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An Investigation into the Machining of Titanium 150A in the Forged State

- by -

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SUMMARY

Tests to investigate various aspects of machining have been carried out at The College of Aeronautics on a billet of Titanium - 150A, hot forged by High Duty Alloys. Measurements were made of the drilling forces, and an investigation of the cutting force when turning the blank was made. Tests were also made to determine the effect on tool life of tool shape, cutting speeds, of various rates of feed and of cutting lubricants and coolants.

Conclusions are drawn as to the best tool angles for roughing and finish machining, the best tool grades for turning Ti-150A, and suitable speeds, feeds and lubricants.

This report is based on sections of a thesis submitted in June 1954 by Mr. J.T.D. Holt as a part of the requirements for the award of the Diploma of The College of Aeronautics. Mr. J. Purcell added the results of further tests and prepared the paper for publication.

1. INTRODUCTION

A series of tests has been made at The College of Aeronautics on the maching of Titanium 150A in the forged state. A billet of $4\frac{1}{2}$ in. diameter, of suitable length, was hot forged at the High Duty Alloys plant to the form of turbine rotor blank shown in Figures 1A and B.

The machinability investigation started on the blank in the condition as forged, i.e. it included scale removal by the cutting tools as a preliminary investigation.

The report covers the measurement of drilling forces when drilling in the excessively-worked flash material taken from the forging and also in the base metal; an investigation of the three components of the cutting force when turning the blank in the scale and immediate area under the scale and in the base metal; a determination of the relation between tool shape, cutting speeds and tool life, and in particular the cutting edge side rake and tool life, the clearance angles on tool forces and tool life, cutting speed and tool life, and cutting edge back rake. It continues with the effect on cutting forces and life of various rates of feed, and the effect on tool life of cutting lubricants and coolants such as CO_2, mineral oils and oils soluble in water, together with methods of their application.

2. DRILLING TESTS

As can be seen from Figure 1A, the Titanium 150A forged blank, as supplied, carried a flash around its perimeter of some 3/16" thick and 1/4" to 3/8" wide. After removal of a segment of this flash to provide intermittent cutting for the preliminary turning operation, the removed flash was used to investigate drilling, with high-speed steel tools. These small section pieces of the material could represent forged Titanium 150A in its worst possible condition.

Equipment: Single spindle drilling machine (good condition).
The College of Aeronautics drilling dynamometer.

Tool: Standard high-speed steel twist drills
3/16" diameter 26° spiral angle.
118° point angle, 12° clearance angle.
V.P.N. average:- 750.

Speed: Constant 520 revolutions per minute

Feed: As shown in the following tabulated results.

Cutting and soluble oil was applied but was found to be almost ineffective, and all results are therefore given for cutting dry.

Drill life was very short - average 30 seconds, under the conditions of this test. Table I shows the results for the drilling tests of Titanium 150A.

TABLE I

Drilling Forces in Flash Material

Titanium 150A - - - - - - - V.P.N. 275-400

Feed in inches	Actual Reading from 4 Tests	
	Thrust in pounds	Torque in inch pounds
0.002	157	8.5
	165	9.5
	149	10.0
	181	9.5
	Average 163	9.4
0.003	227	13.5
	205	14.2
	223	14.0
	220	14.2
	Average 219	14.0
0.004	275	17.0
	315	18.2
	328	18.5
	256	17.0
	Average 294	17.7

/For ....

For comparison, the following are forces when drilling under similar conditions with Bright Drawn Mild Steel, S 11 Steel, T1-75 alloy, and Nimonic 90.

TABLE II

MATERIAL	FEEDS					
	0.002"		0.003"		0.004"	
	ins.lbs.	lbs.	ins.lbs.	lbs.	ins.lbs.	lbs.
	Torque	Thrust	Torque	Thrust	Torque	Thrust
B.M.S.	8.5	90	12	119	14.7	151
S 11	9.3	122	13.5	165.6	15.5	201
T1-75	5.1	100	10.2	129.5	13.6	159
Nimonic 90	11	250	16	320	-	-

/Table III ....

TABLE III

Forces for Drilling in Base Metal in Titanium 150A Blank

Feed in inches	Actual Reading from 4 Tests	
	Thrust in pounds	Torque in inch pounds
0.002	122	6.8
	128	7.0
	122.5	6.6
	120	6.8
	Average 123	6.8
0.003	162	8.5
	160	9.0
	160	8.3
	163	8.5
	Average 161	8.6
0.004	181	12.8
	180	13.0
	182	13.0
	179	12.5
	Average 180	12.8

NOTE: The variation from the average shows lower and more constant results than those obtained when drilling in flash material (Table I).

/3. Turning ....

3. TURNING TESTS AND FORCES

3.1 Turning on Rough Forging

The forged blank was flange mounted on a rigid spigot (Figure 1B) and carried in the centre lathe chuck by the spigot and backed up by a tailstock live centre.

As stated in Section 2, the flash was sawn off part of the perimeter of the blank. The material removed was used for the drilling investigation while the remaining flash formed a severe intermittent cutting test for the turning tools. The removal of the flash and scale was commenced with a fairly soft grade Tungsten Carbide tipped tool, with the following characteristics:

Wimet S.58 1" x 3/4" section

Cutting edge Side Rake	+ 5°
Cutting edge Back Rake	- 3°
Plan Approach Angle	30°
Clearance Angles	6°

Surface speed used 25 ft. per minute

Feed 0.012 inches per revolution

Depth of cut varies from zero to 0.15 inches.

The standard tool geometry is shown in Figure 2.

These tools were found to be wearing rapidly, as was to be expected. Further runs were made with Wimet N.S. grade tools and Wimet H grade. The tool life in all cases was extremely short, being in the order of 2 to 4 minutes, the N.S. grades showing the best performance.

No cutting forces are included for this test, as the intermittent loading prevented the taking of readings which would have been of any use.

3.2 Cutting Close to Surface

The readings of cutting forces when cutting in the scale and the immediate area under the scale are given in Table IV.

The figures quoted were accepted only after three consecutive repeated values were found.

For comparison, Table V shows cutting forces for Bright Drawn Mild Steel, S 11, Nimonic 90, and Titanium 75. The tool

/shape ....

shape was constant for Tables IV and V, and was as follows:

Cutting edge Side Rake	+ 5°
Cutting edge Back Rake	0°
Plan Approach Angle	0°
Plan Trail Angle	6°
Clearance Angles	6°
Nose Radius	0.010 in.
Depth of Cut	0.050 in.
Surface Speed	86 ft. per minute

Tool finish honed 320 grade Diamond. 3-5 micro inches.

Cutting dry.

TABLE IV

Titanium 150-A

Feed m/m per rev.	0.12	0.25	0.30
Vertical force in pounds	40	83	115
Feed force in pounds	43	72	91
Back force in pounds	10	18	35

/Table V ....

TABLE V

All conditions as in Table IV.

BRIGHT MILD STEEL

Feed m/m per revolution	0.12	0.25	0.30
Vertical Force (pounds)	31	72.6	80
Feed Force (pounds)	39	60	64

STEEL S.11

Feed m/m per revolution	0.12	0.25	0.30
Vertical Force (pounds)	55	115	121
Feed Force (pounds)	56	98	105

NIMONIC 90

Feed in m/m per revolution	0.12	0.25	0.30
Vertical Force (pounds)	71	154	176
Feed Force (pounds)	60	100	110

TITANIUM 75

Feed in m/m per revolution	0.12	0.25	0.30
Vertical Force (pounds)	27.5	55	60
Feed Force (pounds)	46	60	64

/3.3 ....

3.3 Cutting forces when cutting in the base metal; scale and immediate area under scale removed before tests

From these tests, it was possible to determine the best maximum rake angle (this angle is sometimes called the 'true' rake angle).

As the maximum rake angle is the most important angle in metal cutting, extensive tests were taken for this part of the programme.

The constants of the geometry of the tool were as follows:

Plan Approach Angle	Zero
Cutting edge Back Rake	Zero
Plan Trail Angle	6°
Clearance Angles	6°

The varied angles - cutting edge side rake:
Range - $0^{\circ} + 5^{\circ} + 10^{\circ} + 15^{\circ} + 20^{\circ} + 25^{\circ} + 30^{\circ}$.

The best maximum rake angle was determined by measuring the cutting forces during the machining process using The College of Aeronautics Lathe Tool Dynamometer.

Depth of cut was constant at 0.050 ins., surface speed was constant at 88 ft. per minute; results are taken cutting dry.

The graphs in Figures 3 and 4 show the variation in cutting forces for the various side top rake angles at a number of feed rates. It may be seen that in each case the same trend occurs; the higher reading being at 0° side top rake with rapid decreases in cutting forces both vertical and feed, until side top rake + 15° to 20° is reached; further increase in this angle shows little or no improvement in force.

The back forces were not plotted on these curves as they were found to be negligible.

To show the trend of cutting force with increase in feed rate for constant tool angle (cutting edge side rake), Figure 3 is cross-plotted in Figure 5. The information thus obtained shows that cutting forces increase slightly from 0.1 m/m per revolution (0.004 in.) to 0.2 m/m per revolution (0.008 in.) and then increase more rapidly, i.e. the angle of slope of the force curve increases from the horizontal, and this implies that feeds up to 0.008 in. or 0.010 in. per revolution are most economical for the given set of conditions.

Further reference to Figure 3 shows, as stated previously, that the steep decline in cutting forces flattens out at approximately 15° to 20° cutting edge side rake. Thus, for an angle of 20°, we shall be consuming the least horse power per unit of metal removal.

/This ....

This fact is useful for machine loading up to full capacity, if the stock to be removed from the workpiece permits full cutting capacity to be exploited.

This large volume stock removal is seldom required and when we consider the tool life which is often the more important factor, it may be seen from Figures 3 and 4 that a 10° to $12\frac{1}{2}$° cutting edge side rake will take full advantage of reduction of tool forces and not sacrifice tool cross section.

A choice of maximum rake angle in this area often proves to be the best angle for economic tool life, as will be seen in Section 4 on tool life.

4. THE RELATIONSHIP BETWEEN SURFACE SPEED AND TOOL LIFE

4.1 Definition of Tool Life

The tool life is based on either (a) the duration of cut between re-grinds (Tungsten Carbide Tipped Tools), or (b) complete tool breakdown, often used in high-speed steel life tests.

All conditions other than surface speed of the workpiece are made constant, and a further precaution against variables is to use one tool only, running at each speed and re-grinding the same tool before a further run.

A study of the wear of Tungsten Carbide tipped tools has resulted in a practice of running these until a pre-determined amount of wear takes place, usually 0.030 in. flank loss; if breakdown were used, the tool would probably be destroyed completely.

In these particular tests, a wear of 0.015 in. was taken as tool life; this value is found to take advantage of the most efficient cutting period when applied to Titanium 150A, as after such wear is attained rapid increase in wear occurs.

4.2 The Effect of Cutting Edge Side Rake on Tool Life

In paragraph 3.3 an indication of best tool angle was shown to be between 10° and 15° maximum rake angle.

In many previous investigations, this method of determination of best tool shape, from cutting tool forces curve, has been found a reliable indication of best life, but a full test was carried out in this new material to ensure there were no unique characteristics in this respect. Hence the programme covered the full range of cutting edge side rakes, including one in a negative sense, i.e. -5°.

/Six ....

Six tools were selected, each being ground progressively from -5° to $+30^{\circ}$ cutting edge side rake. Wear measurement was made after a constant tool path for each angle, the results of these tests being shown in the graph in Figure 6.

The results show that minimum wear is obtained for a cutting edge side rake between $+10^{\circ}$ and $+15^{\circ}$, i.e. wear decreasing from -5° to $+10^{\circ}$ and increasing from $+15^{\circ}$. When angles $+25^{\circ}$ to $+30^{\circ}$ were applied, the cutting edge failed almost immediately.

The Taylor Hobson Talysurf was used to measure the amount of wear and independent check was made by using a toolmakers microscope. These two methods were found to give identical values.

4.3 Clearance Angles

The clearance angles were taken at 6° initially and remained constant at this value during the tests. It was quite possible that this first choice was not at optimum, hence the side and front clearance angles were varied.

The optimum clearance angle was determined by measuring the cutting forces and tool wear at a number of feeds for the various clearance angles.

Cutting condition constants were:

Depth of cut	0.050 ins.
Surface speed	138 ft. per minute
Feed range	0.05 m/m (0.002 in.) in steps of 0.05 m/m (0.002 in.) to maximum 0.3 m/m (0.0133 in.) per revolution.

From the results shown in Figures 7, 8 and 9, it is seen that there does not appear to be a great deal of difference between results from various clearance angles so far as cutting forces are concerned. The 8° and 10° angles showed slight decreases in cutting forces. Wear, however, showed a very different result, and there is no doubt that the 6° clearance should lead to the best tool life. Figure 9 particularly shows these results graphically.

/4.4 ....

4.4 The Relationship between Surface Cutting Speed and Tool Life

To determine the relationship between speed and life, all cutting conditions other than surface speed are made constant; these constants were set in this case as follows:

Tool	Cutanit ICC
Feed	0.010 ins. per revolution
Maximum Rake Angle	15°
Plan Approach Angle	0°
Cutting edge Back Rake	0°
Clearance Angles	6°
Nose radius	0.010 ins.
Depth of cut	0.050 ins.
Tool finish	3 to 5 micro-inches.
Cutting	Dry

A study in the type of breakdown and wear which takes place on Tungsten Carbide tipped tools shows that breakdown is not confined to the cutting edge, but splintering often occurs affecting a large portion of the carbide tip. Re-grinding is often impossible and even where there is sufficient Carbide left, the complete failure practice would be uneconomical, as so much metal must be removed to present a new cutting edge.

4.5 Cutting Edge Back Rake

In addition to the angles found in paragraphs 3.3 and 4.3, there is one further angle which could be varied, namely "cutting edge back rake" (see Figure 2). This could be either positive or negative. With modern heavy duty Carbide tools, negative rake is usually used.

During the tests on this angle, it was found that up to -3° showed no improvement or depreciation in forces, but values greater than -3° gave rapid force increases, also heat generation appeared to increase wear. At -2° cutting edge back rake, force and wear measurements were similar to those at zero cutting edge back rake angles, hence this value is adopted.

Therefore, the angles found to be best are:

2° (negative) Cutting edge back rake
15° Maximum rake angle, i.e. angle normal to cutting edge of 14° 52'
6° Clearance angles (side and front)
0.010 ins. Nose radius.

/The ....

The use of plan approach angle does not reduce total load, but cutting edge unit load due to chip thickness being reduced an approach angle of 10° is recommended where possible.

4.6 Life Tests

With the aforementioned breakdown characteristics in mind, it was decided to run the test until 0.015 in. flank "wearland" occurred on the tool side flank. This can be done with complete confidence, as it is serving a comparative role only.

Tool life values were obtained over a range of surface speeds varying from 50 to 150 ft. per minute. The tool life curve obtained from the tests is shown in Figure 10, from which it will be seen that life is extremely short at speeds above 100 ft. per minute. Below 100 ft. per minute, tool life increases until approximately 50 ft. per minute, the curve tending to become asymptotic.

The tool life curve is hyperbolic in shape and can be expressed in the form $VT^{n} = C$, this formula expressing the relationship between cutting speed and tool life per given tool feed and depth of cut. On log-log paper, a straight line is produced, the formula now being $\mathrm{Log}\ V = \mathrm{Log}\ C - n \log T$, the slope n of the line being negative and equal to Y/X and $C = V_1$ (in feet per minute for a 1-minute tool life. The results of this log-log plot are shown in Figure 11 and the constants calculated. For the given set of conditions in this test, the formula becomes:

$$VT^{0.133} = 102.$$

It is preferable to use the curve plotted on Cartesian co-ordinates to those on log-log paper, as the hyperbolic curve gives a far better picture of exactly what is happening during the test. The curve on log-log paper is an aid to determining formula and also evaluating the expected tool life at speeds other than those tested.

It is to be noted that the formula $VT^{n} = C$ has been made the subject of an investigation and found to hold good for a life as short as 6 seconds and as long as 18 hours.[*]

Figure 12 shows time/wear curve for 50 surface feet per minute and the effect of cutting time on wear is clearly shown.

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[*] Unpublished Thesis by J.F.H. Goddard - "Investigations into High Pressure Lubrication of Metal Cutting Tools" (1953).

5. THE EFFECT OF FEED ON WEAR OF TOOL

The method was similar to that used in the previous tests and 'wearland' was plotted against feed.

The tool was exactly as in paragraph 4.4 (i.e. 15° maximum rake angle). Cutting speed was fixed at 178 surface feet per minute with the feeds varying from 0.005 in. per revolution to 0.010 in. per revolution.

Figure 13 shows the results, which, when related to pressure against feed curve - Figure 5 (derived from a cross plot of Figure 3), indicates that pressure and wear are, in this case, similar parameters and permits the use of the pressure data to determine tool life.

6. THE EFFECTS ON TOOL LIFE OF CUTTING LUBRICANTS AND COOLANTS, TOGETHER WITH METHODS OF APPLICATION

The generation of heat and high pressures during the cutting process on Titanium 150A necessitates the use of coolants and lubricants.

The investigation into the best lubricant and coolants was carried out by making comparisons from a base cutting dry; the scope of these tests covers application of:

1. Carbon Dioxide (CO_2);
2. Straight mineral oil by Hi-Jet;
3. Soluble oil in water 1 to 15 ratio;
4. Straight cutting oil;

(3) and (4) being applied by the overhead gravity method.

6.1 CO_2 Coolant

The technique known as CeDeCut used in this test has been developed by Carbon Dioxide Co. of Epsom. The method is to provide a reservoir of this coolant under the tool tip, and prevent the access to the chip, where the maximum temperature is required, allowing the heat generated by shear to maintain the chip in a plastic state. The exhausted coolant is discharged into the workpiece below the cutting zone and assists in maintaining it at normal temperature.

Details of this method of cooling and the equipment are available from The Carbon Dioxide Co., which kindly provided the apparatus for these investigations.

/For ....

For this test, the tool used was Cutanit ICC grade Tungsten Carbide tipped, modified as CeDeCut method to incorporate CO_2 capillary tube.

Rate of flow of CO_2	5 pounds per hour
Depth of cut	0.050 inches
Feed per revolution	0.010 inches
Surface speed	95 feet per minute
Maximum rake angle	15^o
Plan approach angle	0^o
Cutting edge back rake	0^o
Clearance angles	6^o
Nose Radius	0.010 inches

The 0.015 inches 'wearland' was reached after 2 mins. 45 secs. cutting time as against cutting dry 1 min. 10 secs.

6.2 Hi-Jet Lubrication

By this method, straight mineral oil is forced through a jet at a pressure of 400 lb. per sq. in., velocity approximately 275 ft. per second, between the tool side flank clearance and the workpiece.

Cutting conditions and tool geometry were constant as for the CO_2 tests; the 0.015 ins. flank 'wearland' occurred at 4 mins. 30 secs. This result is very good, being four times that of the base dry 1 min. 10 secs.

6.3. Overhead Application of Straight Mineral Oil

In this test straight mineral oil was applied in the overhead manner generally used in machine shops. The type of oil was the same as that used in the Hi-Jet test; results do not compare favourably with the Hi-Jet method of application, tool life being 0.015 in. flank wear in 1 min. 20 secs.

6.4 Soluble Oil

The standard soluble oil in water was applied by the overhead method and found to be similar in effect on tool life to straight mineral oil when applied in this way, i.e. life 1 min. 20 secs., taking experimental error into account, no improvement would be claimed from overhead methods with straight mineral oil or soluble oil compared with the base dry.

/6.5 ....

6.5 Summary of Lubrication Tests

From the results obtained during these tests, it appears that Hi-Jet gives the best performance, showing an increase of tool life of four times the base dry. Table VI gives the details of the tests and the life attained.

From the point of view of reclaiming the swarf for remelting purposes, CO_2 would probably be more economical for leaves the swarf uncontaminated. If acceptable results could be obtained from a cleansing process of the swarf, 'Hi-Jet' would have to be reconsidered.

All test results in this section are the average when three tools are taken to 0.015 in. flank wear with a variation in life of 5 seconds between any accepted reading from similar test runs.

TABLE VI

Comparisons of Cutting Fluids

Method	Tool Life
Cutting Dry	1 minute 10 seconds
CO_2 Coolant	2 minutes 45 seconds
Hi-Jet Lubrication (straight mineral oil)	4 minutes 30 seconds
Overhead Application	
Straight mineral oil	1 minute 20 seconds
6% Soluble oil in water	1 minute 20 seconds.

7. CONCLUSIONS

7.1 Tool Grade

The best grade of tip was found to be WIMET N.S. Grade or other makers' equivalents. Nine different makes of tool were tested and the wear at the end of one minute was measured.

/7.2 ....

7.2 The Tool Geometry

The geometry of the lathe tool found to give best results is:

Cutting edge back rake	-2°
Cutting edge side rake	+14° 52' (maximum rake angle +15°)
Side clearance angle	6°
Front clearance angle	6°
Nose radius	0.010 inches
Plan trail angle	6°

Where possible a 10° plan approach angle should be used.

7.3 Surface Speed

The most economic point in the conditions of this test was 50 - 60 surface feet per minute, which gave a life of 30 minutes.

7.4 Feed

The life of the tool when cutting at feed rates up to 0.010 ins. per revolution is satisfactory.

7.5 Coolants

Carbon dioxide cooling increases tool life $2\frac{1}{2}$ times over the base (cutting dry) and leaves the swarf clean for recovery.

Straight mineral oil applied by the Hi-Jet method gave a four to one increase over the base dry, but swarf is contaminated.

7.6 Special Note

The swarf from Titanium 150A forgings will ignite and burn rapidly under certain cutting conditions, see Appendix III.

/Appendix I .....

APPENDIX I

Hardness Tests

Vickers penetration number (V.P.N.) hardness tests were made on the forging at various depths as cutting proceeded.

(a) The first tests were made before the determination of best composite rake angle was started, i.e. on the major diameter of the forged block after flash and scale removal. The variation in hardness was found to be quite considerable, ranging from 346 to 406 V.P.N.

(b) The second hardness tests were made after the maximum rake angle had been determined, and after approximately 3/4 in. in radius of bright metal had been removed, the variation then found being 368 to 413 V.P.N. A number of tools were broken down during the course of the angle tests; the character of failure appeared to be due to hard inclusions; the radial reduction at this critical point was approximately $1\frac{1}{4}$ inches.

(c) Final hardness tests were taken after all preliminary machining was completed, radial reduction then being 3 ins., the V.P.N. at this point being 375 to 413. It would appear that more consistent figures for V.P.N. are being obtained nearer the centre of the forging.

See Figure 14 for actual results of hardness tests, each value being the average of three impressions.

The variation in hardness obtained can be attributed to the quantity of oxygen and nitrogen existing in the material. These elements are soluble in the molten material and form solid solutions or non-metallic inclusions. The Henderson Research Laboratory of the Titanium Metals Corporation of America have published data showing the graphical correlation of oxygen and nitrogen values in Titanium with hardness. The data shows the effects these interstitial elements have on Titanium. An increase of only 0.04% oxygen will increase the V.P.N. by 20.

The hardness figures quoted by Titanium Metals Corporation for Ti-150A are 340 to 400 V.P.N., so except for a few spots in the material, our results agree with those of the Henderson Laboratory.

/Appendix II ....

APPENDIX II

Determination of Mayer Exponent

The Mayer exponent gives a measure of the capacity of a metal to strain hardening. It gives an indication of the amount of hardening to be expected due to the strain imposed on the metal in cutting. The hardening which the metal undergoes during the cutting process due to plastic deformation has an appreciable effect on the life of the cutting tool.

The exponent is derived from the relationship between load applied by a spherical indenter or ball, as in the Brinell machine to the diameter of the impression caused by the load.

The relationship is of the form

$$L = a\,d^n$$

where

L = applied load Kg.

d = diameter of indentation in m/m

a = constant characteristic of the metal and the diameter of the ball

n = Mayer component.

If the load is plotted against indentation on log-log paper, a straight line results. The slope of this line gives the Mayer exponent n. This exponent must be equal to or greater than 2. A Mayer exponent of 2 signifies that the material has no capacity for work hardening.

The tests were carried out on a Brinell machine using a 10 m/m diameter ball. The results obtained give a Mayer number of approximately 2.25. This value signified that Titanium 150A forged has appreciable work-hardening characteristics.

Results reported by the University of Michigan give the Mayer number for Titanium 150A forged as 2.27.

/Appendix III ....

APPENDIX III

Imflammability of Titanium Swarf

Under certain machining conditions, the swarf cut from Titanium 150A forging becomes ignited. This would appear to take place when the chip cross section is small and surface speed high, i.e. finishing cuts.

The surface speed/cross section of chip relationship to ignition point is not constant but is influenced directly by tool cutting edge wear. For example, a tool ground to the shape recommended in this report was applied at a surface speed of 520 ft. per min. with 0.015 in. depth of cut, and 0.001 in. feed per rev: after cutting for 3 seconds the swarf ignited. The surface speed was reduced to 55 ft. per min. and feed increased to 0.005 in., depth of cut remaining at 0.015 in. After using this tool under these conditions for a period of eight minutes a 0.009 in. flank wearland was produced.

A further finishing test was then made with this worn tool, and at 380 ft. per minute ignition of the swarf occurred. (Feed and depth of cut were as on the previous test, i.e. 0.001 in. and 0.015 in. respectively). It was noticed that a heavily-worn tool tended to ignite the swarf at speeds as low as 75ft. per minute.

It is advised that greater importance be given to the speed-life curve and that a speed and useful life should be selected which is well below the ultimate life of the cutting tool.

A further critical point exists when the tool feed is disengaged. The tool should be withdrawn from engagement with the workpiece immediately, as rubbing is extremely severe on the tool, and should the small particles produced by rubbing become ignited, the heavier strips will also ignite.

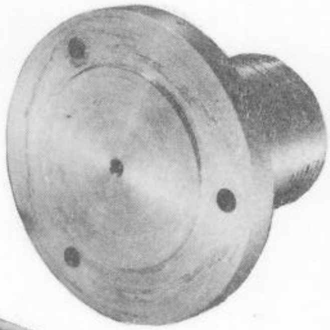
Figure 15 shows a typical photograph of a Titanium alloy fire at the cutting face.

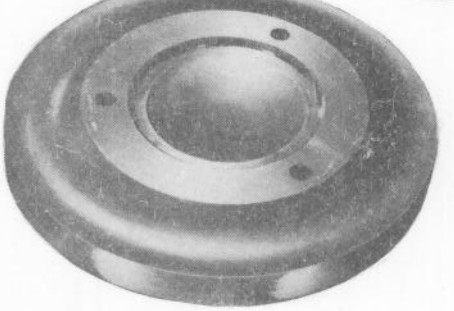
TITANIUM ROTOR BLANK

AS RECEIVED

Dimensions 12ins Dia. X 2ins thk.
Wieght 26lb 11ozs

FIG. 1 A



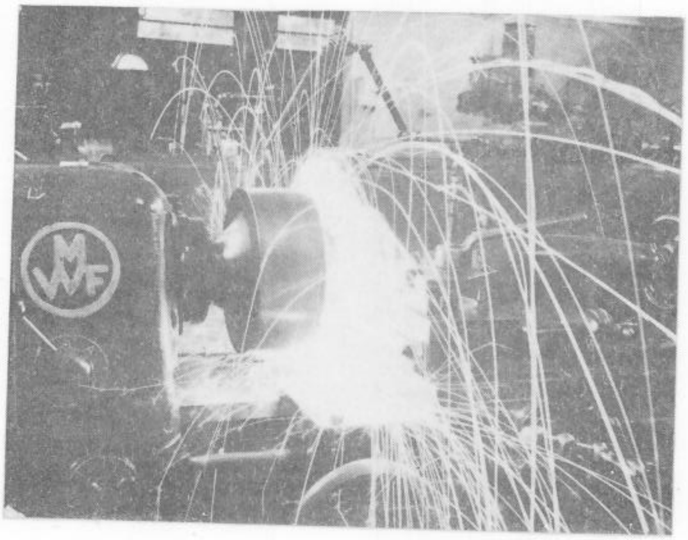


PARTIALLY MACHINED

FORGING AND MOUNTING

SPIGOT

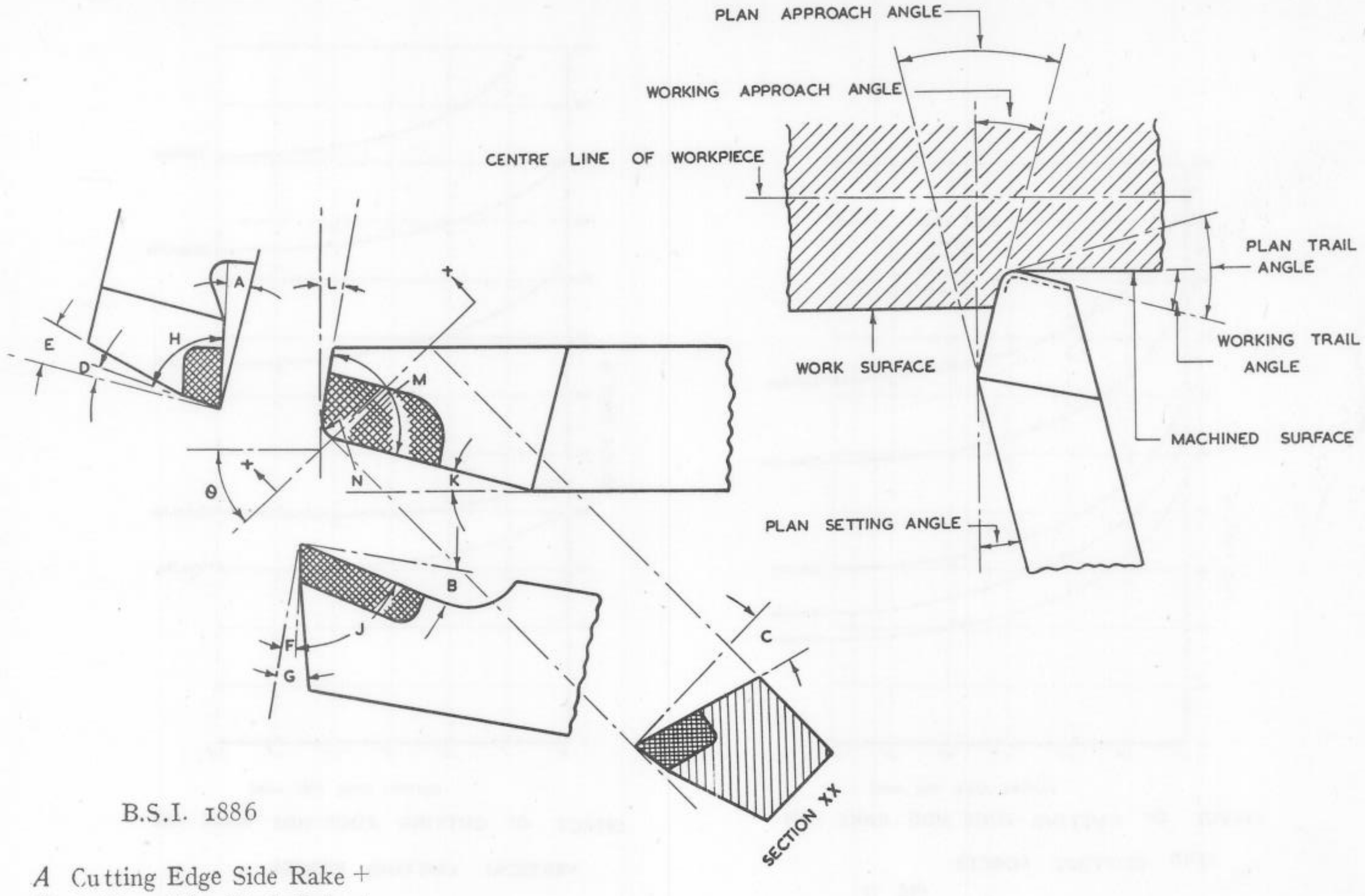
FIG. 1 B



TYPICAL TITANIUM FIRE

FIG. 15

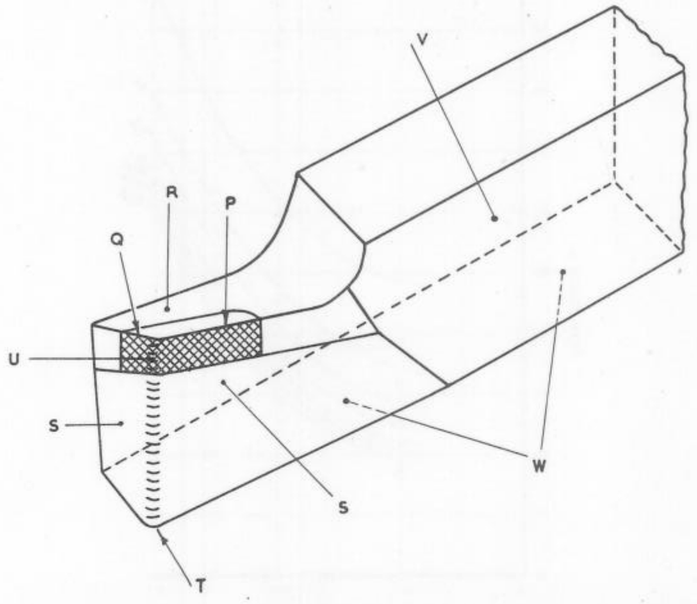
FIG. 2



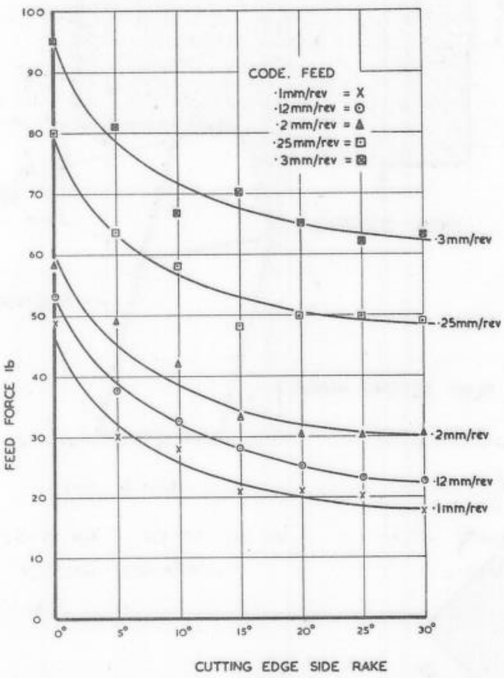
B.S.I. 1886

A	Cutting Edge Side Rake +
B	Cutting Edge Back Rake +
C	Maximum Rake Angle
D	Side Clearance Angle
E	Secondary Side Clearance Angle
F	Front Clearance Angle
G	Secondary Front Clearance Angle
H	Side Wedge Angle
J	Front Wedge Angle
K	Plan Approach Angle
L	Plan Trial Angle
M	Included Plan Angle
N	Nose Radius
θ	Maximum Rake Plan Angle
P	Side Cutting Edge
Q	Front Cutting Edge
R	Face
S	Flank
T	Heel
U	Nose
V	Shank
W	Base

+ *German System*

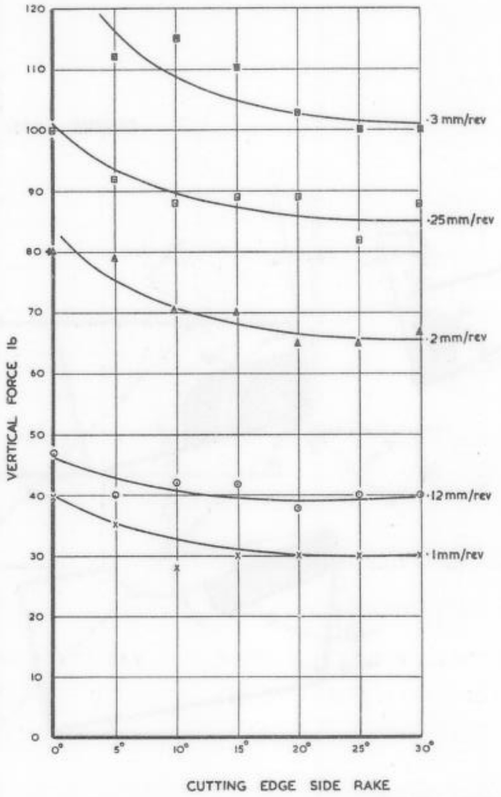


TOOL GEOMETRY



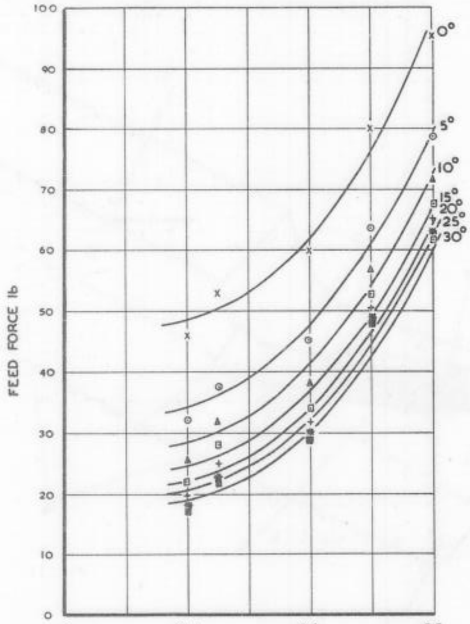
EFFECT OF CUTTING EDGE SIDE RAKE ON FEED CUTTING FORCES

FIG. 3



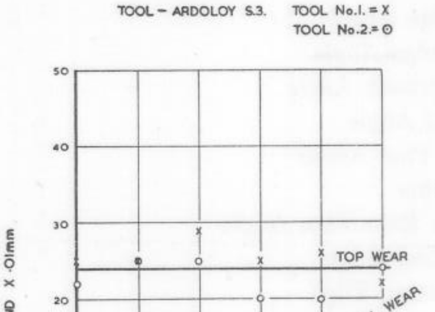
EFFECT OF CUTTING EDGE SIDE RAKE ON VERTICAL CUTTING FORCES

FIG. 4



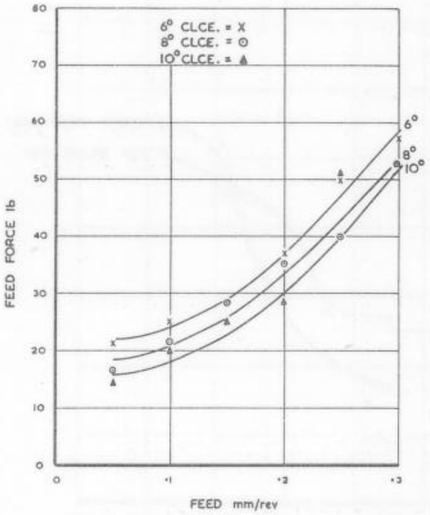
EFFECT OF FEED ON FEED CUTTING FORCE

FIG. 5



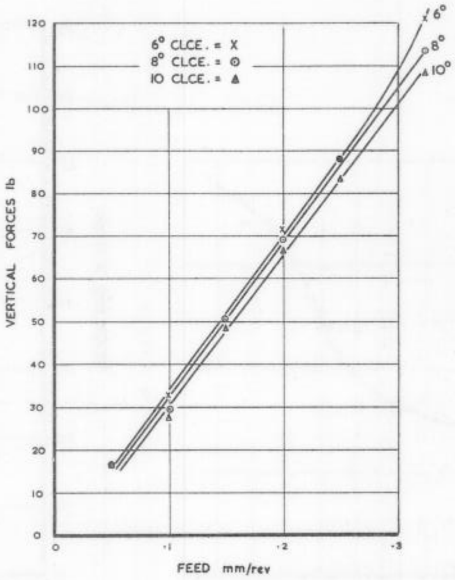
EFFECT OF CUTTING EDGE SIDE RAKE ON TOP & FLANK WEARLANDS

FIG. 6



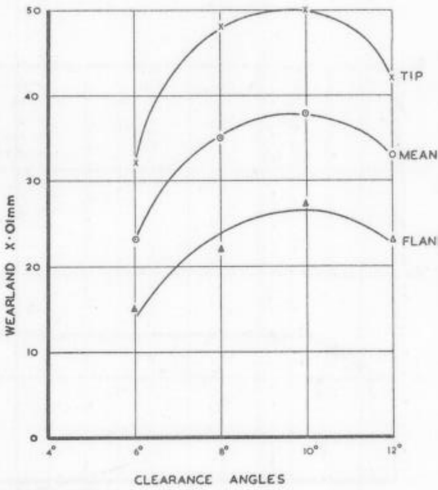
VARIATION OF FEED FORCE ON FEED FOR CLEARANCE ANGLES

FIG. 7



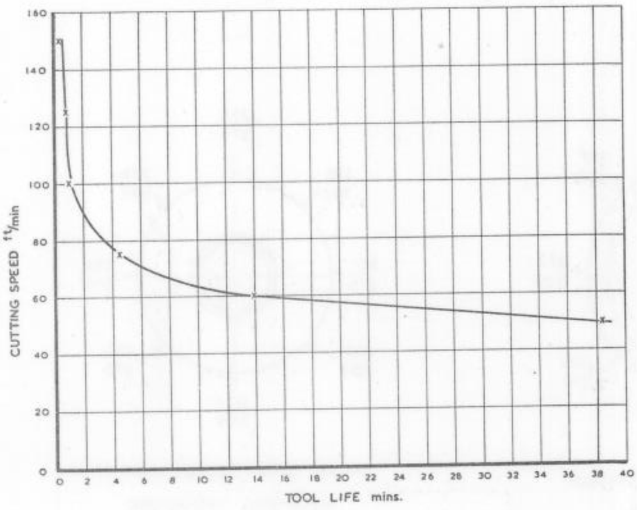
VARIATION OF VERTICAL FORCE WITH FEED CLEARANCE ANGLES

FIG. 8



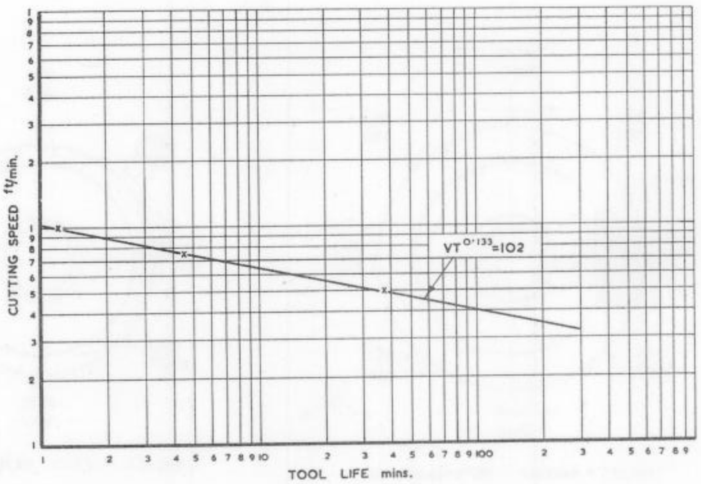
VARIATION OF FLANK WEAR ON CLEARANCE ANGLES

FIG. 9



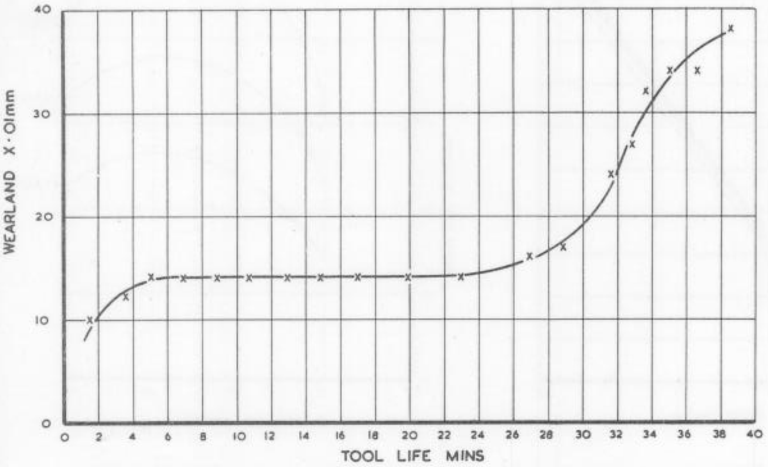
RELATION BETWEEN CUTTING SPEED & TOOL LIFE

FIG. 10



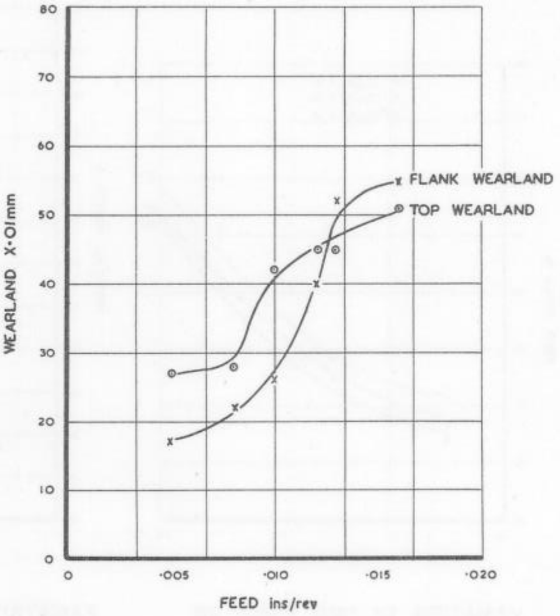
RELATION BETWEEN CUTTING SPEED & TOOL LIFE

FIG. 11



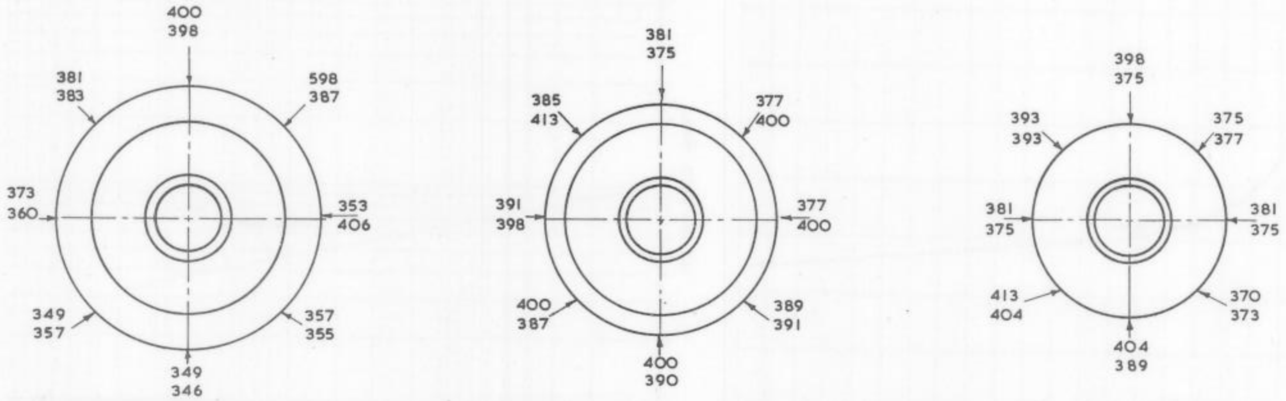
EFFECT OF WEAR ON TOOL LIFE AT A CUTTING SPEED OF 50ft/Min.

FIG. 12



EFFECT OF FEED ON WEARLAND

FIG. 13



VALUES BEFORE DETERMINATION OF RAKE ANGLES

VALUES AFTER DETERMINATION OF RAKE ANGLES

VALUES AFTER COMPLETION OF MACHINING PROGRAMME

VPN HARDNESS TESTS ON TITANIUM 150A FORGING

FIG. 14