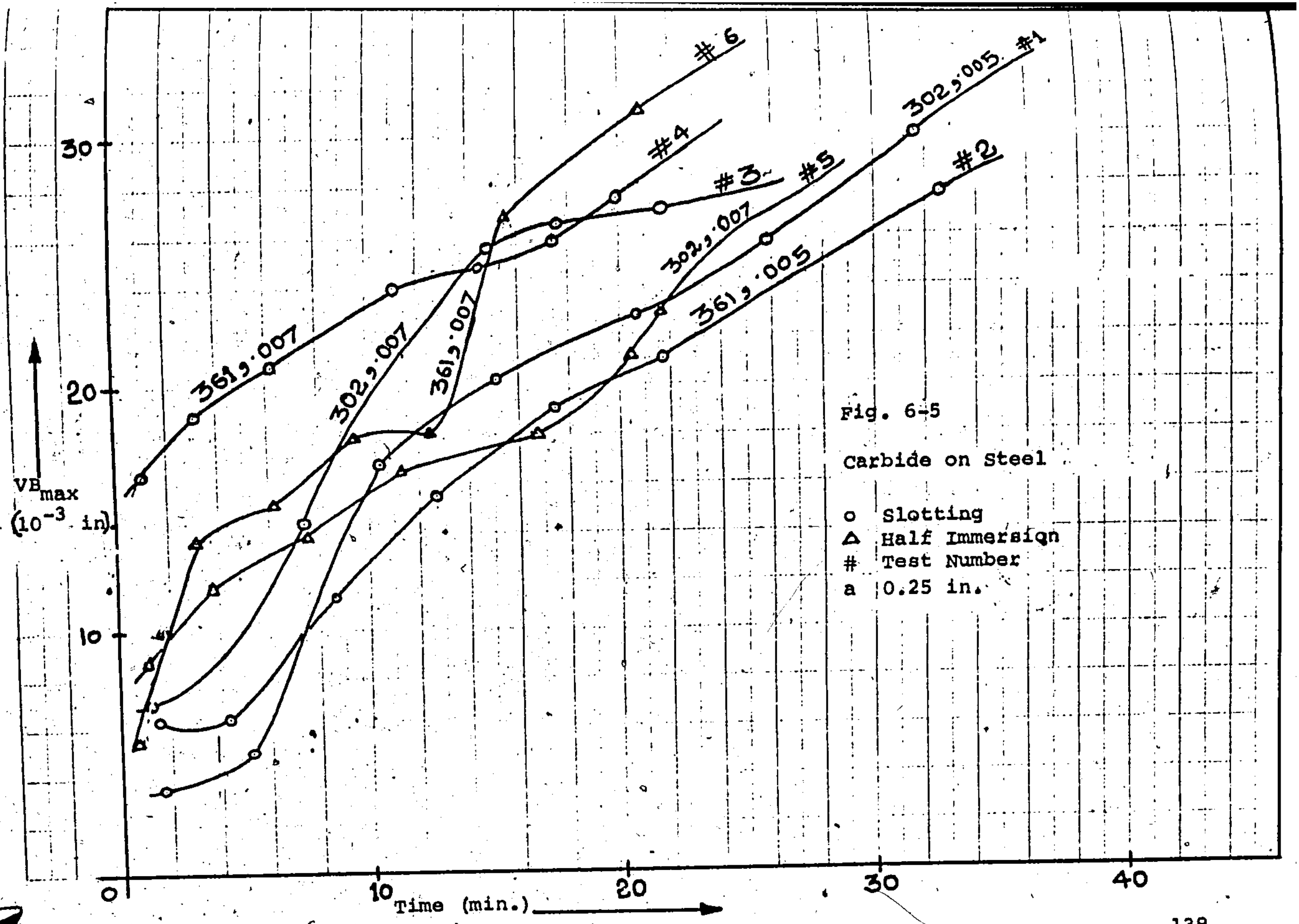

30
20
10
0
10
20
30
40
VBmax
(10-3 in)
Time (min.)
6
4
3
5
2
302, .005 # 1
361, .007
302, .007
361, .007
302, .007
361, .005
Carbide on Steel
o Slotting
Δ Half Immersion
Test Number
a 0.25 in.

Fig. 6-5

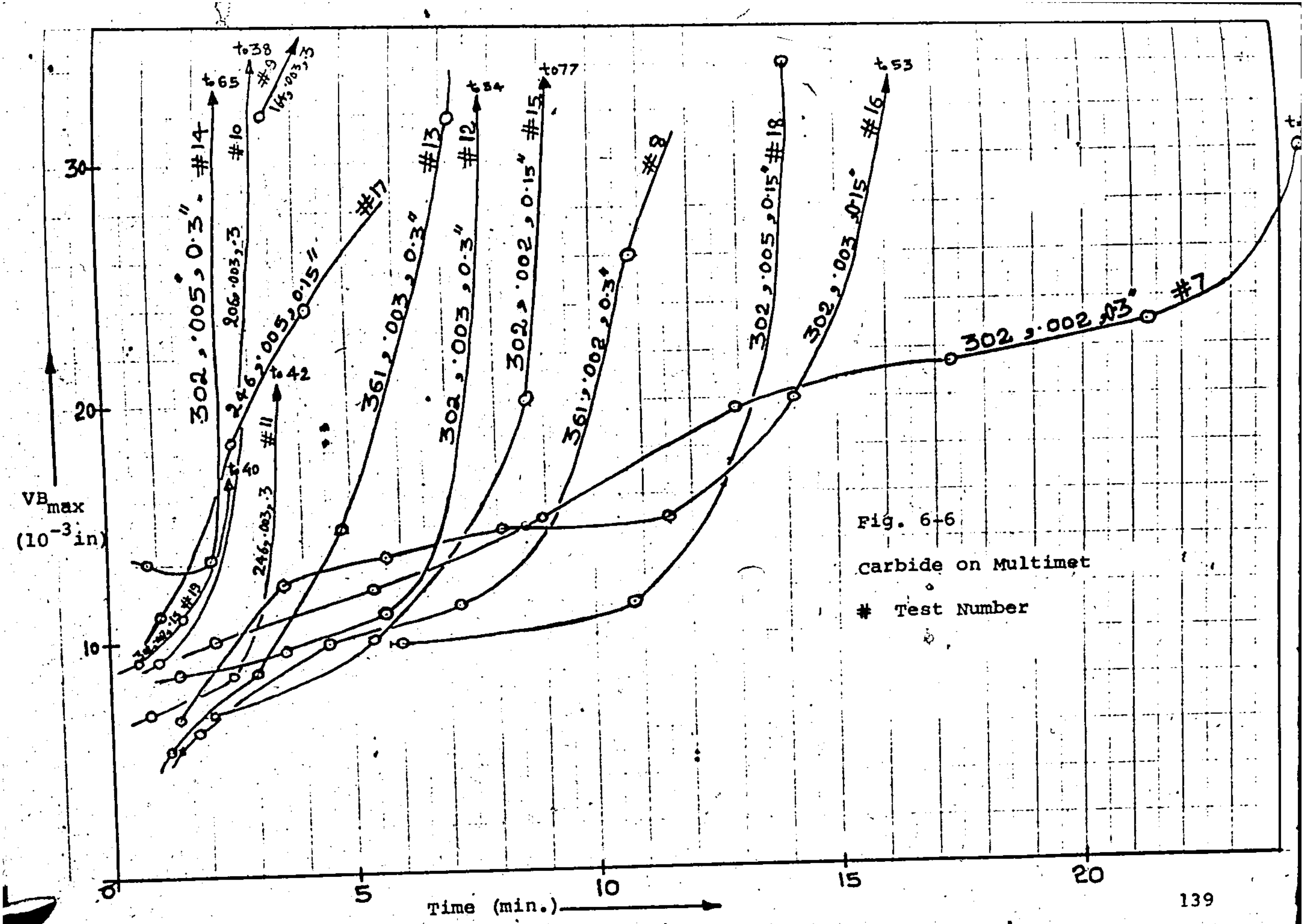


Fig. 6-6

Carbide on Multimet

Test Number

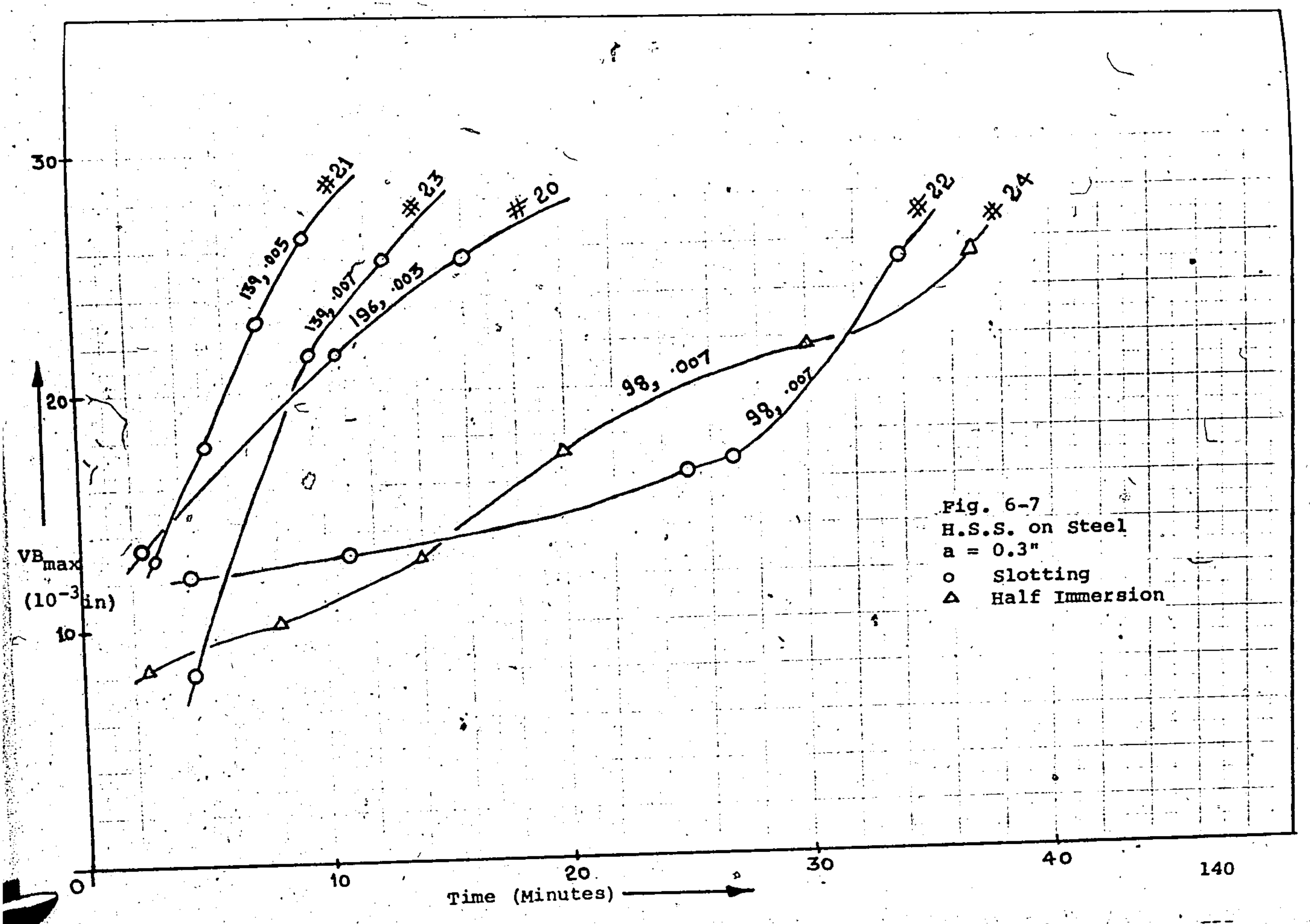
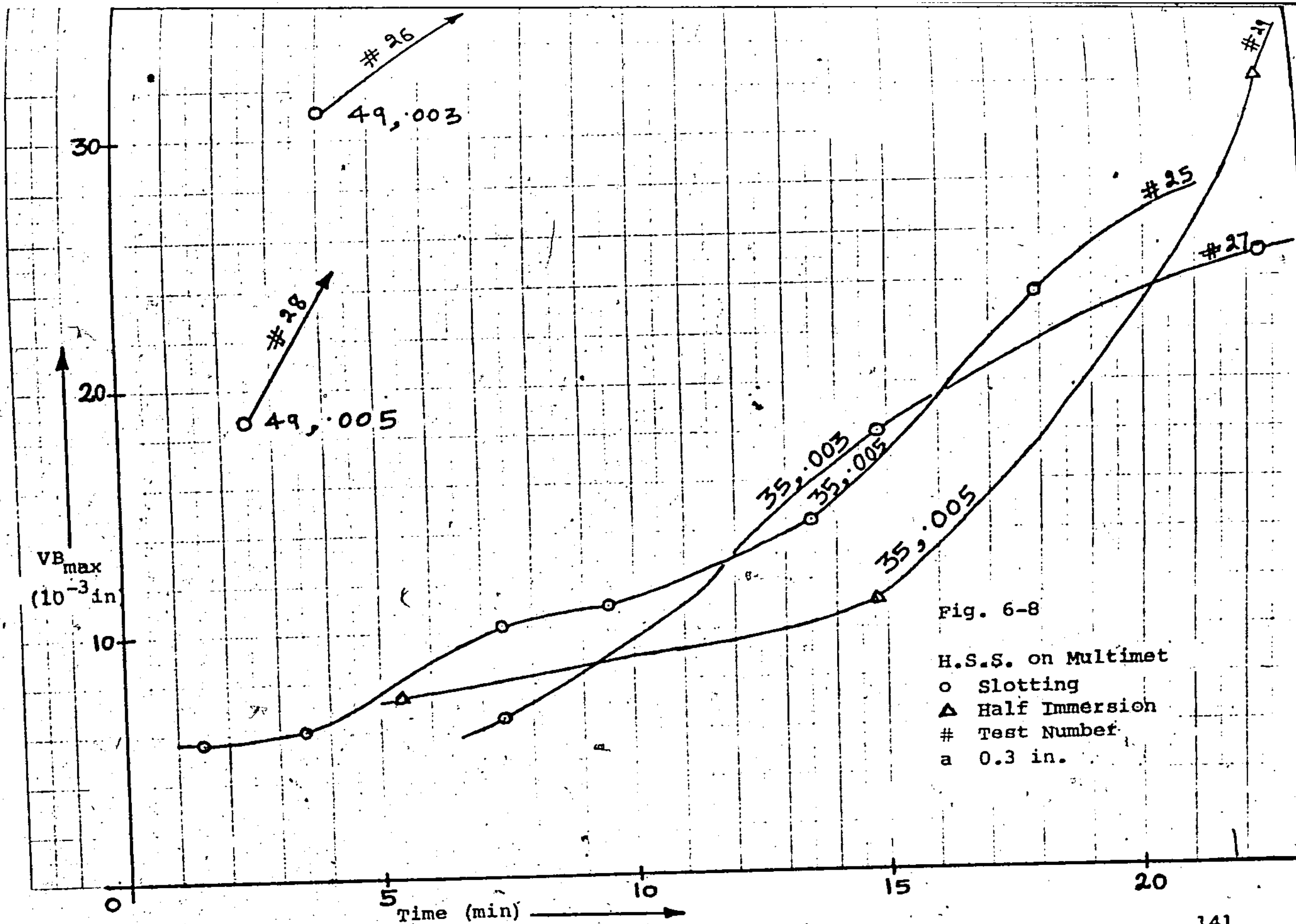


Fig. 6-7
H.S.S. on Steel
a = 0.3"
o Slotting
Δ Half Immersion
#21
#23
#20
#22
#24
139, .005
139, .007
196, .003
98, .007
98, .007
VBmax
(10^-3 in)
30
20
10
0
10
20
30
40
140
Time (Minutes)



#26
49,.003
#28
49,.005
30
20
10
VBmax
(10^-3 in)
0
5
10
15
20
Time (min)
35,.003
35,.005
35,.005
#25
#27
#19
H.S.S. on Multimet
o Slotting
Δ Half Immersion
Test Number
a 0.3 in.

Fig. 6-8

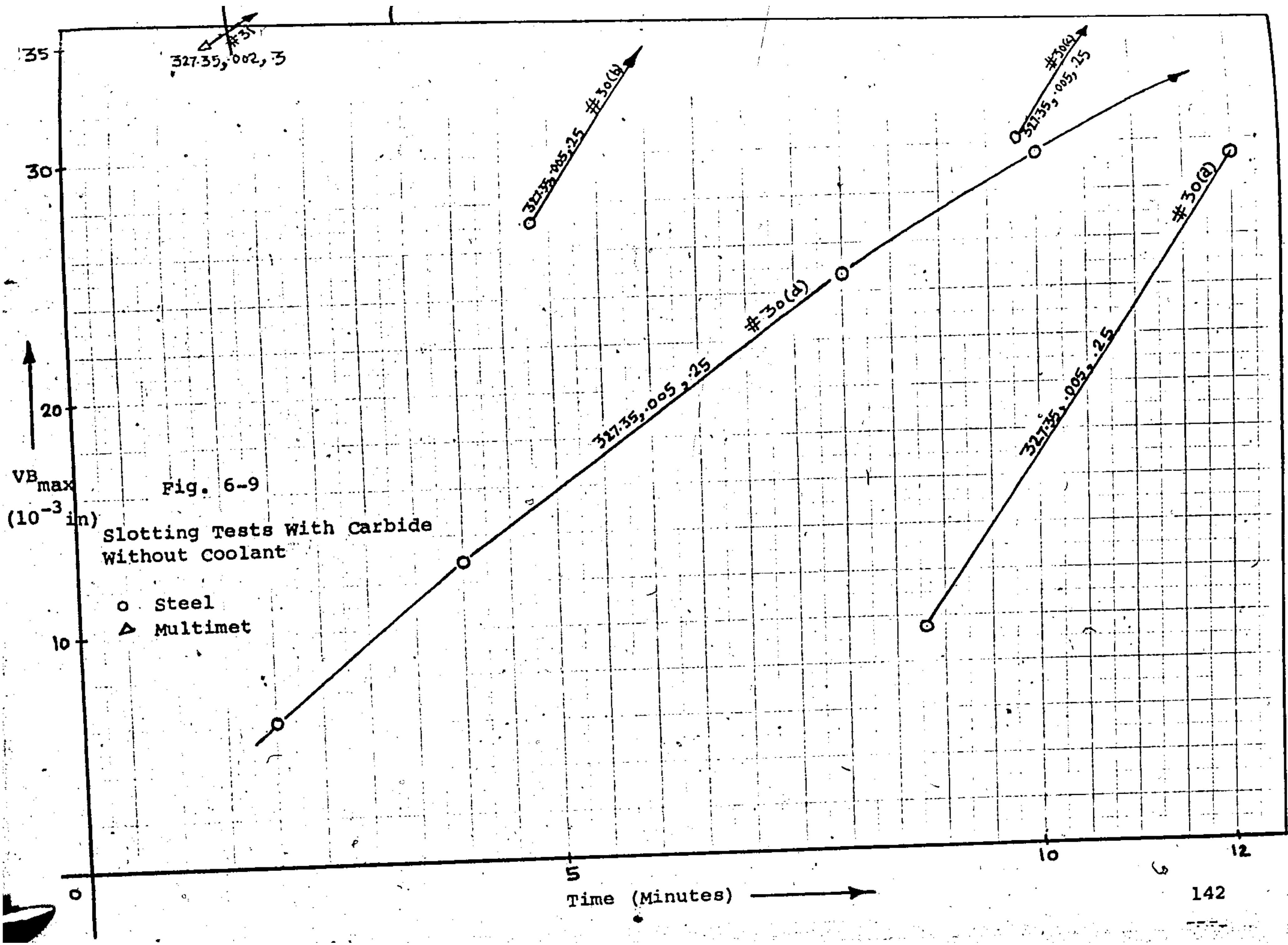


Fig. 6-9
Slotting Tests With Carbide
Without Coolant

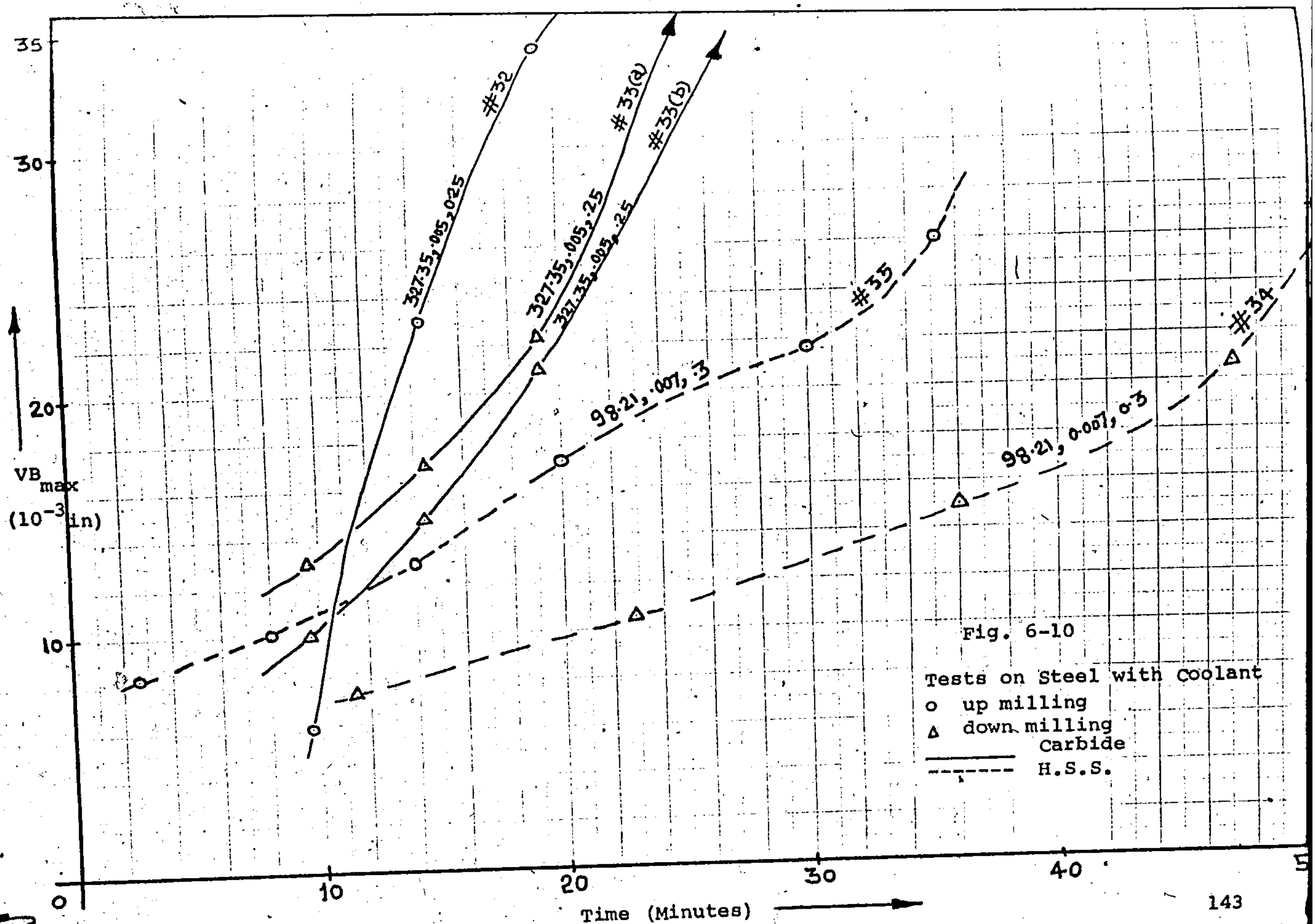
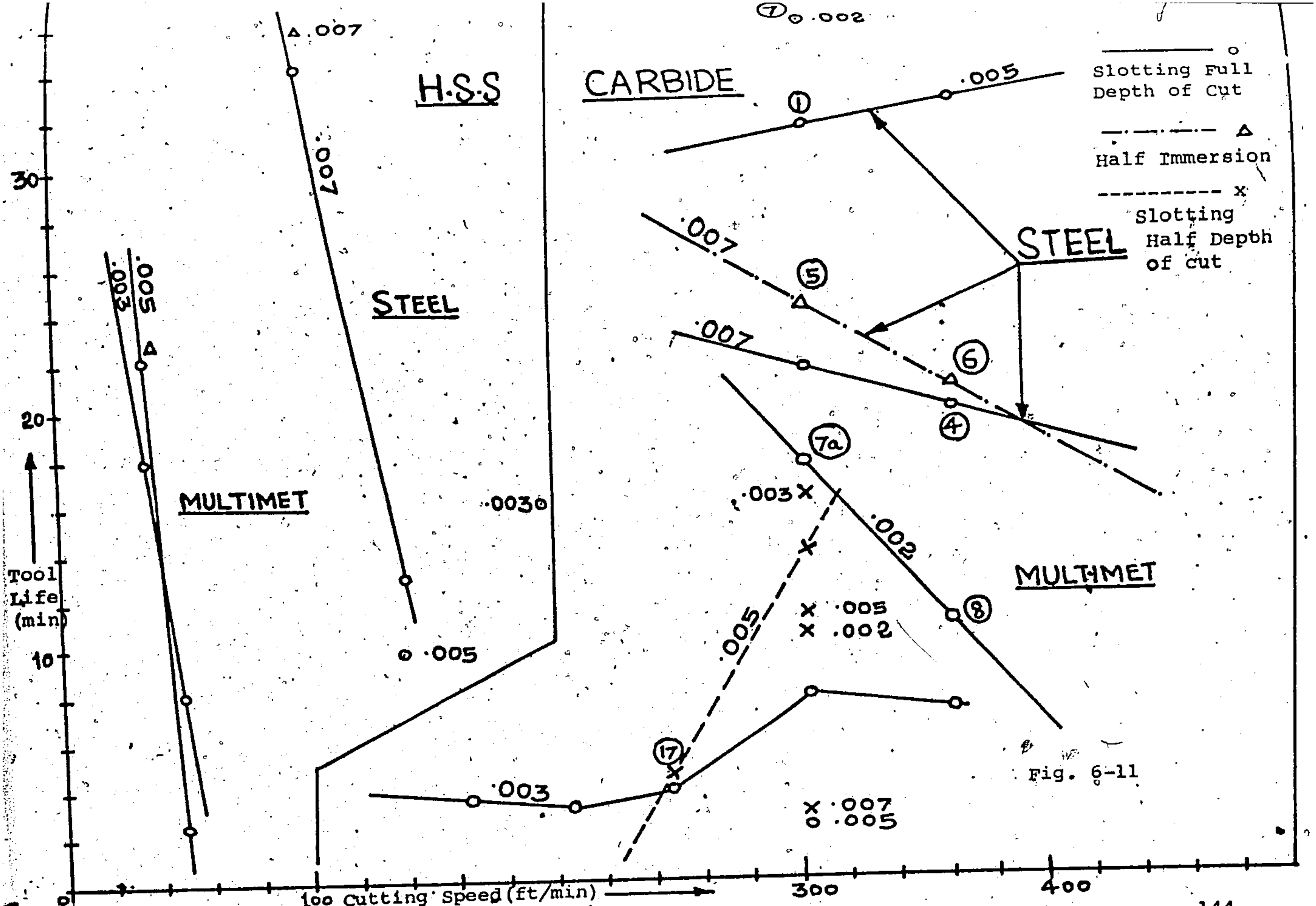

35
30
20
10
0
VB$_{max}$
(10^{-3} in)
10
20
30
40
Time (Minutes)
#32
327.35, .005, .025
#33(a)
327.35, .005, .25
#33(b)
327.35, .005, .25
#35
98.21, .007, .3
#34
98.21, 0.007, 0.3
Tests on Steel with Coolant
o up milling
Δ down milling
Carbide
H.S.S.

Fig. 6-10



H.S.S
CARBIDE
STEEL
MULTIMET
Slotting Full Depth of Cut
Half Immersion
Slotting Half Depth of cut
Tool Life (min)
Cutting Speed (ft/min)
100
300
400
10
20
30
.007
.005
.003
.002

Fig. 6-11

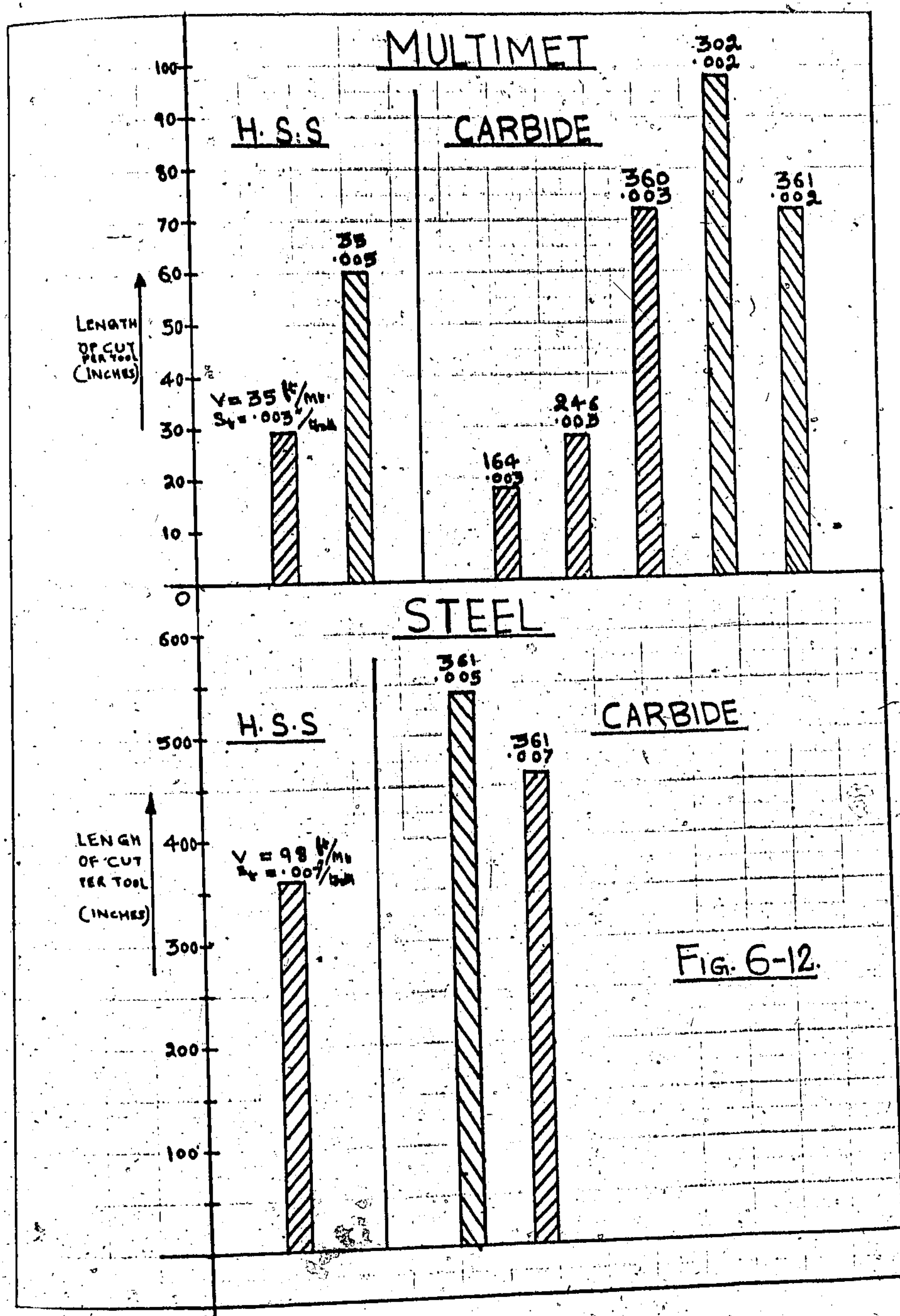

MULTIMET
H.S.S
CARBIDE
LENGTH OF CUT PER TOOL (INCHES)
100
90
80
70
60
50
40
30
20
10
0
V = 35 ft/min
S = .005"/rev
35
.005
164
.005
246
.005
360
.003
302
.002
361
.002
STEEL
H.S.S
CARBIDE
LENGTH OF CUT PER TOOL (INCHES)
600
500
400
300
200
100
V = 98 ft/min
.007
361
.005
361
.007

Fig. 6-12.

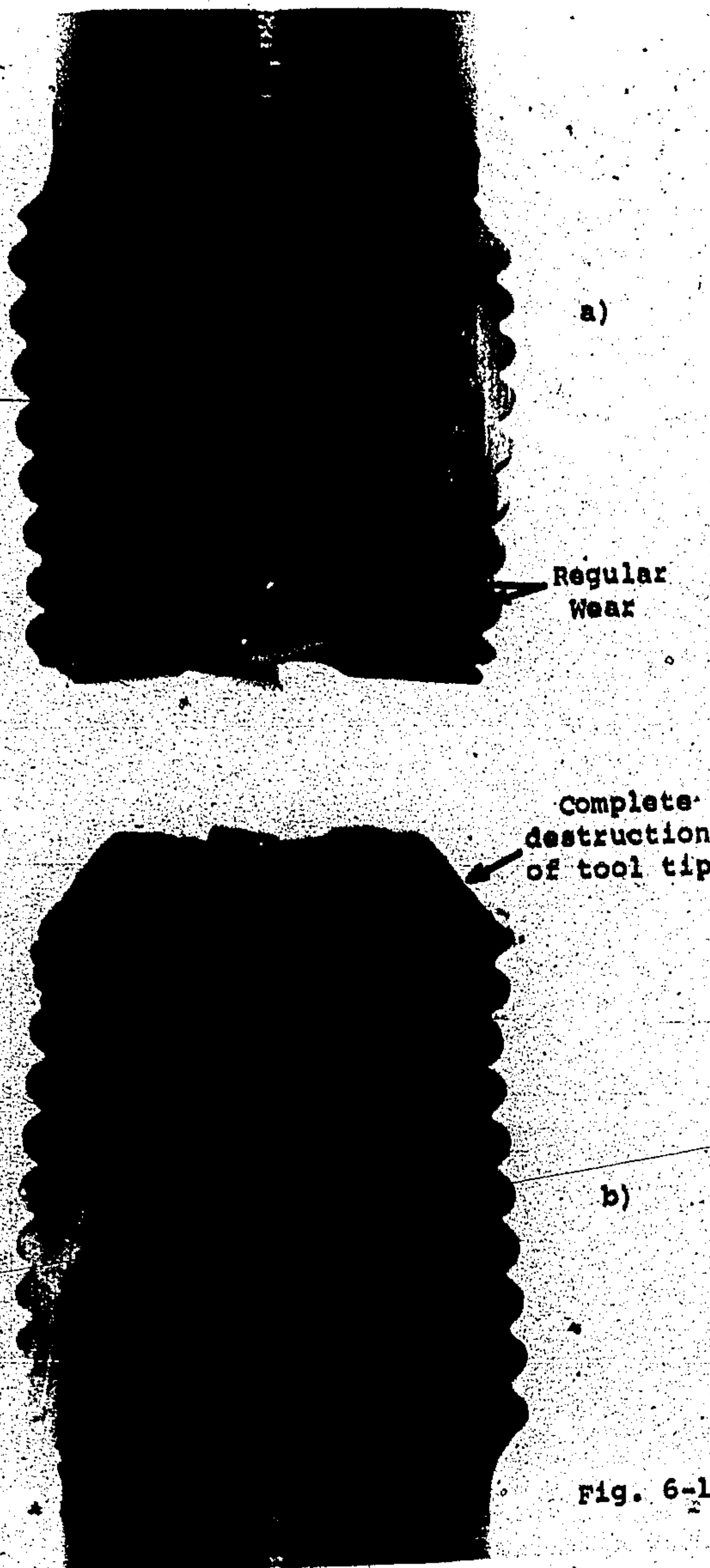


Fig. 6-13

Fig. 6-14. Test #8. Carbide tool on Multimet, v = 361 ft/min., s_t = 0.002. Regular wear.

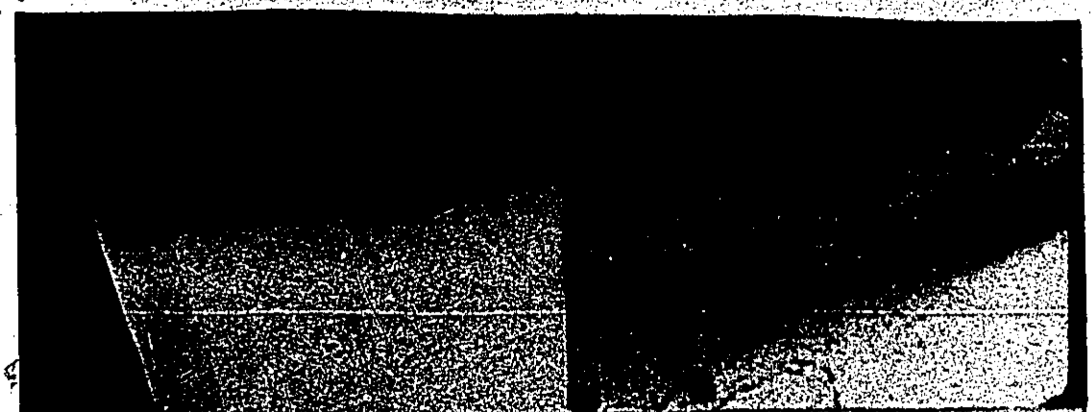


Fig. 6-15. Test #7. Carbide tool on Multimet, v = 302 ft/min., s_t = 0.002. Regular wear. Exceptionally long tool life.

Fig. 6-16. Test #5. Carbide tool on steel, half immersion, v = 302 ft/min., s_t = 0.007. Chipping at the tip.

Fig. 6-17. Test #4. Carbide on steel, v = 361 ft/min., s_t = 0.007. Regular wear with notches at point cutting surface.

Fig. 6-18. Test #1. Carbide on steel, v = 302 ft/min., s_t = 0.005. Regular wear, long tool life.

Fig. 6-19. Test #6. Carbide on steel, half immersion, v = 361 ft/min., s_t = 0.007.

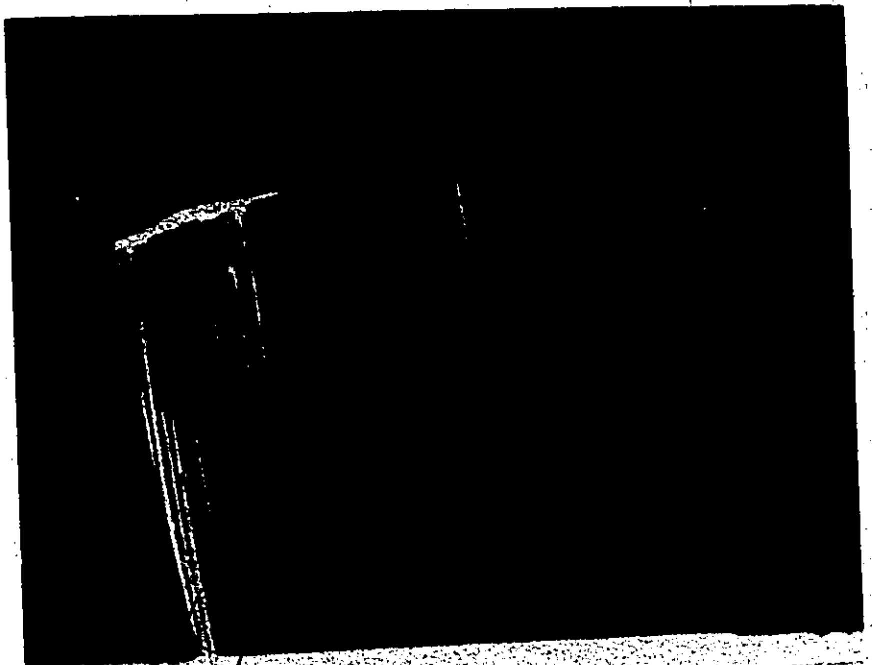


Fig. 6-20. Test #7a. Same conditions as in Fig. 6-15. This time, however, large wear on tool nose.

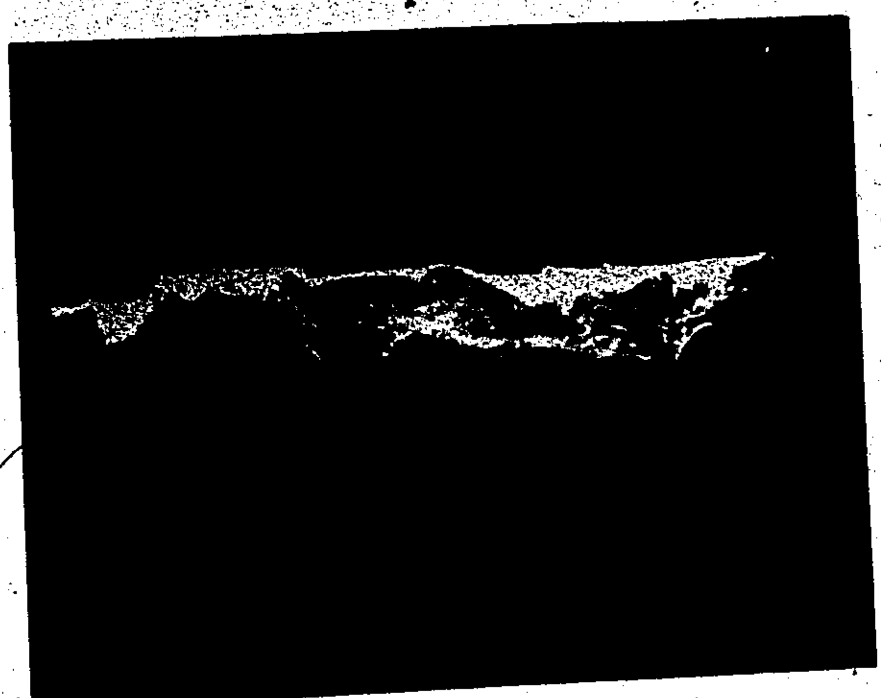


Fig. 6-21. Test #17. Carbide on Multimet, v = 246 ft/min., s_t = 0.005. Rather heavy chipping of edge.

Fig. 6-22. Same as Fig. 6-20 but with large magnification (154x)

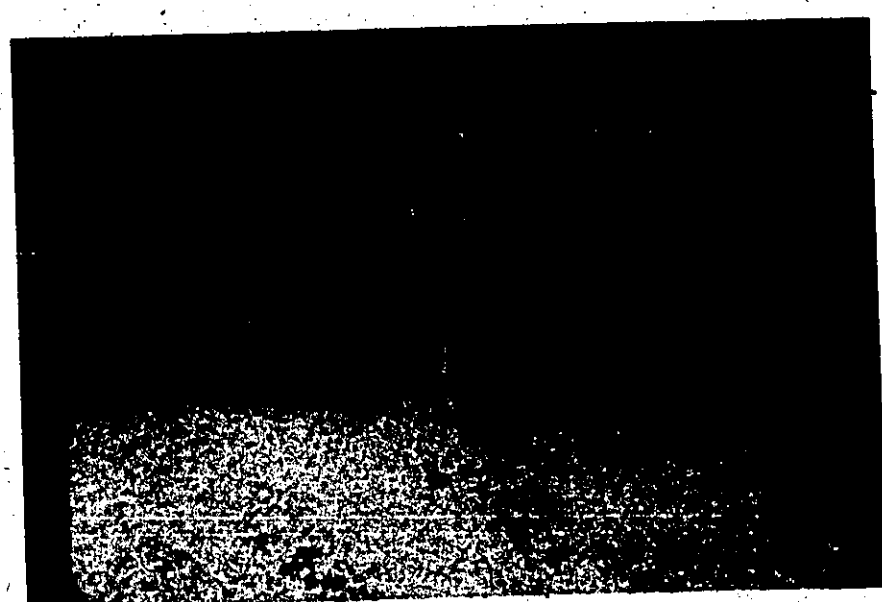


Fig. 6-23. Same as Fig. 6-15 but with large magnification (84x).

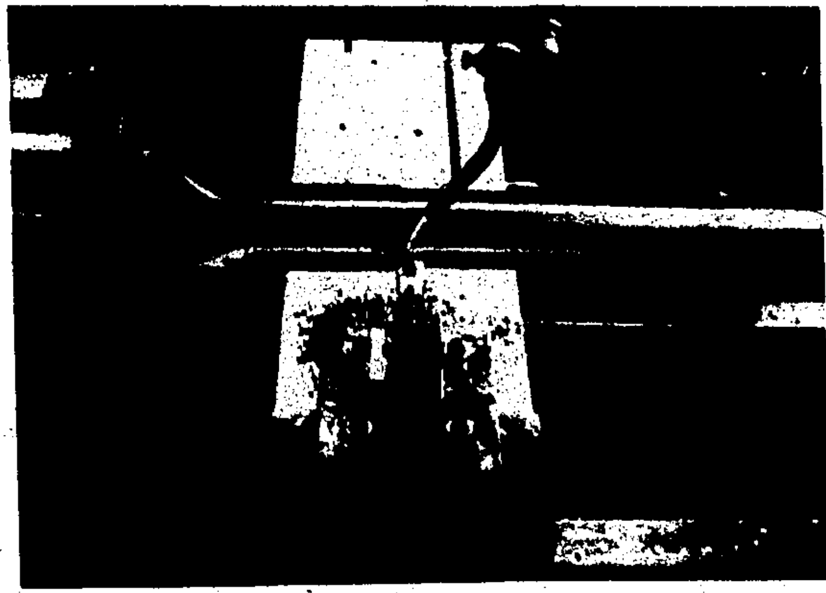


Fig. 7-1. Set-Up for Simulative Experiments

Fig. 7-2. Set-Up for Recording the Cutting Forces

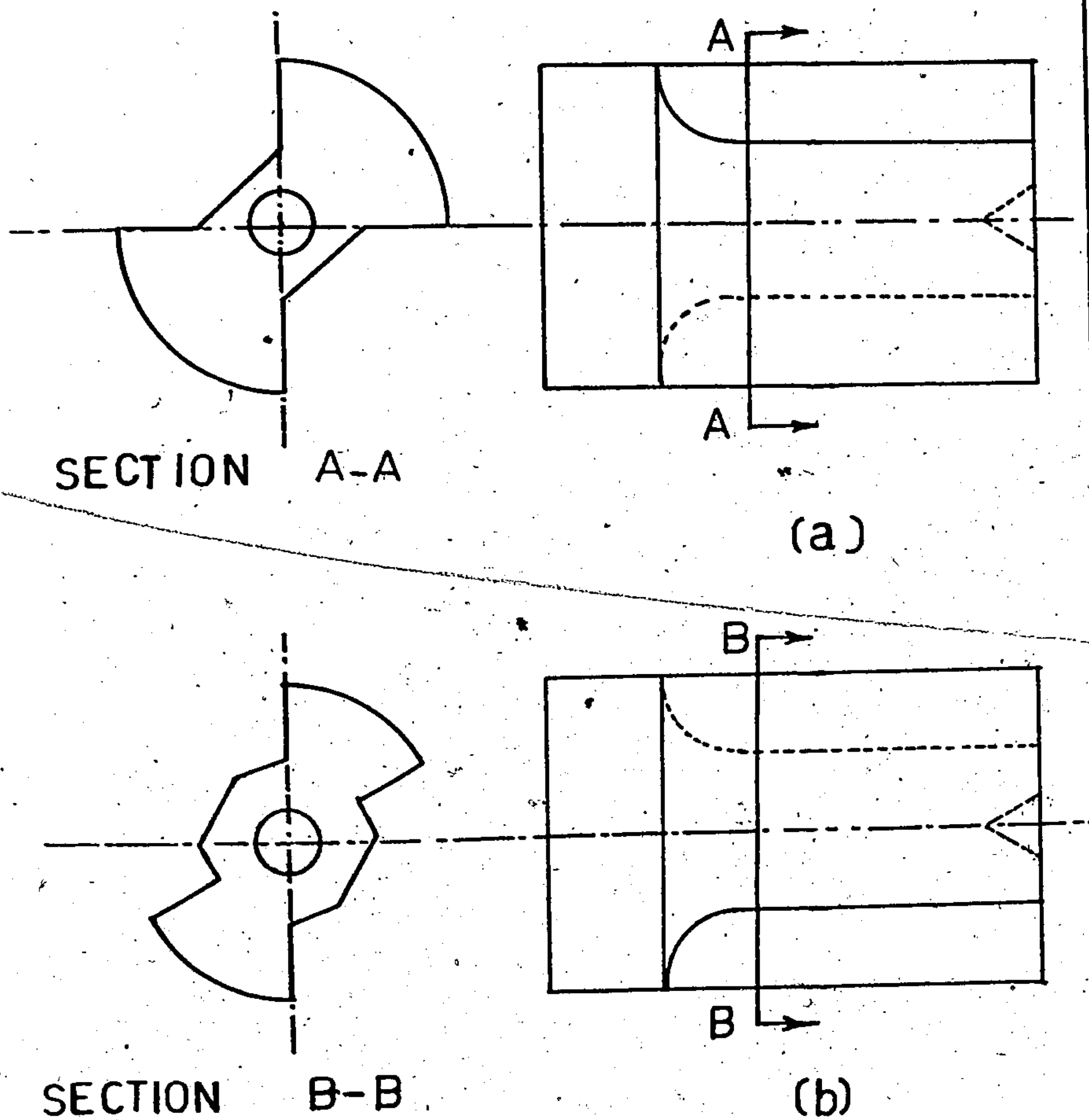


Fig 7.3. Workpiece for simulative experiments.

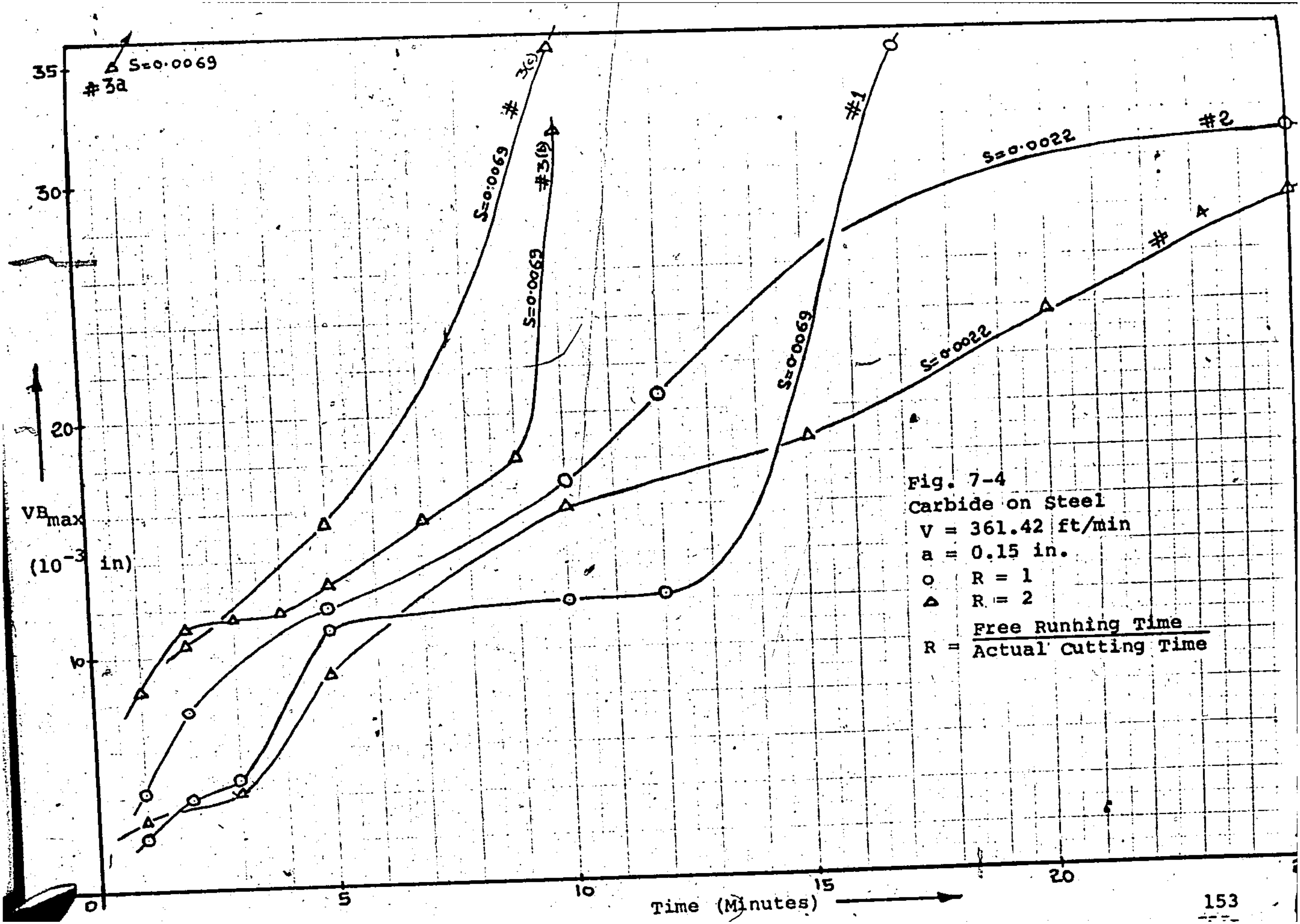


Fig. 7-4
Carbide on Steel
V = 361.42 ft/min
a = 0.15 in.
o R = 1
Δ R = 2
R = Free Running Time / Actual Cutting Time
VBmax (10^-3 in)
Time (Minutes)
35
30
20
10
0
5
10
15
20
#3a
S=0.0069
#3(c)
#3(b)
#1
#2
#4
S=0.0022

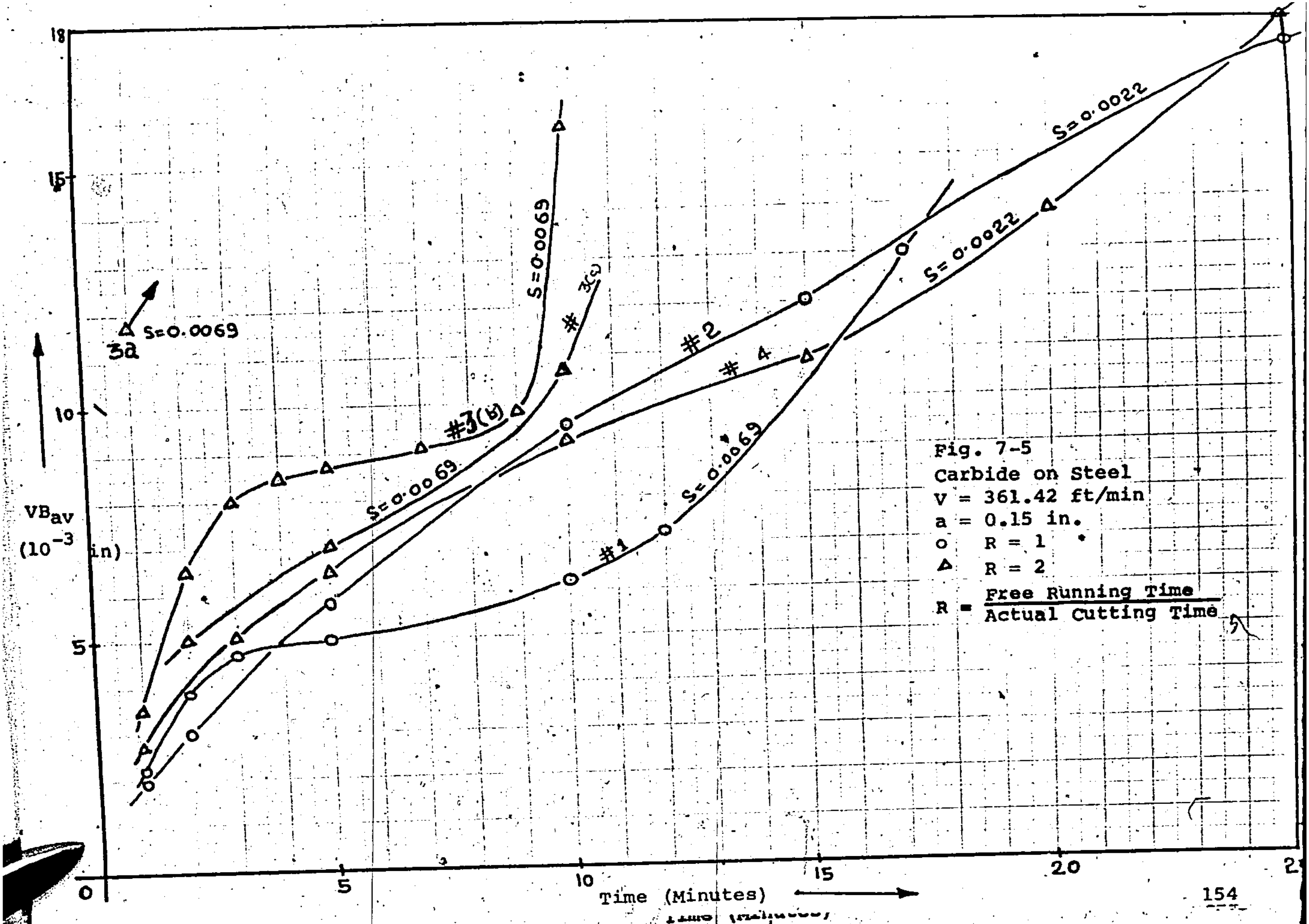
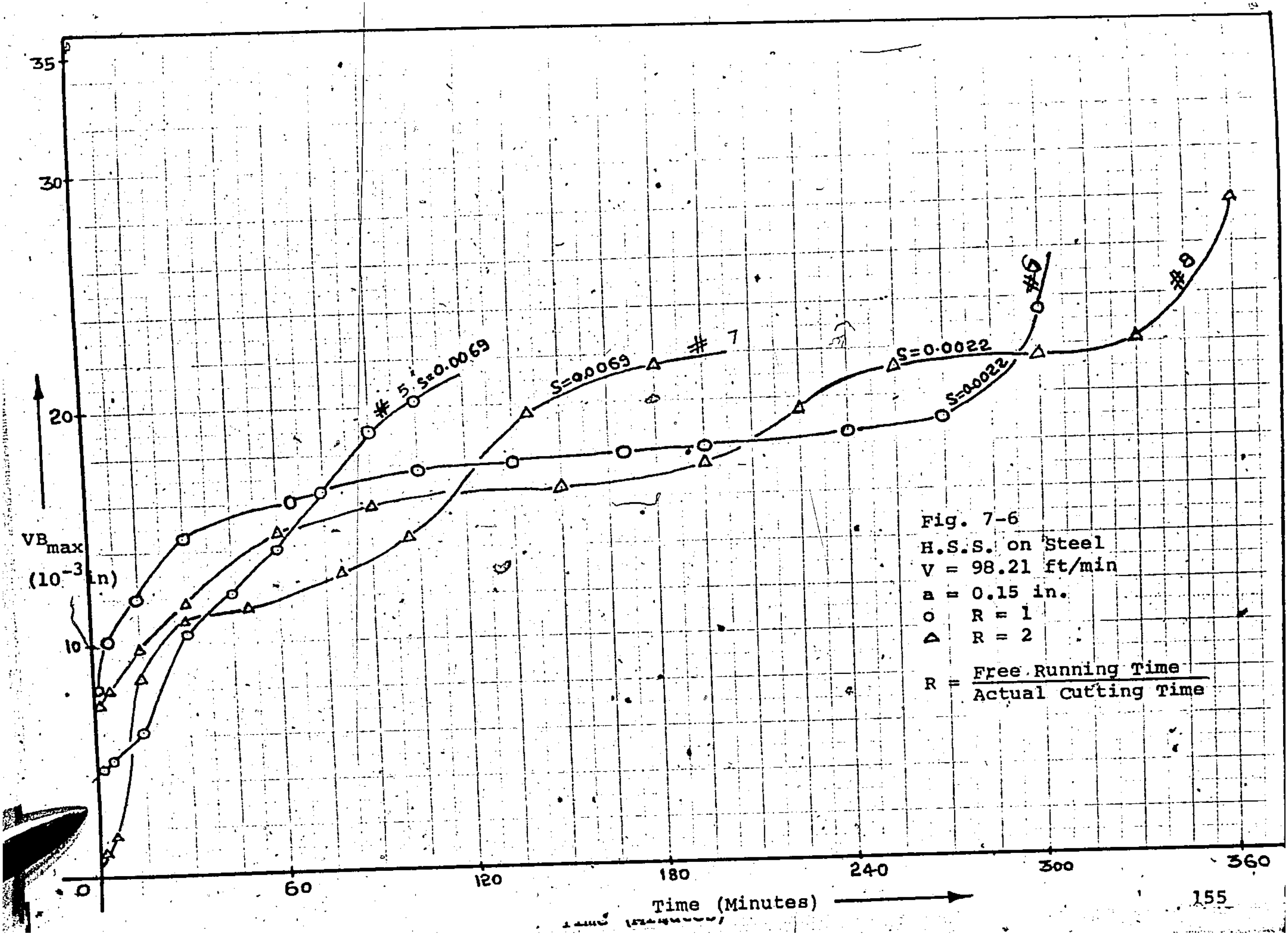


Fig. 7-5
Carbide on Steel
V = 361.42 ft/min
a = 0.15 in.
o R = 1
Δ R = 2

$R = \frac{\text{Free Running Time}}{\text{Actual Cutting Time}}$


35
30
20
10
VB_{max} $(10^{-3}$ in)
0
60
120
180
240
300
360
Time (Minutes)
# 5 S=0.0069
S=0.0069
# 7
S=0.0022
S=0.0022
#6
#8
Fig. 7-6
H.S.S. on Steel
V = 98.21 ft/min
a = 0.15 in.
o R = 1
△ R = 2
R = Free Running Time / Actual Cutting Time

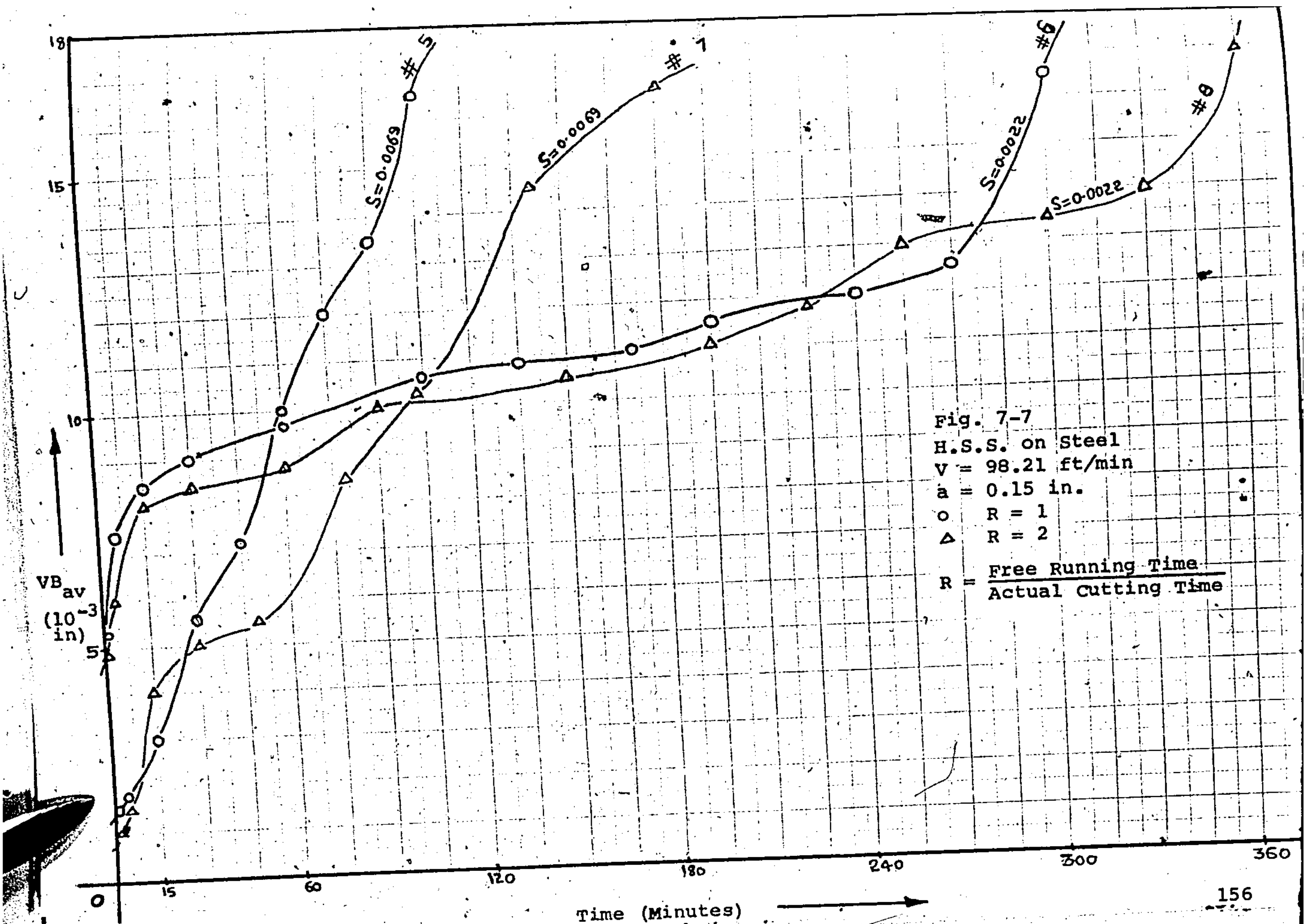


Fig. 7-7
H.S.S. on Steel
V = 98.21 ft/min
a = 0.15 in.
o R = 1
Δ R = 2
R = Free Running Time / Actual Cutting Time
VBav (10^-3 in)
Time (Minutes)
#5
#7
#6
#8
S=0.0069
S=0.0069
S=0.0022
S=0.0022
0
15
60
120
180
240
300
360
5
10
15
18

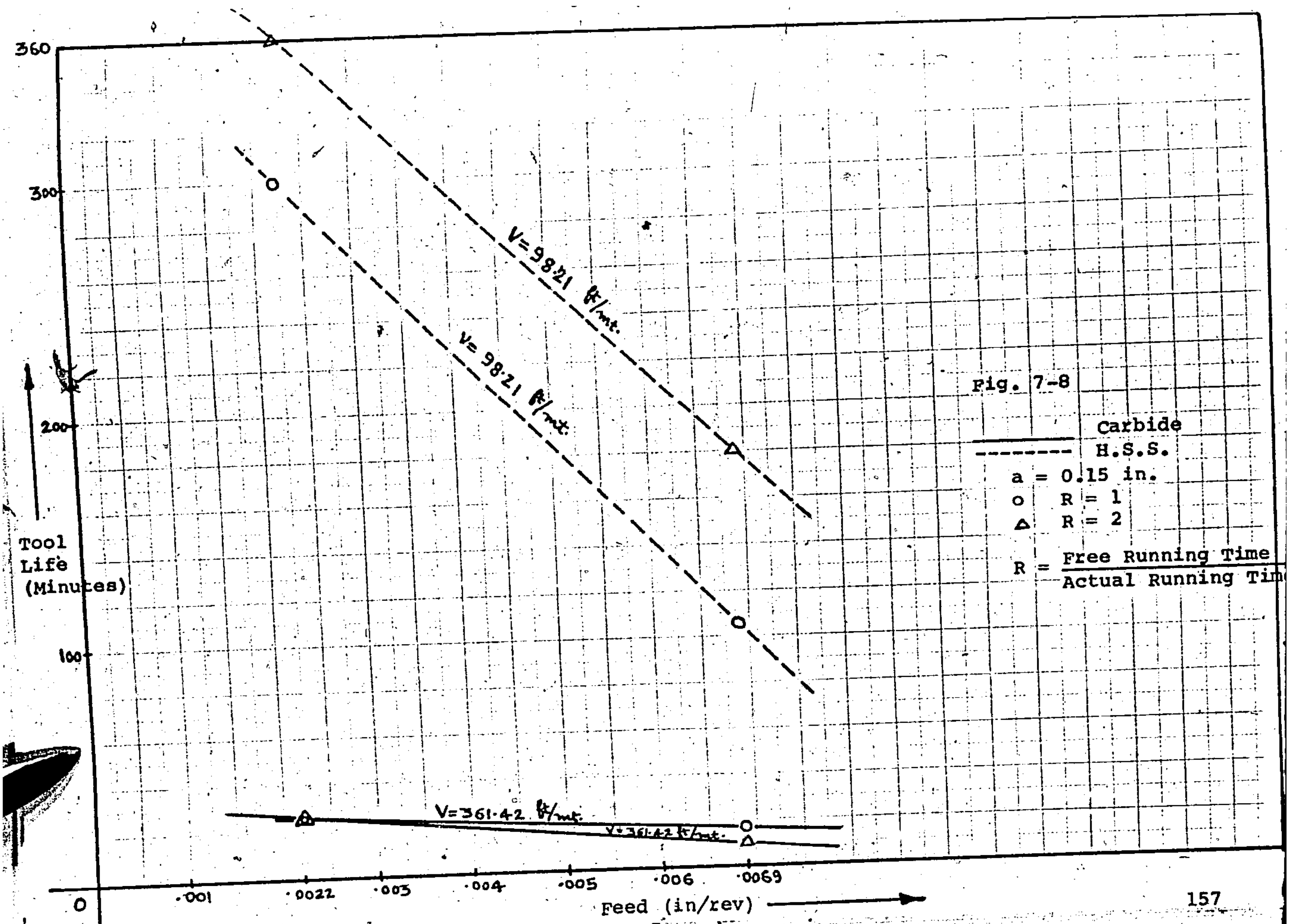

360
300
200
100
0
Tool Life (Minutes)
·001
·0022
·003
·004
·005
·006
·0069
Feed (in/rev)
V=98·21 ft/mt.
V= 98·21 ft/mt.
V=361·42 ft/mt.
V=361·42 ft/mt.
Carbide
H.S.S.
a = 0.15 in.
o R = 1
Δ R = 2
R = Free Running Time / Actual Running Time

Fig. 7-8

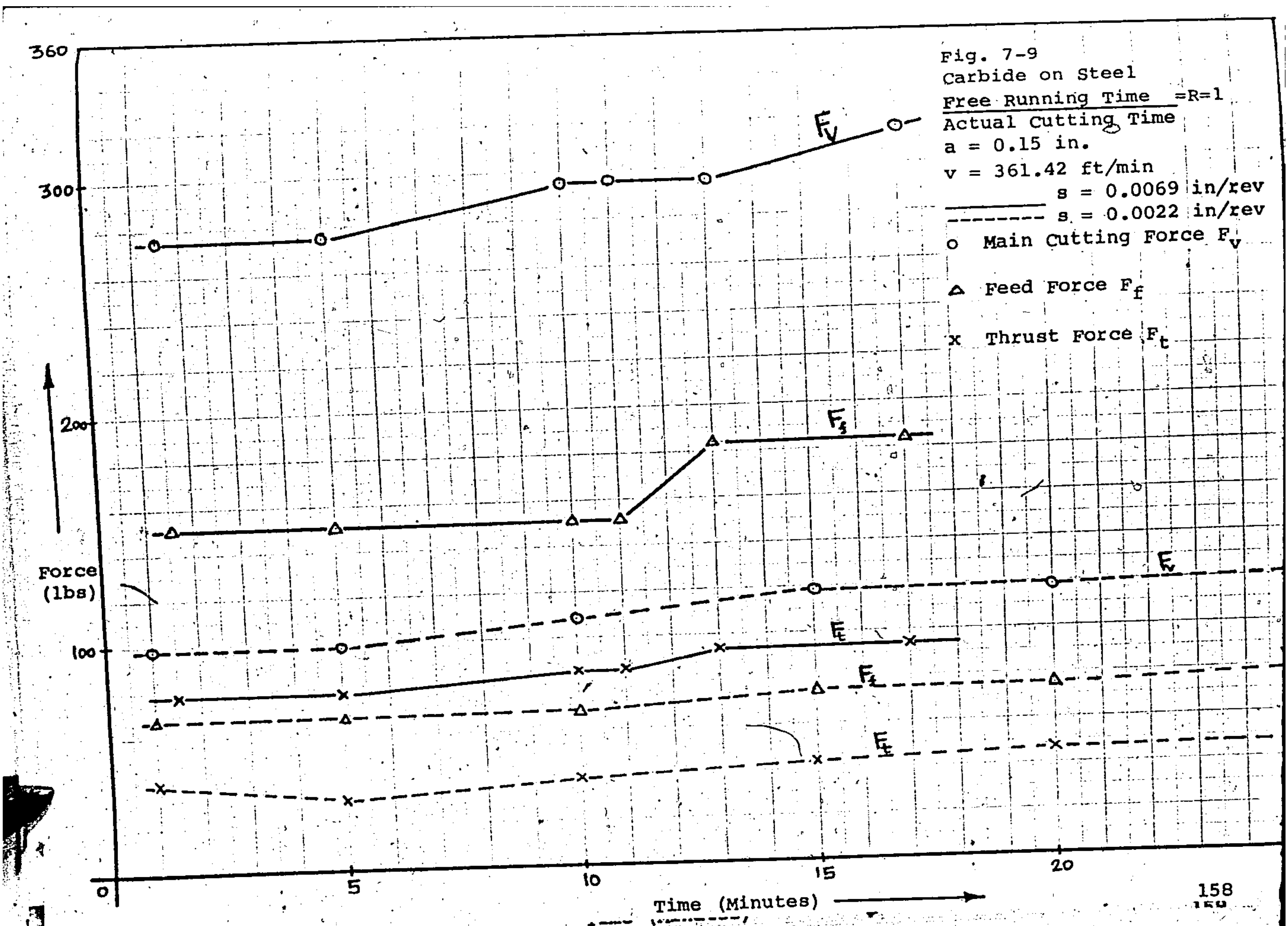


Fig. 7-9
Carbide on Steel
Free Running Time / Actual Cutting Time =R=1
a = 0.15 in.
v = 361.42 ft/min
s = 0.0069 in/rev
s = 0.0022 in/rev
o Main Cutting Force F_v
Δ Feed Force F_f
x Thrust Force F_t
360
300
200
100
0
Force (lbs)
5
10
15
20
Time (Minutes)
F_v
F_f
F_t

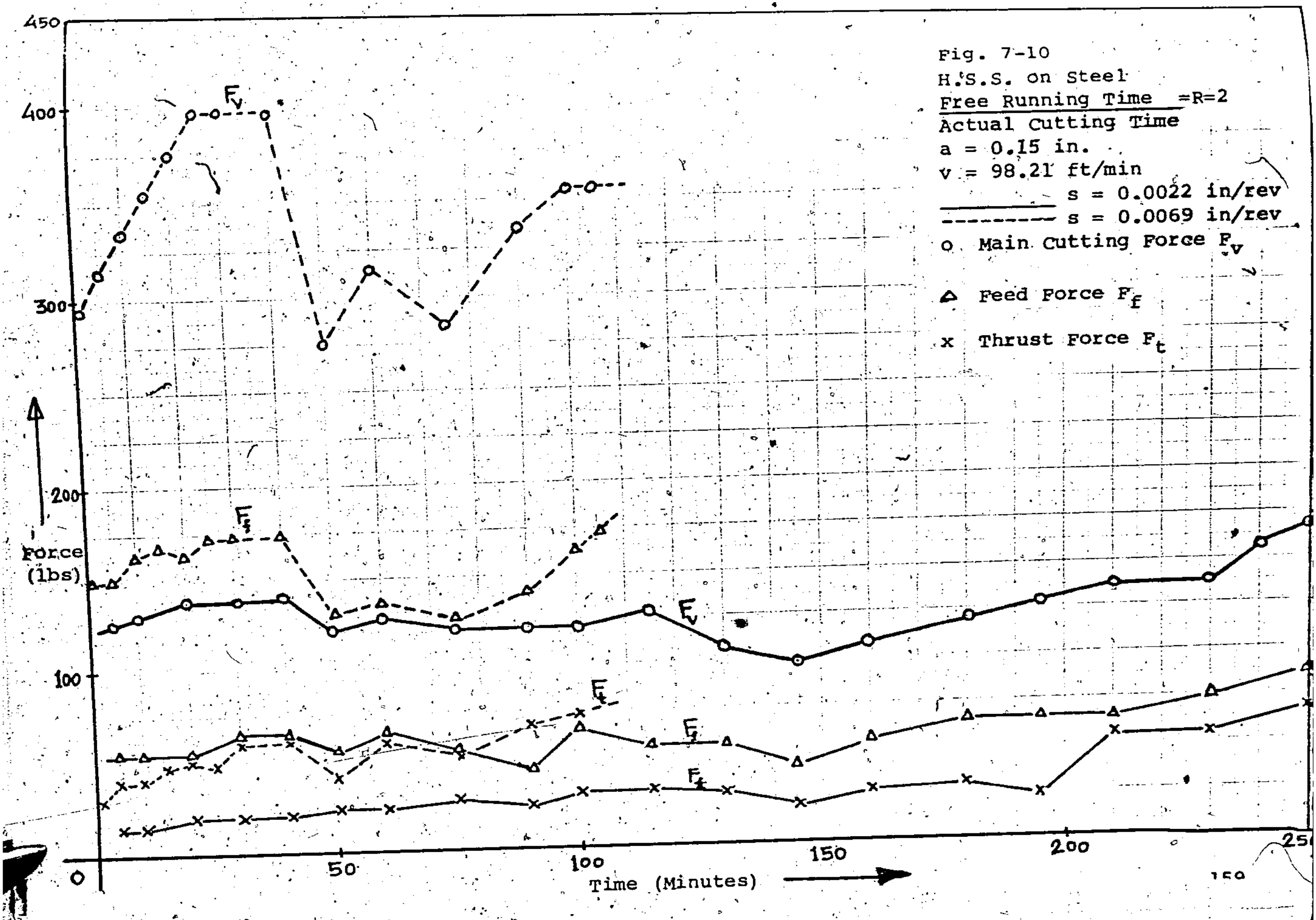


Fig. 7-10
H.S.S. on Steel
Free Running Time / Actual Cutting Time =R=2
a = 0.15 in.
v = 98.21 ft/min
s = 0.0022 in/rev
s = 0.0069 in/rev
o Main Cutting Force F_v
Δ Feed Force F_f
x Thrust Force F_t
F_v
F_f
F_t
450
400
300
200
100
Force (lbs)
0
50
100
150
200
250
Time (Minutes)

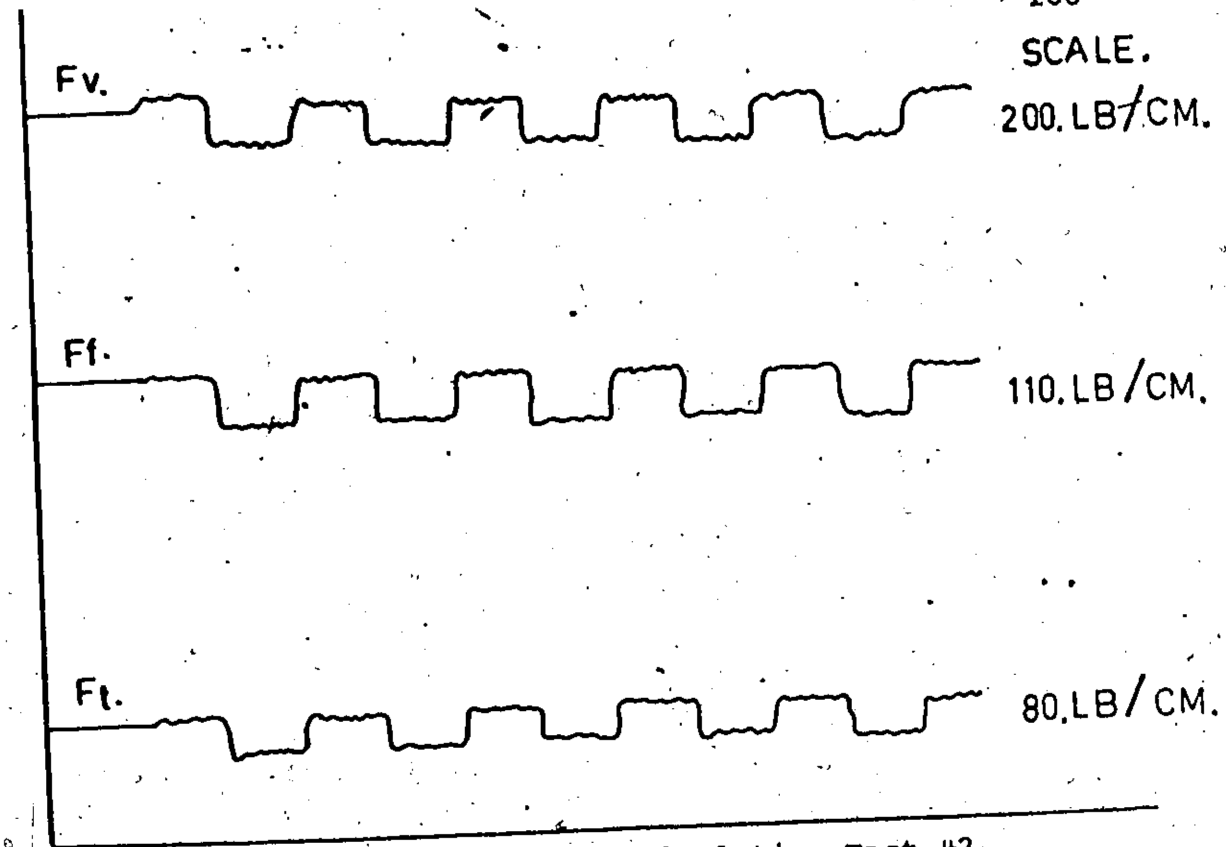


Fig. 7-11. Cutting Forces in Simulative Test #2.
V = 361.42 ft/min., s = 0.0022 in/rev, R = 1

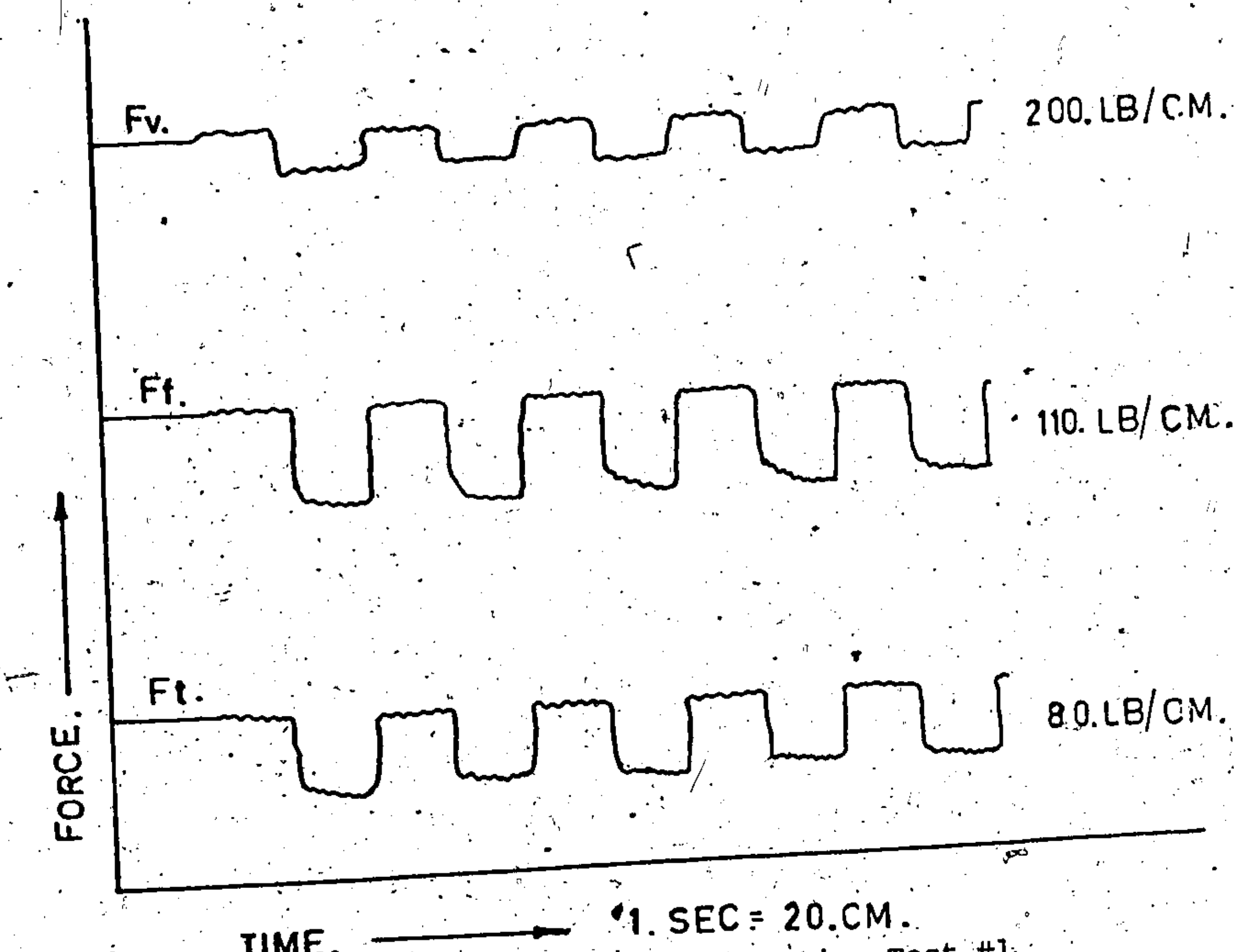


Fig. 7-12. Cutting Forces in Simulative Test #1
V = 361.42 ft/min., s = 0.0069 in/rev, R = 1

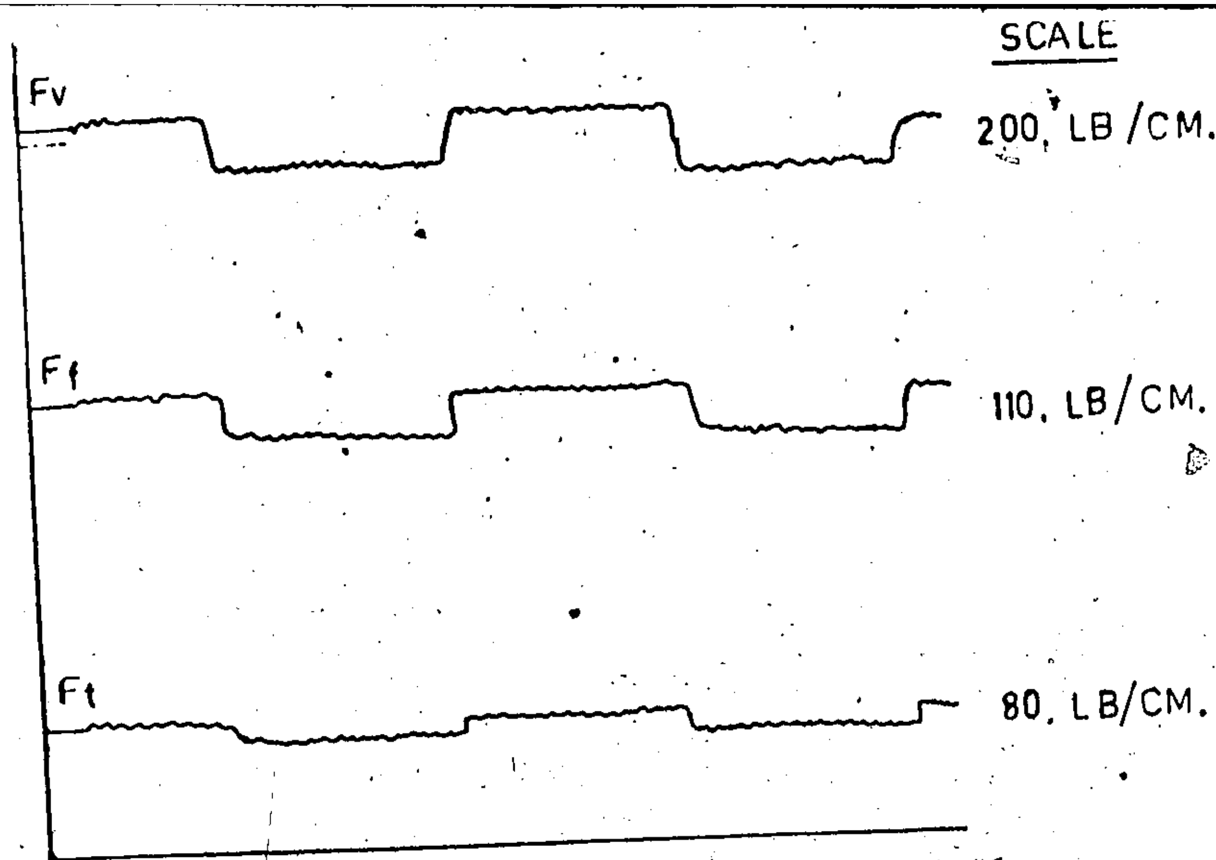


Fig. 7-13. Cutting Forces in Simulative Test #6
v = 98.21 ft/min., s = 0.0022 in/rev, R = 1

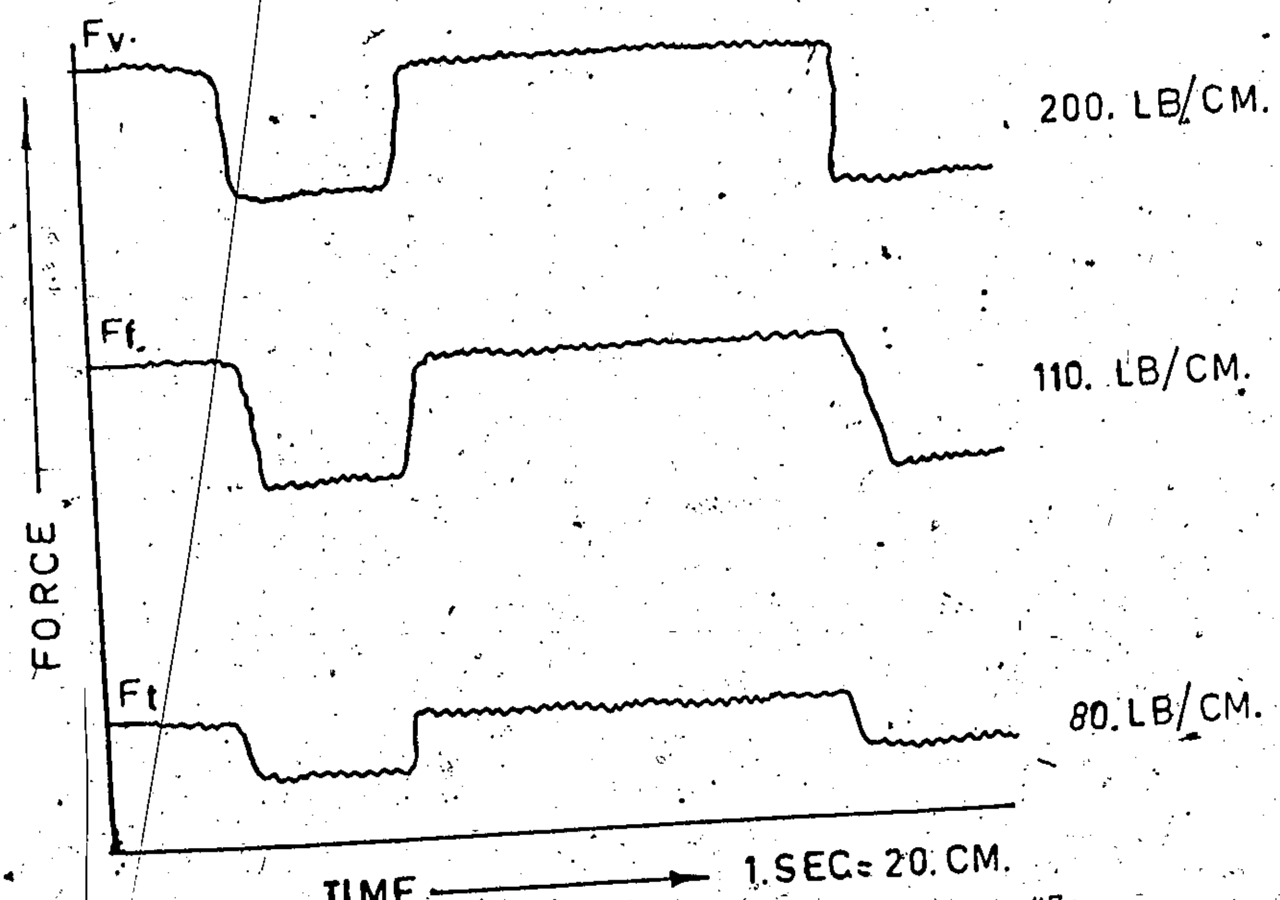


Fig. 7-14. Cutting Forces in Simulative Test #7
v = 98.21 ft/min., s = 0.0069 in/rev, R = 2

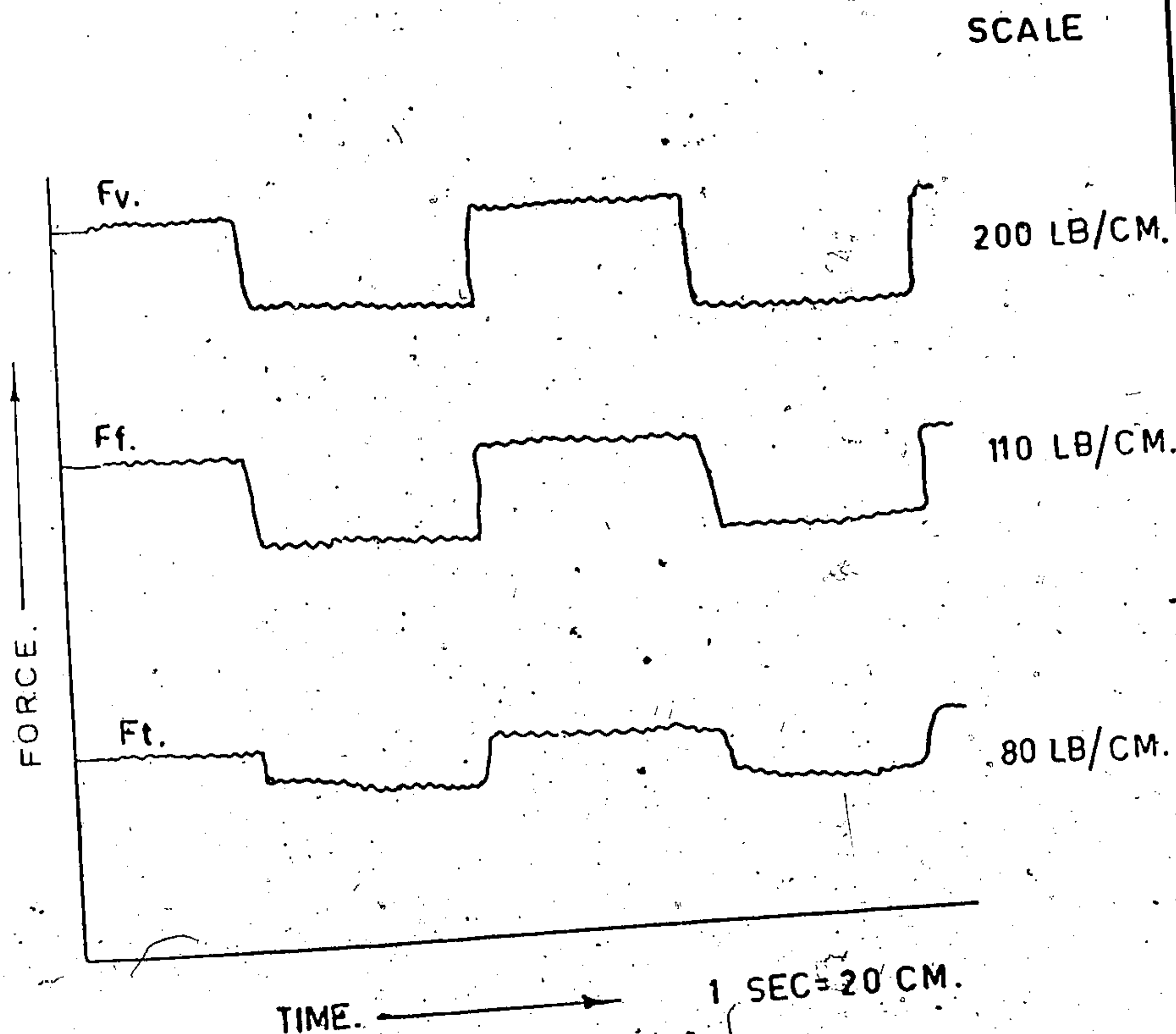


Fig. 7-15. Cutting Forces in Simulative Test #5
v = 98.21 ft/min., s = 0.0069 in/rev, R = 1[illegible]

Fig. 7-16. Test #1, Carbide on Steel,
V = 361.42 ft/min, R = 1, S = 0.0069 in/rev
16.8X

Fig. 7-17. Test #3 (b), Carbide on Steel,
V = 361.42 ft/min, R = 2, S = 0.0069 in/rev.
22X

Fig. 7-18. Test #4, Carbide on Steel, V = 361.42 ft/min, S = 0.0022 in/rev, R = 2, 16.8X

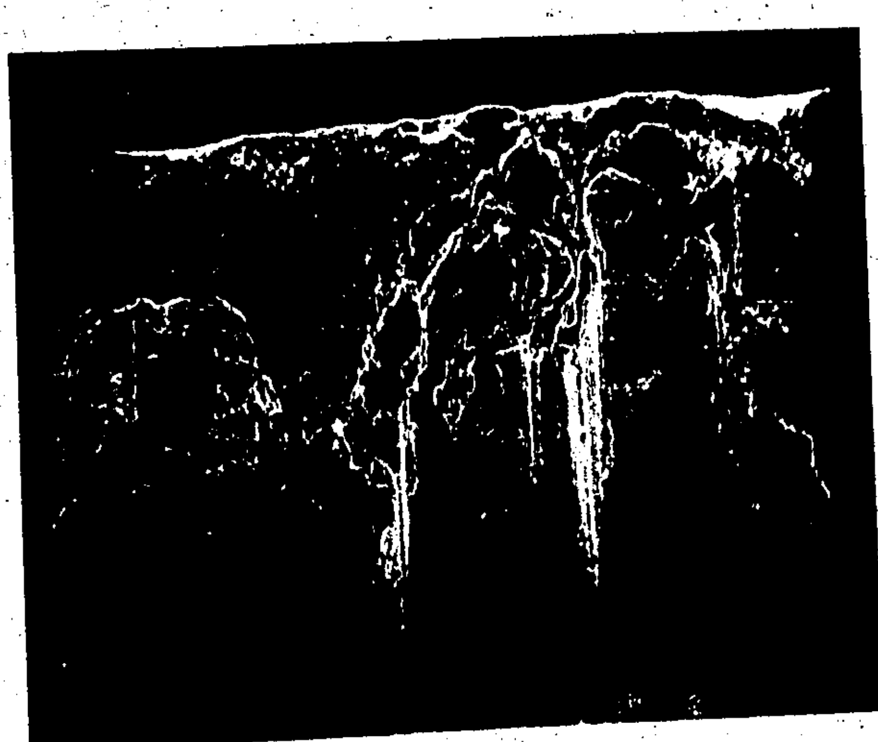


Fig. 7-19. Same as Fig. 7-18 but at higher magnification. 84X

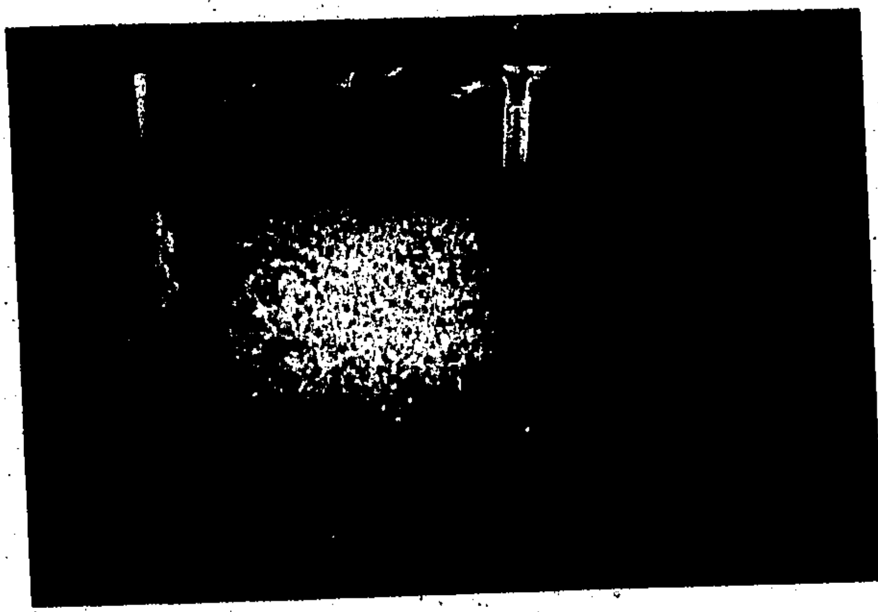


Fig. 7-20. Test #2, Carbide on Steel Flank Face, V = 361.42 ft/min, S = 0.0022 in/rev, R = 1, 15.4X

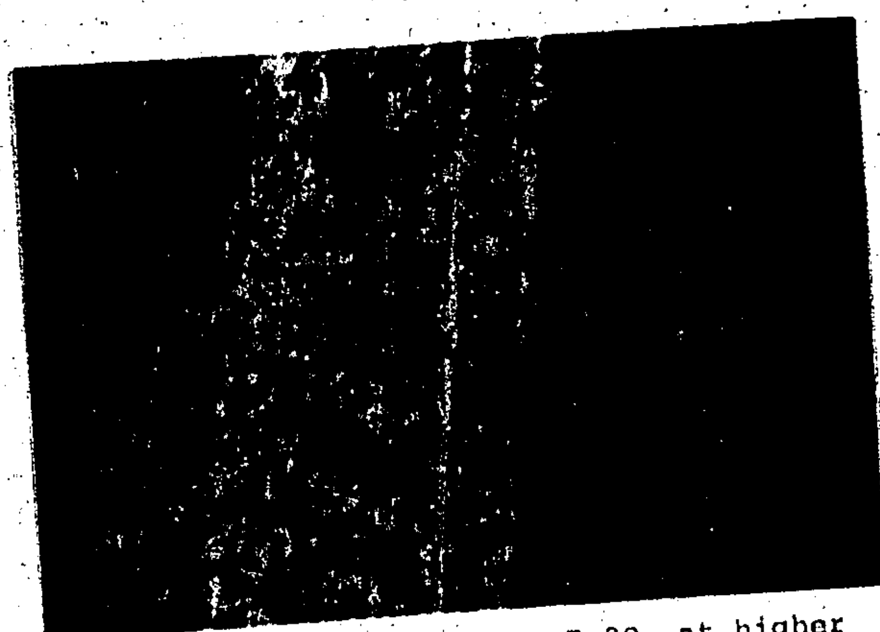


Fig. 7-21. Same as Fig. 7-20, at higher magnification, 840X

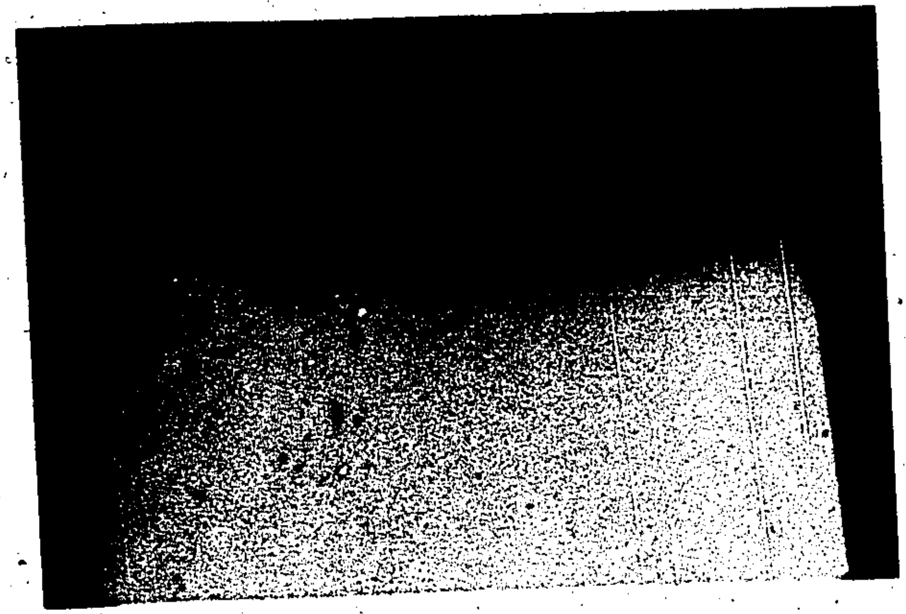


Fig. 7-22. Same as Fig. 7-20 but this shows the rake face. 15.4X

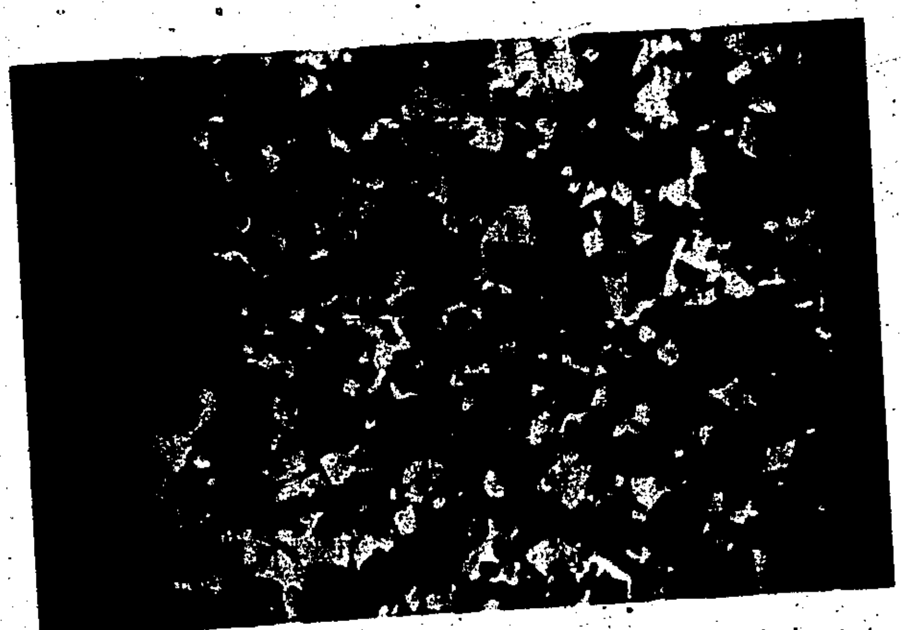


Fig. 7-23. Same as Fig. 7-22, at higher magnification. 1540X

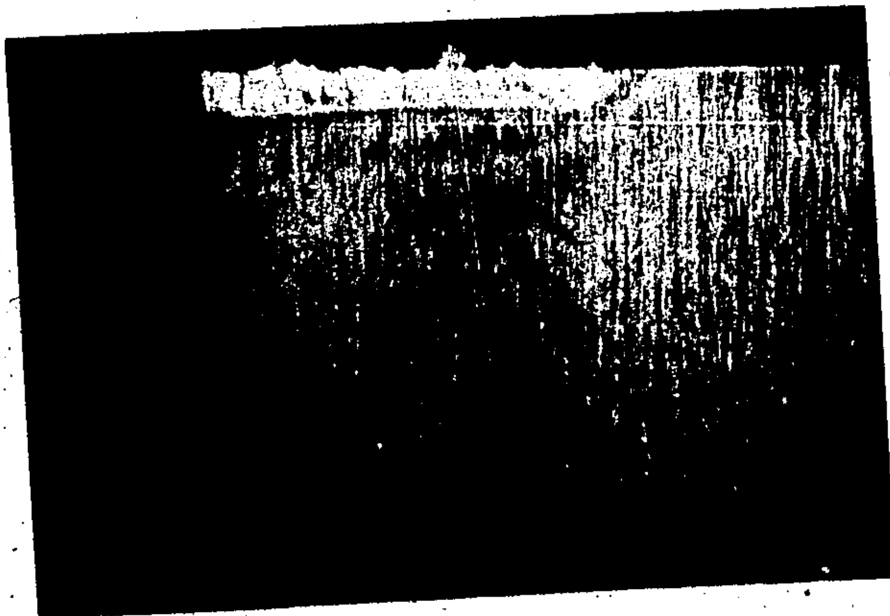


Fig. 7-24. Test #8, H.S.S. on Steel,
V = 98.21 ft/min, S = 0.0022 in/rev, R = 2

Fig. 7-25. Test #6, H.S.S. on Steel,
V = 98.21 ft/min, S = 0.0022 in/rev, R = 1

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