ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

Final Report

# MACHINING TITANIUM

O. W. Boston
R. M. Caddell
L. V. Colwell
R. E. McKee
K. F. Packer
P. R. Visser

Production Engineering Department

Project 1993

DETROIT ORDNANCE DISTRICT, DEPARTMENT OF THE ARMY
CONTRACT NO. 20-018-ORD-11918
DETROIT, MICHIGAN

June 1955

TABLE OF CONTENTS

| | Page |
|---|---|
| LIST OF FIGURES | vi |
| LIST OF TABLES | xii |
| OBJECTIVE | xiii |
| CHAPTER I. INTRODUCTION, by L. V. Colwell | 1 |
| CHAPTER II. GENERAL PROPERTIES OF TITANIUM, by W. C. Truckenmiller and K. F. Packer | 3 |
| CHAPTER III. COMMON CUTTING PROPERTIES, by L. V. Colwell | 9 |
| CHIP FORMATION | 9 |
| SHEAR ANGLE | 9 |
| Built-up Edge | 12 |
| Work Hardening | 15 |
| CUTTING TEMPERATURE | 17 |
| CUTTING FORCES | 20 |
| Tangential and Normal Force | 20 |
| Effect of Tool Angles | 20 |
| Effect of Size of Cut | 23 |
| Effect of Cutting Fluids | 23 |
| POWER | 25 |
| TOOL LIFE | 27 |
| Effect of Coolants | 29 |
| SURFACE FINISH | 30 |
| SIZE CONTROL | 32 |
| CHAPTER IV. LATHE OPERATIONS, by R. M. Caddell | 33 |
| REVIEW OF IMPORTANT FACTORS | 33 |
| SUMMARY OF TEST RESULTS | 33 |
| RECOMMENDED PRACTICE | 34 |
| A. Tool Design | 34 |

| | |
|---|---|
| B. Size of Cut | 39 |
| C. Cutting Speed | 41 |
| D. Cutting Fluids | 42 |
| CHAPTER V. MILLING, by R. E. McKee | 43 |
| REVIEW OF IMPORTANT FACTORS | 43 |
| SUMMARY OF TEST RESULTS | 43 |
| A. High-Speed-Steel Tools | 43 |
| B. Sintered-Carbide Tools | 44 |
| RECOMMENDED PRACTICE | 46 |
| A. Tool Design | 46 |
| B. Size of Cut | 47 |
| C. Cutting Speeds | 48 |
| D. Cutting Fluids | 49 |
| CHAPTER VI. DRILLING, by P. R. Visser | 50 |
| REVIEW OF IMPORTANT FACTORS | 50 |
| SUMMARY OF TEST RESULTS | 52 |
| RECOMMENDED PRACTICE | 55 |
| DEEP-HOLE DRILLING | 55 |
| CHAPTER VII. BROACHING, by R. E. McKee | 57 |
| REVIEW OF IMPORTANT FACTORS | 57 |
| SUMMARY OF RESULTS | 57 |
| RECOMMENDED PRACTICE | 59 |
| A. Tool Design | 59 |
| B. Size of Cut | 59 |
| C. Cutting Speed | 60 |
| D. Cutting Fluids | 60 |
| CHAPTER VIII. SHAPING, by R. E. McKee | 61 |
| IMPORTANT FACTORS | 61 |
| SUMMARY OF TESTS | 62 |
| RECOMMENDED PRACTICE | 64 |
| A. Machine Setup | 64 |
| B. Tool Design | 64 |
| C. Cutting Speed | 64 |
| D. Size of Cut | 65 |
| CHAPTER IX. TAPPING, by P. R. Visser | 66 |
| UNIQUE FACTORS | 66 |
| SUMMARY OF TESTS | 66 |
| RECOMMENDED PRACTICE | 67 |
| A. Tap Design | 67 |

B. Cutting Speed 68
C. Cutting Fluids 68

CHAPTER X. REAMING, by R. M. Caddell 69
UNIQUE FACTORS 69
TEST RESULTS 69
RECOMMENDED PRACTICE 70
A. Tool Design 70
B. Feed, Speed, and Depth of Cut 71
C. Cutting Fluids 73

CHAPTER XI. SAWING, by R. E. McKee 76
UNIQUE FACTORS 76
TEST RESULTS 76
A. Hacksawing 76
B. Bandsawing 78
RECOMMENDED PRACTICE 80
A. Hacksawing 80
B. Bandsawing 82

CHAPTER XII. CUTTING FLUIDS, by R. M. Caddell 84
CLASSIFICATIONS AND FUNCTIONS 84
REVIEW OF TEST RESULTS 85
RECOMMENDED PRACTICE 86
A. Coolants 86
B. Lubricants 91

# LIST OF FIGURES

Page

CHAPTER II

1. Strength of titanium compared to iron and aluminum. 4

2. Relative weights of equal volumes of titanium, steel, and aluminum. 4

3. Diameters of round bars of equal strength. 6

4. Amount of deflection in beams of the same size and different materials when supporting the same load. 6

5. Heat-conduction characteristics of various metals. 7

6. Comparative ability of various materials to prevent temperature buildup during machining. 7

CHAPTER III

1. Chip formation versus material cut. 10

2. The shear angle when cutting steel and similar metals is relatively low as shown at (a). Titanium cuts with an unusually large shear angle as shown at (b). Chip thickness varies inversely with shear angle; thin chips accompany large shear angles while thick chips go along with small shear angles. 11

3. Chip formation versus titanium alloy for alloys 75A, 130B, and 150A. 14

4. Entrance conditions (shape of cut) versus rake angle for type 130B titanium alloy using smooth ground tools. 14

5. Grid specimens showing unit distortion and evidence of lateral stress in chip and work material for three titanium alloys. 16

6. A "grid specimen of 18-8 stainless steel machined at the same conditions as the titanium alloys illustrated in Fig. III-5. 17

7. Cutting temperatures measured at the same cutting speed for a range of materials correlate well with the cutting speed required to give a 60-minute tool life. The measured temperature for RC-130B probably is less than the actual temperature because of pulsating motion accompanying chip segmentation. 19

8. Nomenclature in common use for designating cutting forces on cutting tools. 19

9. Cutting force in the direction of cutting motion for SAE-1045 steel. Feed rate or chip thickness was varied as well as was the rake angle of the tools. 21

10. The normal or thrust force for cutting SAE-1045 steel for a range of feed rate and rake angle. 21

11. Cutting force for a titanium alloy when cutting at the same conditions as for steel shown in Fig. III-9. 22

12. Normal or thrust force for a titanium alloy showing that the thrust force with medium-to-large rake angles are substantially greater than for steel. 22

13. Effect of lubricants on torque requirements when tapping commercially pure titanium. 24

14. Titanium alloys exhibit the property of terminal cutting speed above which the torque requirements increase so rapidly that tap breakage may result. 25

15. Typical cutting speed tool life lines for three different sizes of cut when turning the titanium alloy. The dependency of tool life on cutting speed is orderly and predictable. 27

16. Effect of chip thickness or feed rate on the cutting speed required to produce constant tool life at all speed rates. This relationship is predictable. 28

17. The effect of tool rake angle on tool life. The optimum will be shifted to smaller angles with less rigidity and to larger angles with greater rigidity. 29

18. A typical example of the increase in cutting speed made possible by the use of effective coolants. 30

19. Surface finish in machining titanium is seldom a problem, since measured values of surface roughness seldom exceed half that of steel. 31

CHAPTER IV

1. The effect of rake angle on tool life when turning titanium RC-130B at 48 fpm. 35

2. The effect of rake angle on tool life when turning titanium Ti-150A at 74 fpm. 35

3. A summary of the effect of rake angle when turning several grades of titanium and steel. 35

4. A typical tool-life line obtained when turning titanium RC-130B with a tool having a rake angle of 24°. 35

5. The effect of side rake angle on the cutting speed for a one-hour tool life when turning titanium RC-130B. 36

6. The effect of nose radius on cutting speed for a one-hour tool life. 37

7. Typical wear curves showing the influence of rake angle when turning Ti-75A with a carbide tool. 38

8. A summary of Fig. IV-7 showing the influence of rake angle on tool life. 38

9. Effect of carbide tool material when turning titanium. 38

10. Typical comparison of two grades of carbide tool material. 38

11. The effect of feed on the cutting speed for a one-hour tool life. 40

12. The effect of depth of cut on the cutting speed for a one-hour tool life. 40

13. Family of tool-life lines for different feed rates. 41

CHAPTER VI

1. The effect of cutting speed on the depth of work hardening for titanium 75-A at a feed of .004 ipr. 51

2. The effect of drill sharpness on the depth of work hardening for Ti-75A, Ti-150A, and RC-130B. 51

3. Short drills are more rigid and can be expected to give longer life when drilling titanium. (By courtesy of the National Twist Drill and Tool Company of Rochester, Mich.) 52

4. Exponents and constants for the torque and thrust formulas as obtained in drilling pure titanium and various alloys. Actual torque, thrust, and unit horsepower values obtained when drilling these same materials with a 1/2-inch high-speed-steel drill at 225 rpm at 0.009 ipr feed. 53

5. Graphic representation of the torque and thrust values obtained when drilling titanium alloys with a 1/2-inch-diameter standard high-speed-steel drill at 29.4 fpm and various feeds. 53

6. Torque and thrust curves versus feed for SAE-1045 and various titanium alloys. 54

7. Torque and thrust curves versus drill diameter for SAE-1045 and various titanium alloys. 54

CHAPTER VIII

1. Machine requirements for shaping titanium. 61

2. Effect of cutting speed on tool life. Titanium oxide scale reduces tool life erratically. 62

3. Effect of feed rate on cutting speed for constant tool life. 63

4. Effect of depth of cut on cutting speed for constant tool life. 63

CHAPTER IX

1. The effect of cutting speed on torque for various titanium alloys. 67

CHAPTER X

1. The influence of margin width when reaming titanium Ti-75A. 70

2. This shows the effect of chatter due to having too small a margin width. 70

3. The effect of chatter at the entry of the hole, as caused by an excessive chamfer relief angle. 71

4. A scarred hole caused by excessive pickup of work material on the margin of the reamer. 72

5. The effect of feed when reaming titanium Ti-75A. 72

6. Typical examples of reamers run at excessive speeds and feeds. 73

7. Typical example of a reamer that picked up work material during reaming of a hole as shown in Fig. X-4. 73

8. Typical example of a reamer free from pickup after reaming a hole as shown in Fig. X-9. 74

9. Example of a reamed hole that has a good surface finish and is free from chatter, scars, and other defects. 74

10. Typical torque curves recorded by Sanborn equipment. 75

CHAPTER XII

1. A summary of experimental data showing the relative effectiveness of various cutting fluids on tool life when turning commercially pure titanium (Ti-75A). 87

2. A comparison of the results obtained when turning the titanium alloy RC-130B dry and with the water-base fluid. The use of this fluid indicated that the velocity for a ten-minute tool life, $V_{10}$, may be increased 40 percent above the velocity that would produce this same tool life when cutting dry. 87

3. Relative comparisons of various fluids showing the effect on torque when drilling titanium Ti-75A. 90

4. Relative comparisons of various fluids showing the effect on thrust when drilling titanium Ti-75A. 90

5. A summary of tapping and back-out torques required when tapping titanium Ti-75A using various cutting fluids. 91

6. The effect of cutting fluids when reaming titanium Ti-75A. 92

## LIST OF TABLES

Page

CHAPTER II

1. PHYSICAL PROPERTIES OF VARIOUS MATERIALS 8

CHAPTER IV

1. CUTTING SPEED FOR A ONE-HOUR TOOL LIFE 36

2. $V_{60}$ VERSUS FEED AND DEPTH OF CUT FOR RC-130B 40

CHAPTER XII

1. EFFECTIVENESS OF SODIUM NITRITE CUTTING FLUID ON TITANIUM ALLOYS 88

# OBJECTIVE

The objective of the project in machinability was to determine from a series of tests the machinability characteristics when cutting titanium and several of its alloys when face milling, turning, tapping, broaching, drilling—conventional and deep hole—and reaming, shaping, and sawing. For sake of background, a plain carbon steel and a stainless steel were similarly tested. The list of materials tested is as follows:

SAE 1045 Steel, hot rolled
304 Stainless steel (18 Ni and 8 Cr)
Ti-75A Titanium
RC-130B Titanium
RC-130A Titanium
Ti-150A Titanium
RC-110A Titanium
3Al-5Cr Titanium

Cutting speeds for given tool life, unit net horsepower at the cutter, which is the horsepower at the cutter required to remove one cubic inch of metal per minute, surface quality, and cutting temperatures are used as a basis of comparison. Tests in all processes were run with tools made of high-speed steel, and some tests in face milling, turning, and drilling were made with tools of sintered carbide.

Further details of the objective, together with a brief resumé of the report, are given in Chapter I, Introduction, page 1.

All these tests were run in the laboratories of the Department of Production Engineering at the University of Michigan as a project of the Engineering Research Institute.

# CHAPTER I

## INTRODUCTION

Titanium is not a new metal, but only in the last few years has it been available in sufficient quantities to be considered for industrial applications. Both government agencies and private industry have undertaken the development of better alloys of titanium and methods for processing them economically into finished products. This manuscript is the result of an investigation sponsored by the Watertown Arsenal into the problems involved in the machining of titanium. It is intended as a final report but, unlike most technical reports, the emphasis is on application of the results of the investigation. The objective will be to answer the question of how to machine titanium as simply and directly as possible. The detailed results of laboratory investigations will be included only where they serve to illustrate a point or where it seens desirable to substantiate a machining property that is either more important in titanium or non-existant in other metals.

Economical methods do not exist for quickly determining the best machining conditions for any metal, including cast iron, steel, aluminum, and the other materials that are machined in far greater quantities than titanium. In view of this factor and the limited funds available for studying titanium, it seemed advisable to concentrate on determining in what ways the necessary conditions for machining titanium differ from those in common use for steel. For this reason, both hot-rolled SAE-1045 steel and 18-8 stainless steel were tested along with titanium alloys in the laboratory investigations. Consequently, the emphasis in this report is on those situations where it is necessary to depart significantly from general practice in the machining of steel.

A further objective is to give recommended operating conditions as to tools, size of cut, cutting speeds, and cutting fluids. It is intended that these recommendations be conservative, but it is inevitable that situations will arise where they will prove to be optimistic. In other situations, they may prove to be ultraconservative. In any event, they should be considered only as a realistic starting point which can be improved upon.

Finally, an attempt is made to anticipate some of the troublesome problems that may be encountered in connection with each machining operation and to suggest useful approaches to the solution of those problems. Titanium does behave differently from some other metals and it is relatively difficult to machine when compared to ordinary, unhardened carbon steel. However, stainless steel and high-strength carbon or alloy steels present equally difficult problems. It has been found that such difficulties in connection with machining titanium can be kept at a minimum if due consideration is given to the unique cutting characteristics of titanium.

The second and third chapters are devoted to the unique physical and mechanical properties of titanium, while subsequent chapters take up specific machining operations. Chapter II presents a discussion of the mechanical properties of titanium alloys with emphasis on those properties which differ substantially from steel and which appear to be responsible for some of the unique machining characteristics.

Chapter III is a resumé of the machining properties which either are common to all cutting operations or assume particular significance in connection with a few operations. This includes the mechanism of chip formation, power requirements, cutting forces, cutting pressures, cutting temperatures, work-hardening, tool wear, etc.

Each subsequent chapter takes up a particular machining operation like turning, milling, drilling, tapping, and so on, and begins with a review of those cutting properties of particular significance to the operation being considered. This is followed by specific recommendations as to tool design, tool materials, and other operating conditions.

# CHAPTER II

## GENERAL PROPERTIES OF TITANIUM

For the past several years, the metal titanium has been subjected to a very extensive amount of development work stimulated by a series of unique properties which may place titanium in a prominent position among our useful structural materials. In order to better understand the machining properties of titanium, it is well to summarize briefly the properties of this metal which make it of interest for general structural uses as well as those properties that influence its machining behavior.

Briefly, the properties of greatest interest are (1) a high strength-weight ratio, (2) resistance to attack by salt water and marine-atmosphere corrosion, (3) a combination of good strength, ductility, and other desirable mechanical properties. In order to better illustrate the unique properties of the metal titanium, a series of comparisons have been drawn between this metal and carbon steel, stainless steel, and age-hardenable aluminum. The dependency of the machining behavior of titanium on these properties will be discussed later.

Yield strength and tensile strength of unalloyed titanium at room temperature are superior to magnesium, aluminum, carbon steels, and annealed 18-8 stainless steel. Alloys of titanium may be treated to give strength as high as 200,000 psi, which is exceeded only by heat-treated alloy steel. Figure II-1 shows a comparison of the relative strength of commercially pure titanium, annealed steel, and aluminum. It should be noted that these comparative values can be varied considerably by heat treatment. In particular, the relative strength of steel can be made to exceed that of the titanium. Another significant property of titanium is illustrated in Fig. II-2. It shows the relative weights of equal volumes of metals. Titanium is about two-thirds as heavy as all steels, including stainless, while aluminum is approximately two-thirds as heavy as titanium. A cross comparison between Figs. II-1 and II-2 will show that titanium has an advantage of lower weight for the same strength or, in other words, a better strength-weight ratio. This is an important prop-

STRENGTH COMPARISON

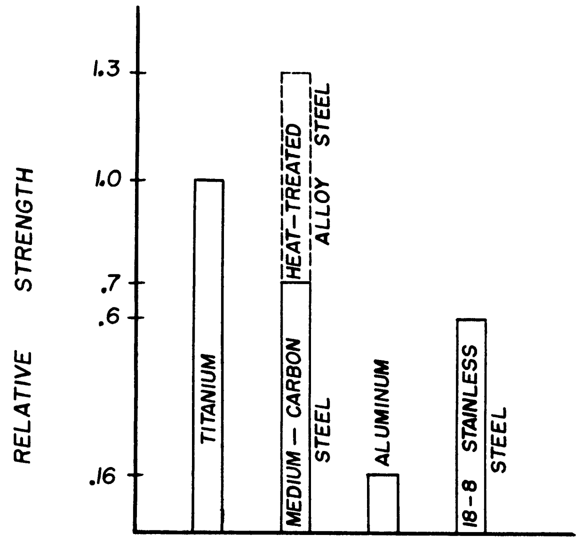



Fig. II-1. Strength of titanium compared to iron and aluminum. (These relative values can be changed considerably by heat treatment.)

COMPARATIVE WEIGHT

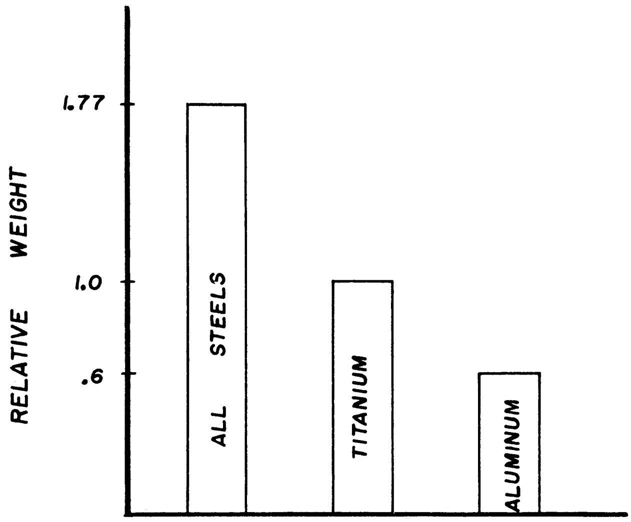



Fig. II-2. Relative weights of equal volumes of titanium, steel, and aluminum. 18-8 Stainless steel is included in "all steels."

erty when designing aircraft or other components where high strength and low weight are important. (See also Fig. II-3 to illustrate this property.)

At somewhat higher temperatures (around 800°F), titanium is stronger than either aluminum or magnesium alloys operating at 400°F. It can, therefore, be considered as a substitute for aluminum and magnesium as well as a possible substitute in certain applications where steel and stainless steel are now used. Titanium does not have good high-temperature properties, but it does fill in the gap between the properties of steels at elevated temperatures and of the aluminum and magnesium alloys, particularly in the working range around 800°F.

The relative strength and weight of titanium are not the whole story in a discussion of its comparative properties. The stiffness or the amount that a beam bends under a given load is important in design as well as in setting up and machining a particular part. Comparative deflections for the same size beams of aluminum, titanium, and steel are shown in Fig. II-4. Aluminum deflects the most, three times as much as steel, while titanium deflects twice as much for the same load. In other words, titanium is only half as stiff as steel. This is a product of the modulus of elasticity of these various materials, which for steel is 30 million lb/sq in., for titanium approximately 15 million lb/sq in., and for aluminum 10 million lb/sq in. This is one of the most important properties related to machining behavior, since the thrust force which deflects parts being machined is often considerably greater for titanium than for steel. Consequently, a titanium part may deflect several times as much as a similar steel part during machining. Aluminum would be even worse if thrust forces were high, but actually they are only a few percent as high as for steel. This explains why aluminum is one of the easiest materials to machine.

In most machining operations, heating effects are extremely important since they influence both dimensional control and the life of the cutting tool. It will be noted from Table II-1 that the thermal conductivity of titanium is comparable to that of stainless steel and considerably lower than that of 1020 steel and aluminum. This means simply that the amount of heat conducted away from a given heated area will be much less for titanium than it will be for low-carbon steel and 75-S aluminum. (See Fig. II-5.)

Here again the thermal conductivity does not tell the whole story. The heat-transfer characteristics of titanium which are important in metal cutting are those which influence the interface temperature between the cutting tool and the chip. These characteristics are the thermal conductivity, density, and the specific heat or heat storage capacity of the material. We find that titanium is much poorer in this respect than any of the other materials commonly machined. This means higher temperatures in the cutting zone and more rapid thermal breakdown of the tool. (See Fig. II-6.) This property will be discussed further in later chapters.

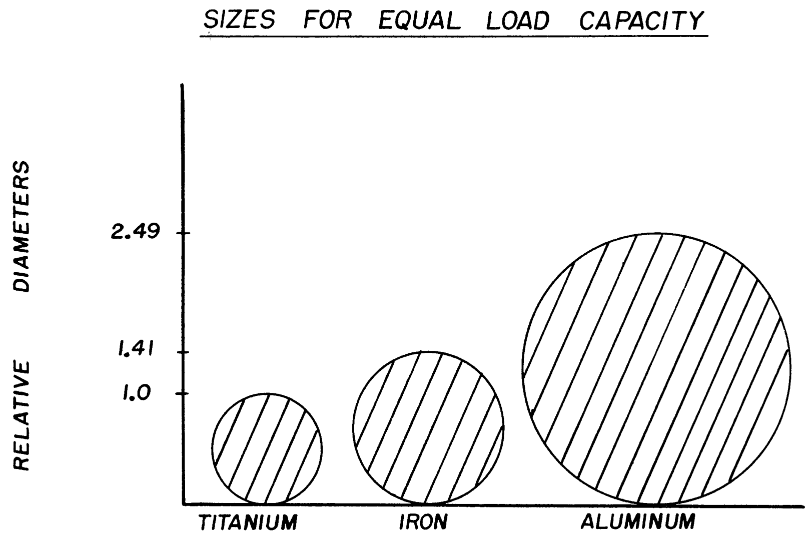



Fig. II-3. Diameters of round bars of equal strength.

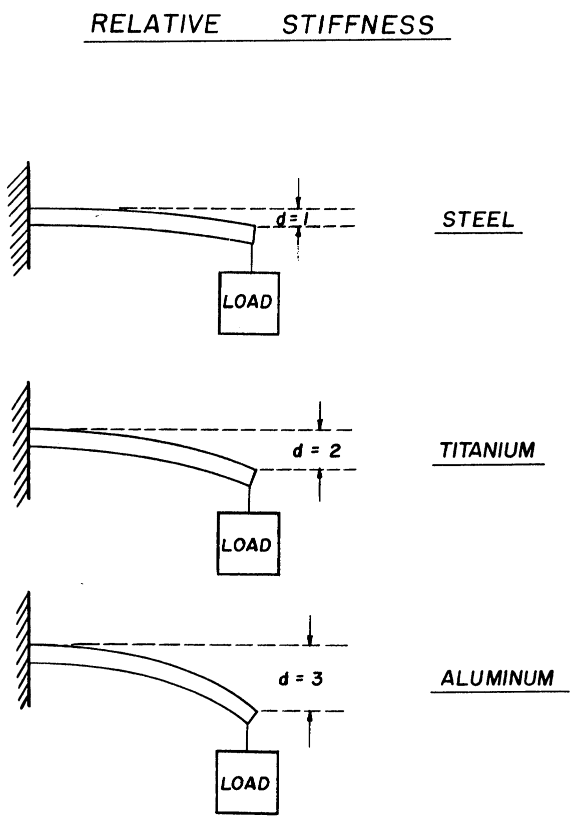



Fig. II-4. Amount of deflection in beams of the same size and different materials when supporting the same load.

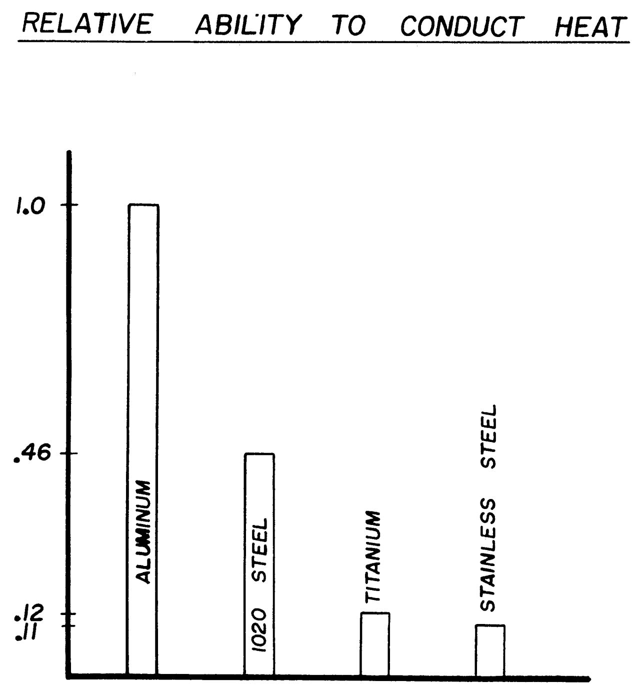



Fig. II-5. Heat-conduction characteristics of various metals.

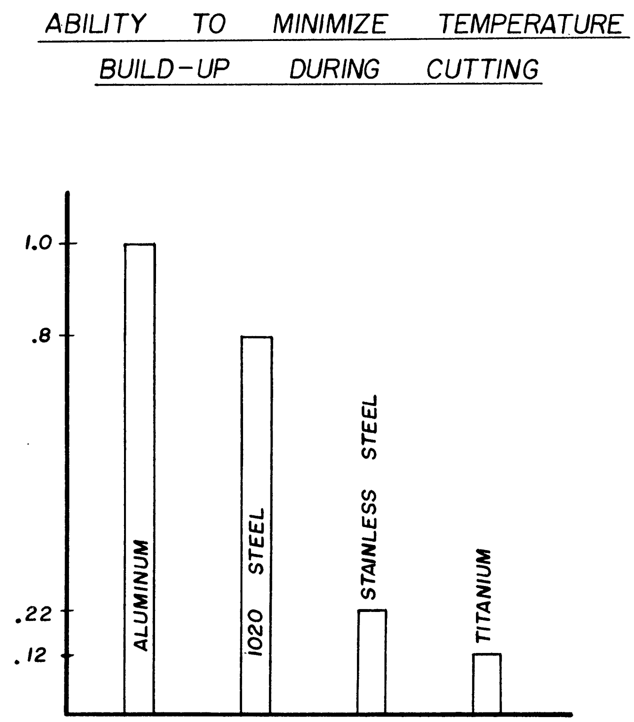



Fig. II-6. Comparative ability of various materials to prevent temperature buildup during machining. (Based on thermal conductivity K, density P, and specific heat C.)

Still another property of titanium and its alloys that is important in machining behavior is the high chemical activity of the material with most of the known elements, with the exception of the inert gases. As a result, it forms a surface film very rapidly. The surface film may affect the frictional characteristics of this material and, consequently, the wear rate of the materials rubbed against it. Again, this property will be discussed later with the wear of cutting tools.

TABLE II-1

PHYSICAL PROPERTIES OF VARIOUS MATERIALS

| Property | Commercially Pure Titanium | Age-Hardened Aluminum | 302 Stainless Steel | 1020 Steel |
|---|---|---|---|---|
| Melting range | 3135°F | 890-1180°F | 2550-2590°F | 2720-2760°F |
| Density | .163 lb/in.$^3$ | .101 | .290 | .290 |
| Thermal Conductivity Btu/ft$^2$/hr/°F/in. | 105 | 845 | 101 | 390 |
| Specific heat Btu/lb/°F | .13 | .21 | .12 | .117 |
| Volume Specific Heat $\rho C$ Btu/in.$^3$/°F | .021 | .021 | .034 | .031 |
| $k\rho C$ Btu/in.$^2$/°F | 4.2 | 34 | 7.5 | 27 |

# CHAPTER III

## COMMON CUTTING PROPERTIES

Certain aspects of metal cutting behavior are common to all machining operations in varying degree. This chapter will discuss those aspects for two reasons; first, as a basis for comparing titanium with other metals and, secondly, to avoid repetition with regard to specific operations in later chapters.

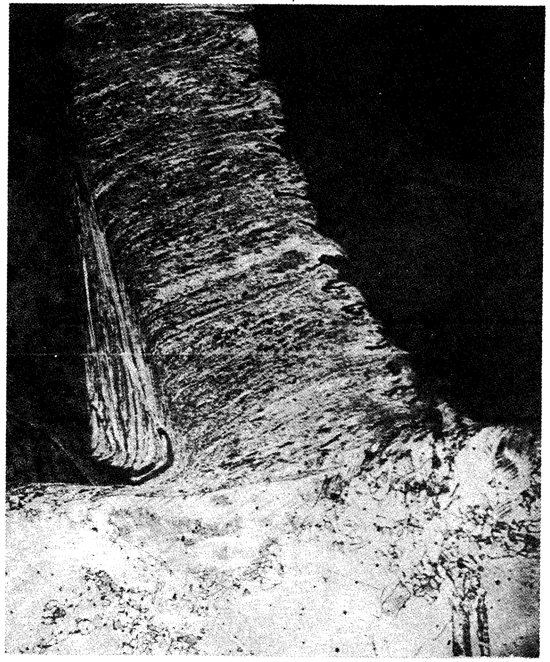
The factors of common concern are chip formation, cutting temperature, cutting forces, power requirements, tool life, surface finish, and dimensional tolerances. The first two factors, chip formation and cutting temperature, are not involved directly in the decisions that must be made in planning machining operations. On the other hand, they are significant properties which have considerable influence on the machinability of a material. The other factors merit some consideration in practically all machining operations.

### CHIP FORMATION

Chip formation refers not only to the shape and size of chips, but also to a number of related factors such as built-up edge or tool loading, surface finish, shear angle, friction, and work hardening. The problem of chip handling or chip disposal will be discussed in later chapters.

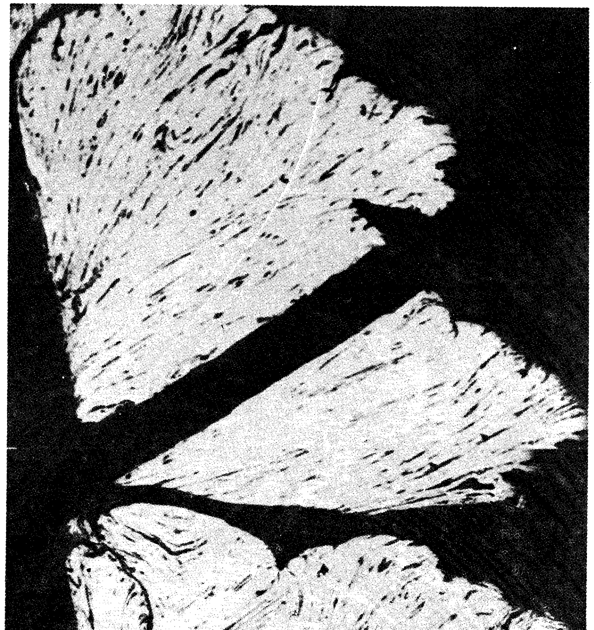
### SHEAR ANGLE

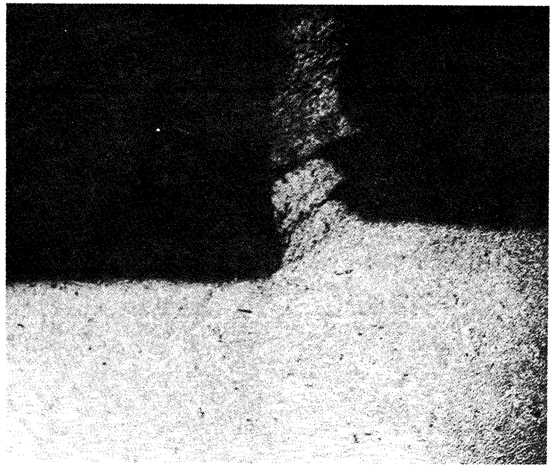
Figure III-1 shows pictures taken through a microscope of chips being formed in three different metals cut at identical conditions of speed, size of cut, tool shape, etc. The metal at the right is titanium alloy RC-130B, the one in the center is cold-rolled steel, and the one at the left is 18-8 stainless steel.



Type 304 Stainless Steel

SAE-1020 Steel





Type 130B Titanium

Fig. III-1. Chip formation versus material cut. Cutting conditions: at end of shaper stroke with 9" stroke, 9 strokes per minute, 0.005" depth of cut, 0.250" width of cut. Tool signature: 8, 0, 6, 3, 0, 0, 0. SAE-1020 steel, nital etch; type 304 stainless steel, electrolytic chromic acid etch; type 130B titanium, 48% hydrofluoric acid in glycerine etch.

One of the most significant facts to be noted from Fig. III-1 is that titanium produces a much thinner chip for the same size of cut. This is an important property for several reasons. First, because it means that the cutting force is concentrated on a much smaller area of the cutting tool, giving rise to unusually high pressures. Since the chip is thinner it must rub over the face of the cutting tool at substantially higher velocities, which means more heat from friction; furthermore, this heat is concentrated on a smaller area with considerably higher temperature as the result. The thinner chip and the small contact area with the cutting tool are both related to the relatively large shear angle which bears an inverse relationship to the friction between the chip and the cutting tool. Lower friction results in an increase in the shear angle, which in turn produces a thinner chip, higher chip velocity, and smaller contact area with the tool. Unless lower friction is accompanied by lower strength of the work material, the net result is higher temperatures and higher pressures as in the case of titanium. Without exception, all titanium alloys as well as commercially pure titanium exhibited this same property. It would appear to be the most important cutting property of titanium, since no other metal has exhibited this behavior to the same degree.

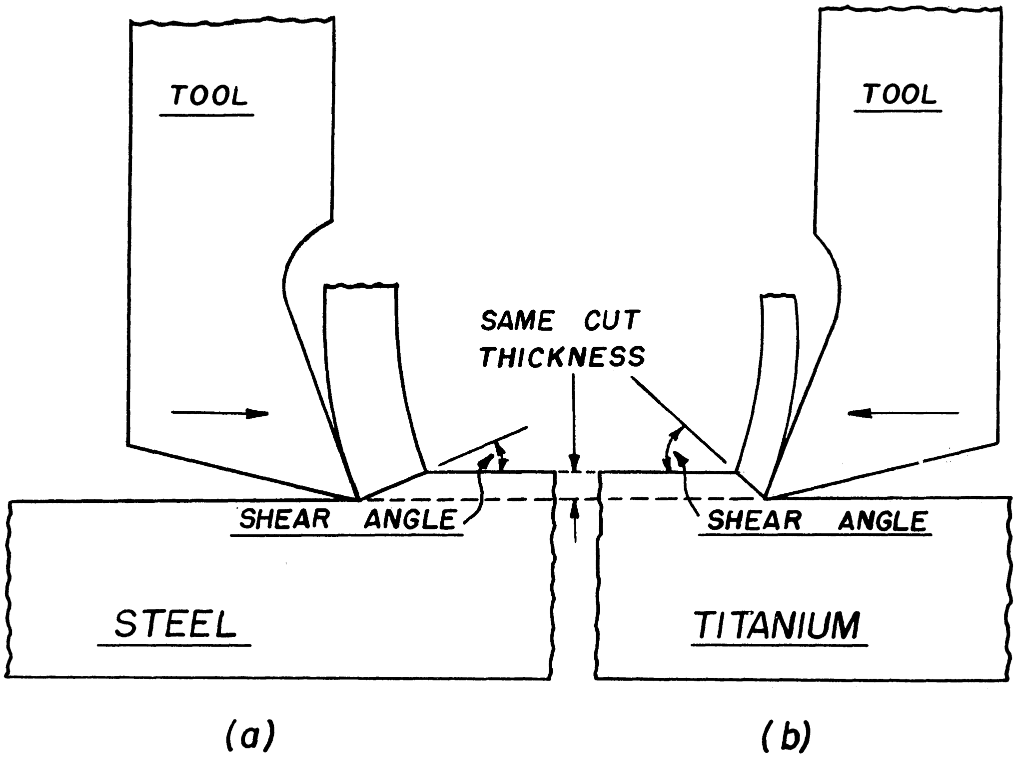



Fig. III-2. The shear angle when cutting steel and similar metals is relatively low as shown at (a). Titanium cuts with an unusually large shear angle as shown at (b). Chip thickness varies inversely with shear angle; thin chips accompany large shear angles while thick chips go along with small shear angles.

Figure III-2 illustrates the terms used to describe this highly unique characteristic of titanium. The schematic drawing of the chip being formed in titanium is shown at the right in the figure. Note that the shear angle and the contact area between the chip and the cutting tool for the same size of cut are radically different from that shown for other metals like steel, at the left in the figure. The large shear angle for titanium results directly in a thinner chip. This in turn causes the resulting chip to flow across the surface of the tool at a higher velocity for any given cutting speed. The higher chip velocity in turn results in more heat being generated due to the flow of the chip across the cutting tool.

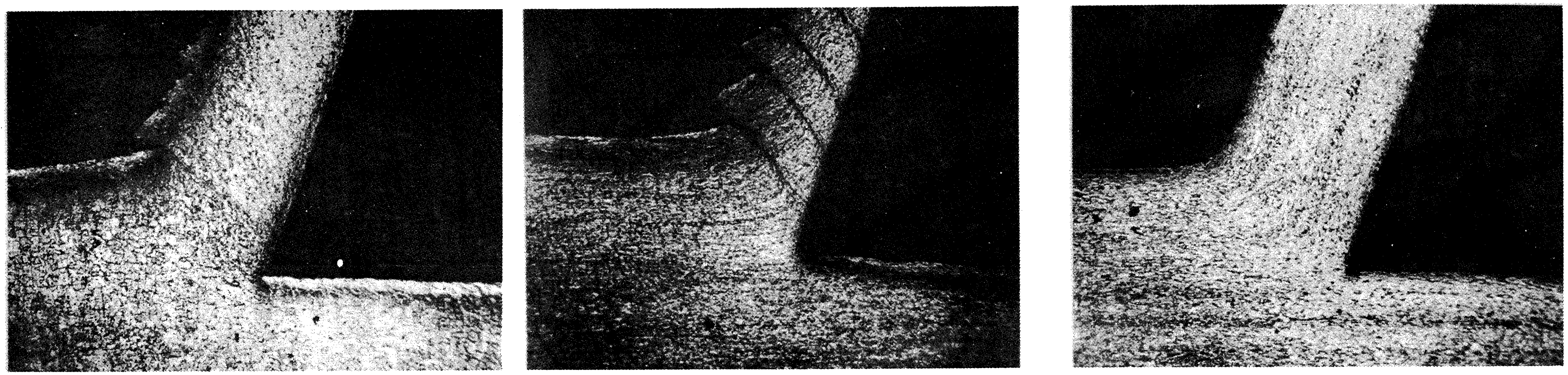
The smaller contact area in contrast to other metals which is demonstrated by the titanium is significant for three reasons. First, the cutting force is distributed over a substantially smaller area, resulting in significantly higher pressures even though the force required for a given size of cut in titanium is of the same magnitude as that required for a medium-carbon steel. Secondly, the small contact area coupled with higher pressures and more frictional heat results in very high temperatures being generated at the tool-chip interface. And third, the small contact area makes it relatively easy to lose the cut altogether in situations where either the workpiece or the cutting tool cannot be supported with a high degree of rigidity. Thus, the large shear angle and the accompanying thin chip and small contact area constitute unique cutting characteristics for titanium which require special attention for all machining operations.

Built-up Edge.—Referring again to Fig. III-1, it will be noted that the cutting tool is not in direct contact with the chip in machining the type 304 stainless steel shown in the upper left of the figure. Some of the work material seizes on the face of the cutting tool, forming what is commonly called "loading" or a "built-up edge." This built-up edge is common to most machining operations in steel and contributes several significant characteristics to the machining operations in which it occurs. Some of these characteristics are beneficial while others are distinctly troublesome.

The beneficial characteristics are associated with temperature and pressure. It is obvious that the presence of the built-up edge protects the cutting edge of the tool from the high rubbing temperatures where the chip flows across the top surface of the built-up edge. Otherwise, this high temperature zone would be on the tool face immediately adjacent to the cutting edge. A further benefit arises from the fact that the built-up edge aids in distributing the total cutting force over a substantially larger area, resulting in lower pressures and lower rates of wear. The presence of a built-up edge makes it more difficult to obtain good surface finish and to retain control over size of the work piece. Thus, efforts aimed at improving surface finish and achieving closer control over size usually are directed toward elimination or reduction in size of the built-up edge. In summary, it can be said that the presence of a built-up edge tends to lengthen tool life through reduced wear rate, but also increases surface roughness and size variation. Therefore, when machining metals with a pronounced tendency to form a built-up edge, the choice of operating conditions represents a compromise between tool life on the one hand and surface finish and size control on the other.

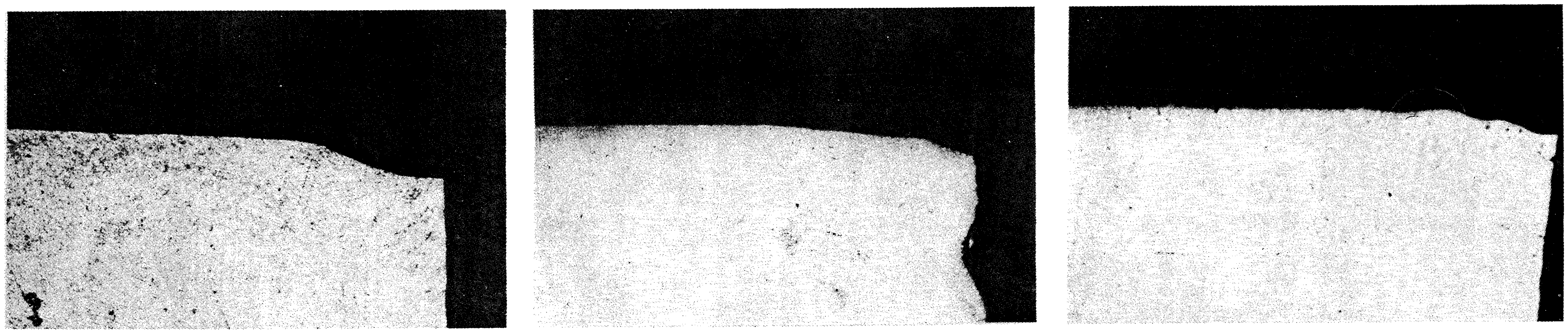
Despite extensive and extreme efforts to do so, investigators have not succeeded in producing a built-up edge during the machining of titanium. This is another significantly unique machining characteristic of titanium. In view of the discussion in the previous paragraph it would appear that little difficulty will be experienced in obtaining good surface finish in machining titanium as compared to steel, but that considerably greater difficulty will be experienced in obtaining economically long tool life. It will be pointed out in subsequent chapters that good surface finish in machining titanium can be achieved very easily. This can be attributed to the absence of the built-up edge. It will also be pointed out that cutting speeds for titanium must be substantially lower than for other materials of similar strength in order to obtain good tool life; this can also be attributed to attributed to the absence of the built-up edge, among other contributing factors.

Figure III-3 shows photomicrographs of the chips obtained in stopping a cut in each of the three typical titanium metal compositions. These are commercially pure titanium shown at the left in the figure and designated as Ti-75A; an aluminum-manganese alloy in the center, designated as RC-130B; and a chromium-iron alloy at the right, designated as Ti-150A. These chips represent the full range of cutting conditions observed in the machining of titanium. The two extremes of the range are represented by the alloys RC-130B and Ti-150A. The segmented chip shown for the RC-130B represents a relatively difficult property in that it tends to initiate and sustain chatter unless the machining setup is exceptionally rigid. This behavior characteristic of the RC-130B has persisted in spite of all efforts to make the setups rigid enough to prevent a segmented chip. It will be noted that the commercially pure Ti-75A showed a moderate tendency toward segmentation with the same degree of rigidity, while the Ti-150A produced a completely continuous chip under the same conditions. Chip segmentation does aid in the problem of chip removal but, in general, it appears desirable from a machining viewpoint to have a work material which will produce continuous chips. It should be pointed out that segmented chips have been obtained with all titanium alloys as well as with the commercially pure material. This situation is the result of reducing the rigidity of the machining setup. Thus, a useful criterion for identifying improvement in rigidity is the incidence of chip segmentation, since an increase in rigidity will at least reduce the frequency of segmentation. It is practically impossible to express



Ti-75A RC-130B Ti-150A

Fig. III-3. Chip formation versus titanium alloy for alloys 75A, 130B, and 150A. Cutting conditions: at end of shaper stroke, 4" stroke, 9 strokes per minute, 0.015" depth of cut, 0.250" width of cut. Back rake angle of tool + 20°.



-15° Rake 0° Rake +20° Rake

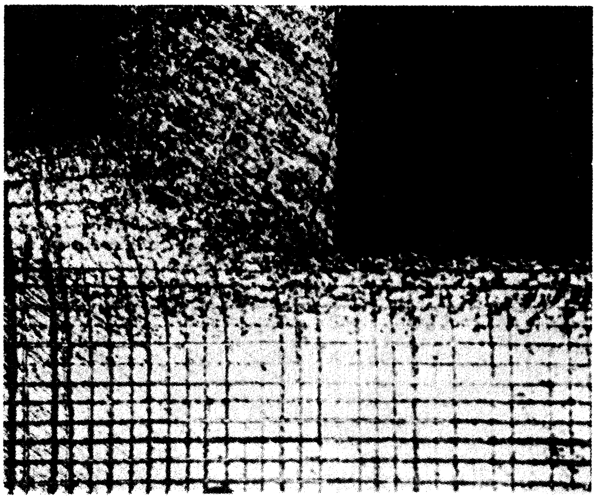
Fig. III-4. Entrance conditions (shape of cut) versus rake angle for type 130B titanium alloy using smooth ground tools.

the rigidity of the machining setup with a number, but it is emphasized repeatedly in this report that exceptional measures should be taken to provide unusual rigidity when machining titanium. It is believed that a high degree of rigidity is more important than any other single factor to the successful machining of these alloys.

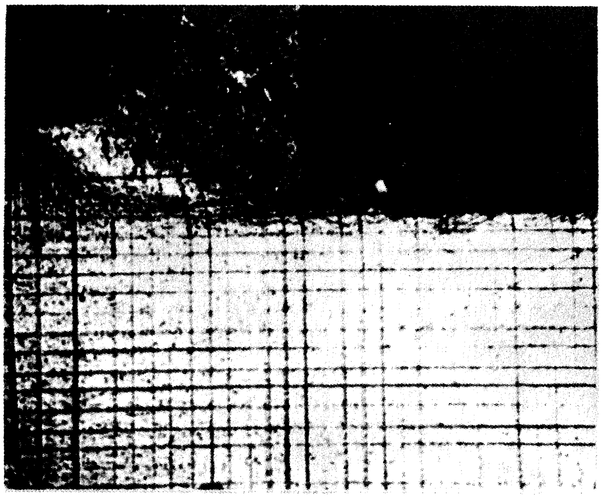
Figure III-4 illustrates the importance of rigidity and the influence of tool rake angle in maintaining size of the work piece. These are photomicrographs showing a section of the work surface at the point where the tool enters the cut. It will be noted that in all instances the tool is forced away from the work piece. The amount of this movement is greater at small rake angles. It will also be noted that the larger rake angles, particularly the 20° rake, tends to oscillate about the line of cutting action, thus producing a chatter pattern. An increase in the rigidity of the machine setup would improve both of these factors.

Work Hardening.—Figure III-5 shows pictures of chips being formed on titanium work specimens on which a fine grid pattern has been scribed prior to cutting. This investigation was made for the purpose of studying chip formation and, in particular, to determine the extent of smearing or work hardening of the work surface. The grid lines are 0.003 inch apart. It will be noted from Figure III-5 that there is little disturbance beyond about 0.003 inch, except in the case of RC-130B, where the highly segmented chip was accompanied by vibration of the tool, which resulted in an undulating work surface. If the same size of cut is made in 18-8 stainless steel, a grid pattern like that shown in Fig. III-6 is produced. Here it will be noted that the work material near the surface has been dragged along with the cutting tool, thus producing distortion and work hardening to a depth of approximately 0.020 inch or more than five times as much as is obtained with titanium. It should be pointed out that the work hardening and smearing of the work surface will be greatly aggravated by flank wear of the cutting tool, while the conditions illustrated in Fig. III-5 and III-6 were obtained with freshly sharpened cutting edges.

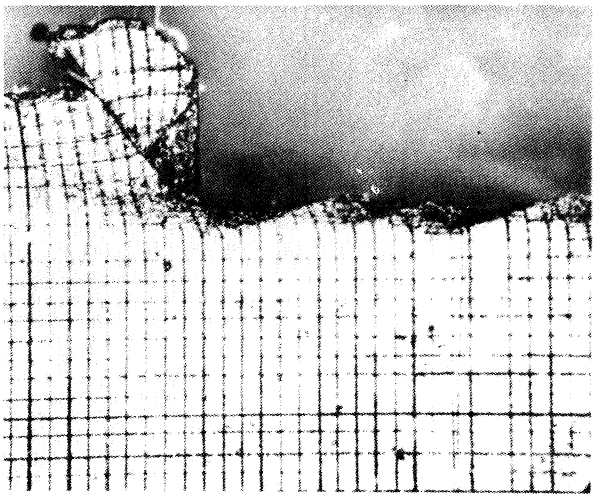
It is difficult to obtain complete information about the work hardening and residual stresses from machining operations. Knowledge of this phase of the subject, particularly in regard to titanium, is incomplete. Consequently, some difficulties from this origin are anticipated, especially where cutting tools are permitted to become too dull. However, the evidence obtained up to the present time appears to indicate that difficulties arising from work hardening of the machined surface can be minimized and brought under control by using only sharp cutting tools. In practice this should mean that the cutting tools would not be permitted to become as dull as is common practice in machining steel. For example, it is common to permit a carbide tool to be used until the flank wear is approximately 0.030 inch in cutting steel. The same tools used for titanium should not be permitted to wear beyond 0.010 inch.



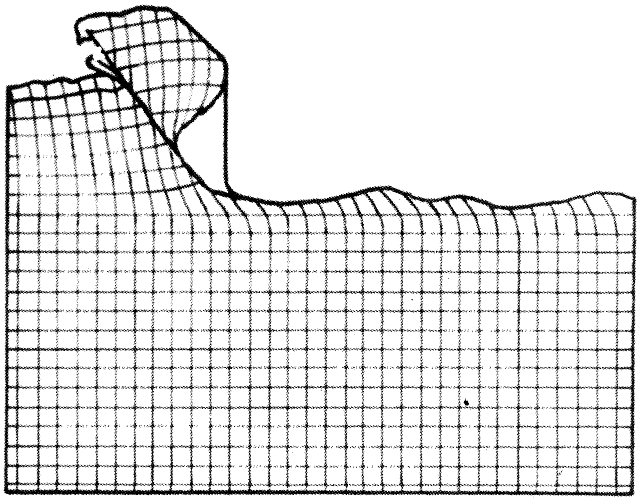
Ti-75A



Ti-150A



Ti-130B



Ti-130B

Fig. III-5. Grid specimens showing unit distortion and evidence of lateral stress in chip and work material for three titanium alloys. Grid spacing 0.003" in both directions. Lower right figure is a tracing of lower left figure (130B). Rake angle of tool = 0°. Photographed with polarized light.

Summarizing the significant information concerning chip formation in titanium, it should be emphasized that titanium and its alloys demonstrate extreme cutting characteristics in terms of the following:

1. very thin chip,
2. unusually small contact area,
3. no built-up edge.

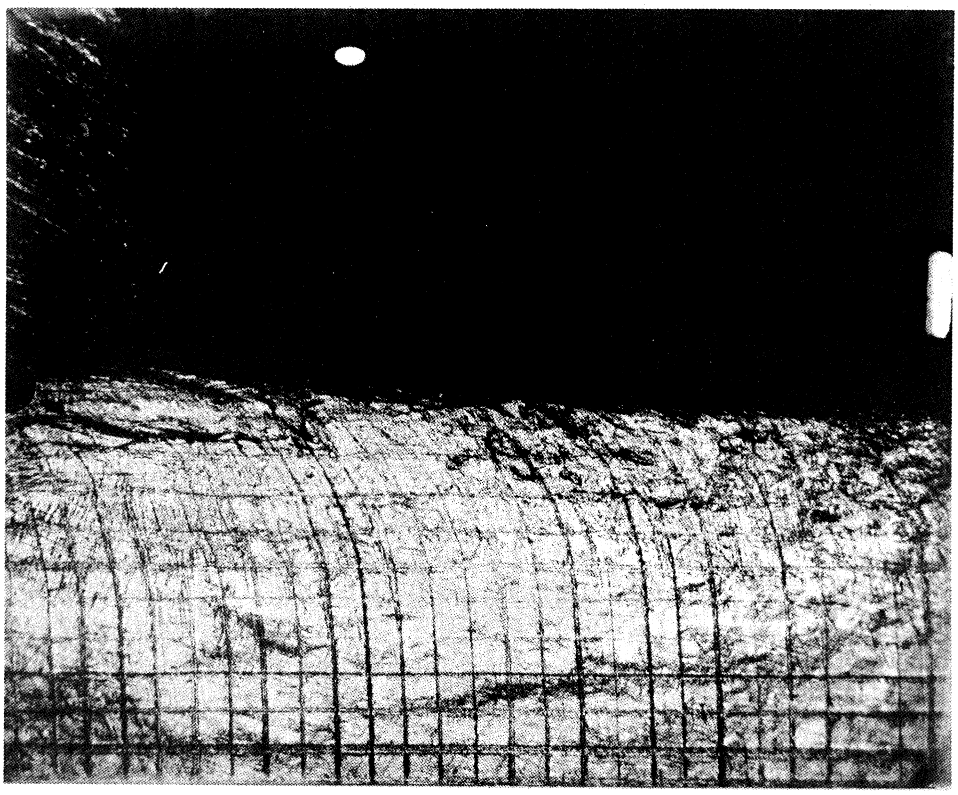


Fig. III-6. A "grid" specimen of 18-8 stainless steel machined at the same conditions as the titanium alloys illustrated in Fig. III-5. Note the considerable depth of disturbed metal as indicated by curvature of the vertical lines.

In planning production machining operations or in coping with existing machining troubles, it is well to keep in mind the above three properties, along with their resulting effects, and to concentrate on improving machining conditions with respect to these factors.

CUTTING TEMPERATURE

The cutting temperature does not enter directly into the decisions made in planning production machining operations, although it is probably the most important determining factor of metal cutting behavior. For this reason, attempts have been made by many investigators to measure cutting temperatures accurately and to find out in what way they determine the life of the cutting tool at a given set of cutting conditions. Cutting temperatures were similarly studied as a part of the titanium machining investigation. This study consisted primarily of temperature measurements over ranges of feed and depth of cut for each of the work materials under consideration. The temperature measurements were made by imbedding thermocouples in drilled holes terminating a short distance from the tool face. This method does not necessarily reveal the maximum cutting temperature, since the maximum should exist either in the shear zone or between the chip and any built-up edge that might be present.

Measured cutting temperatures correlate well with cutting speed, as demonstrated in Fig. III-7. This chart shows cutting speed plotted vertically against cutting temperature plotted horizontally. The temperatures are those determined for each material at a constant cutting speed of 25 fpm, while the cutting speeds are those which resulted in a tool life of one hour for the same size of cut. It will be noted that the materials which produce higher temperatures at the same speed must be cut at low speeds in order to have an adequate tool life. The only exception to the general correlation was the manganese-aluminum alloy, RC-130B, which gave temperature indications substantially lower than would be expected because of the low speeds at which it must be cut. It is believed that this anomalous result was due to the fact that this particular titanium alloy always cut with an intermittent action characterized by a segmented chip. Thus, the motion of the chip across the face of the tool was jerky, which could result in a pulsating temperature while only the average value would be indicated by the measuring method used; peak temperatures tend to determine tool life.

It is particularly significant, as shown in Fig. III-7, that titanium alloys produce cutting temperatures considerably higher than SAE-1045 steel and type 304 stainless steel, despite the fact that most of the titanium alloys require the same or even less energy to cut than either of the steels. This confirms, as was pointed out above, that the considerably smaller contact area between the chip and tool when cutting titanium causes increased temperatures and pressures, which in turn result in increased rate of tool wear for otherwise identical cutting conditions. This situation is further aggravated by the property of titanium to not form a built-up edge which can protect the tool from high temperature.

The practical conclusions to be drawn from the cutting-temperature behavior of titanium relative to that for steel are that:

1. Cutting speeds must be substantially lower than for cutting steel at similar conditions.

2. Cutting tools should be kept sharper so as to minimize the increase in cutting temperature that always is associated with tool dulling.

3. Effective coolants should be used as cutting fluids whenever

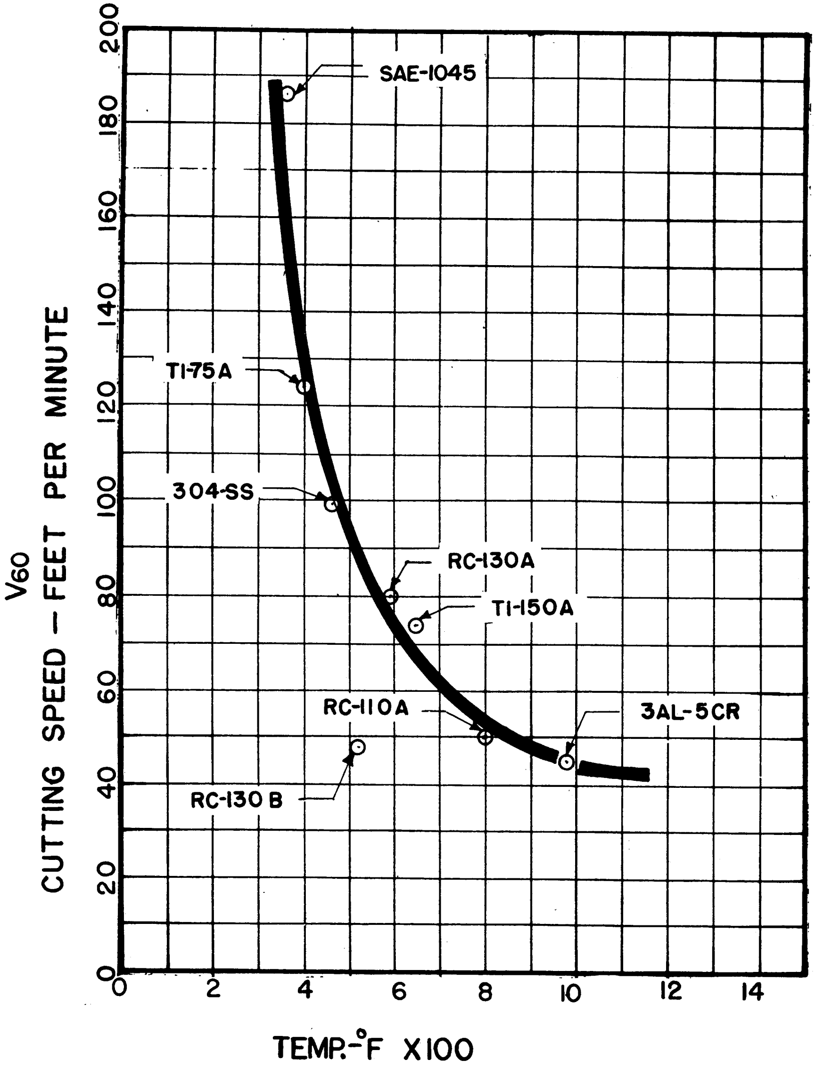
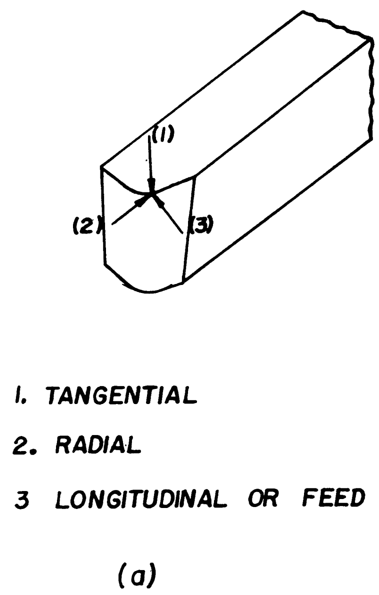



Fig. III-7. Cutting temperatures measured at the same cutting speed for a range of materials correlate well with the cutting speed required to give a 60-minute tool life. The measured temperature for RC-130B probably is less than the actual temperature because of pulsating motion accompanying chip segmentation.



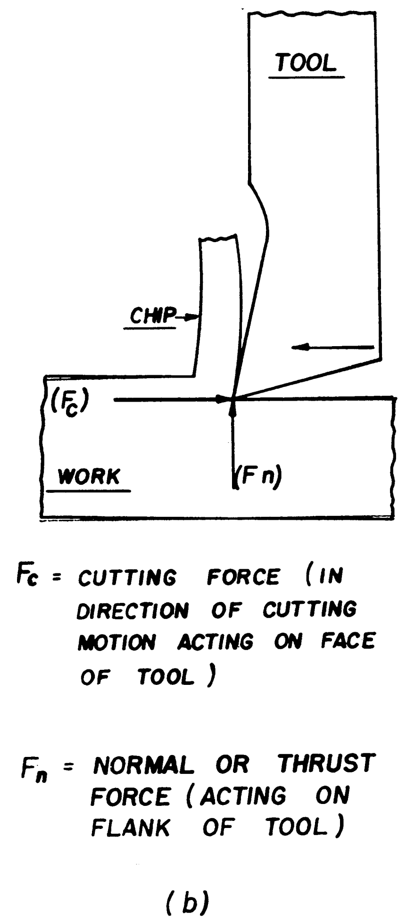




Fig. III-8. Nomenclature in common use for designating cutting forces on cutting tools. The arrangement at (a) applies to single-point tools. The arrangement at (b) is simpler and is suggested for analytical purposes.

the nature of the cutting operation makes it feasible for the coolant to penetrate in sufficient quantity to the high temperature zone.

## CUTTING FORCES

The forces required to cut titanium are particularly significant since they differ substantially from those in steel-cutting practice. Cutting forces are of general concern to those planning machining operations since they determine not only the power requirements, but also the incidence of chatter and the level of rigidity required in the machine setup.

Tangential and Normal Force.—Figure III-8 illustrates nomenclature in common use for cutting forces on cutting tools. At (a) is an illustration of a typical single-point tool such as might be used for turning, shaping, or planing operations. It is common practice to resolve the total cutting force into three components designated as tangential, feeding, and radial. These terms describe the direction of action of the force components since these directions are readily understood in connection with the aforementioned operations. The relative magnitude of the feeding and radial components will be sensitive to tool angles so it is difficult to generalize cutting force behavior with this approach without explicit information on tool shape in every instance. However, every small length of cutting edge behaves the same as any other; therefore, it is possible to simplify the analysis and application of cutting force information by resolving the total cutting force into only two components, one in the direction of cutting motion or cutting velocity, and the other perpendicular to this direction and acting toward the flank of the cutting tool. The latter component is often referred to as a normal or thrust force. The terms cutting force ($F_c$) and normal force ($F_n$) are used throughout this report.

Effect of Tool Angles.—Figures III-9 and III-10, respectively, illustrate cutting force and normal force behavior when machining SAE-1045 steel. This information is given for comparison with similar results for the aluminum-manganese alloy of titanium, RC-130B, shown in Figs. III-11 and III-12, respectively. It will be noted in the first two figures that both the cutting force ($F_c$) and the normal force ($F_n$) decrease with increasing rake angle for a given thickness of cut. Furthermore, the normal or thrust force does not exceed approximately one-half the cutting component at smaller rake angle and is considerably less than half for larger rake angles approaching 30°. For titanium, the feeding component of force is a larger fraction of the cutting component and neither component falls off as rapidly with increased rake angle as steel does. The latter property is due to the high incidence of chipping or spalling with larger rake angles. The data shown in Figs. III-9 to III-12 were obtained with a cutting-force dynamometer, which introduced undesirable flexibility in

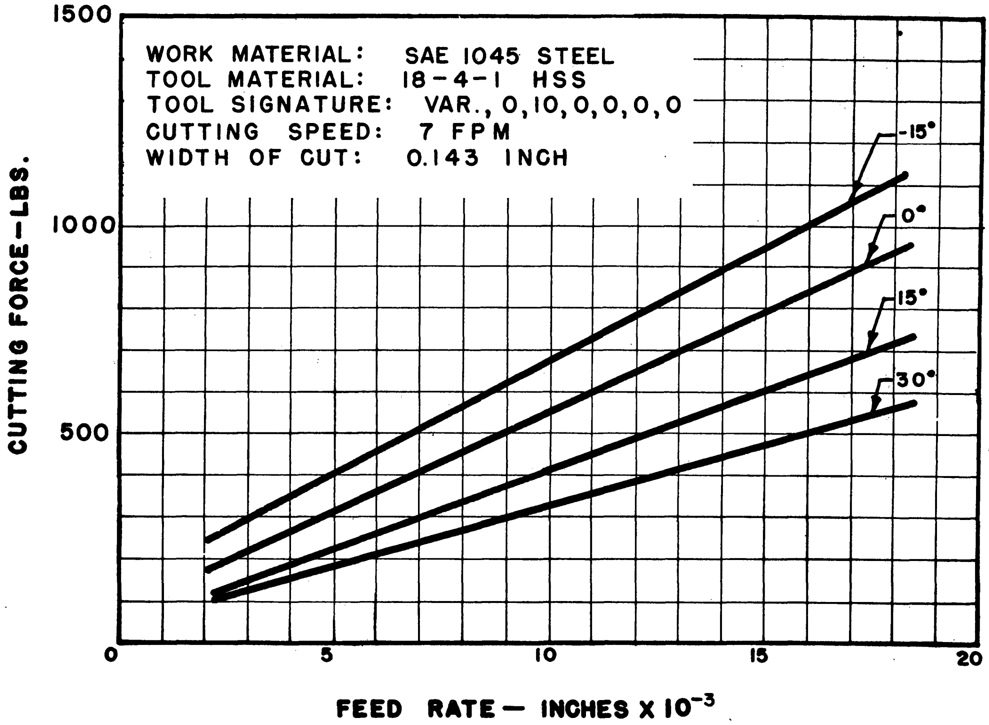



Fig. III-9. Cutting force in the direction of cutting motion for SAE-1045 steel. Feed rate or chip thickness was varied as well as was the rake angle of the tools.

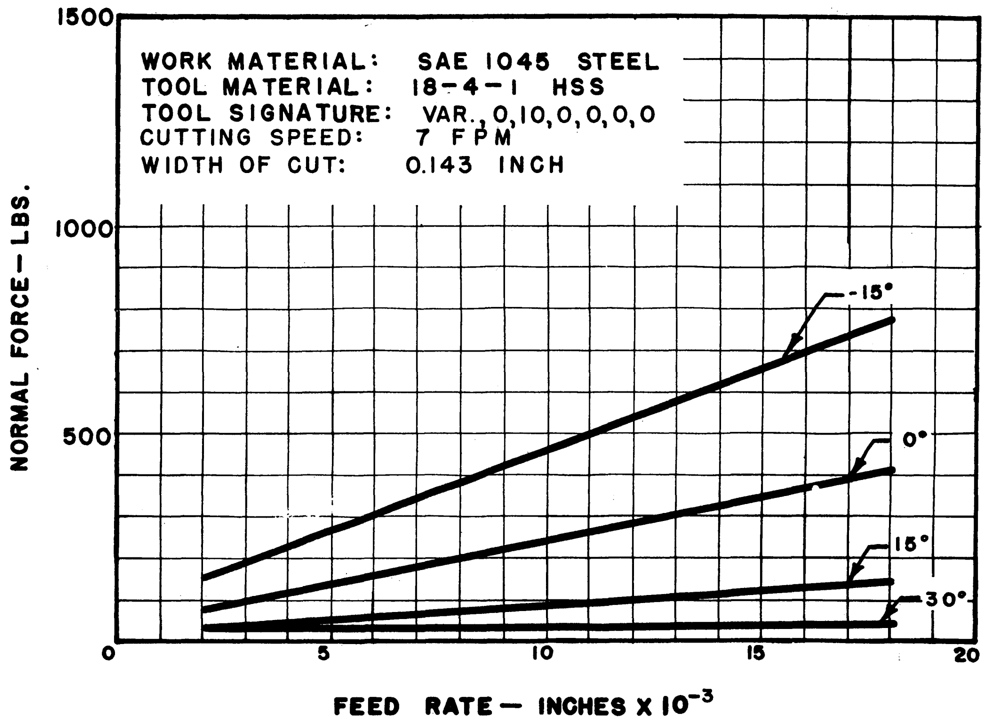



Fig. III-10. The normal or thrust force for cutting SAE-1045 steel for a range of feed rate and rake angle.

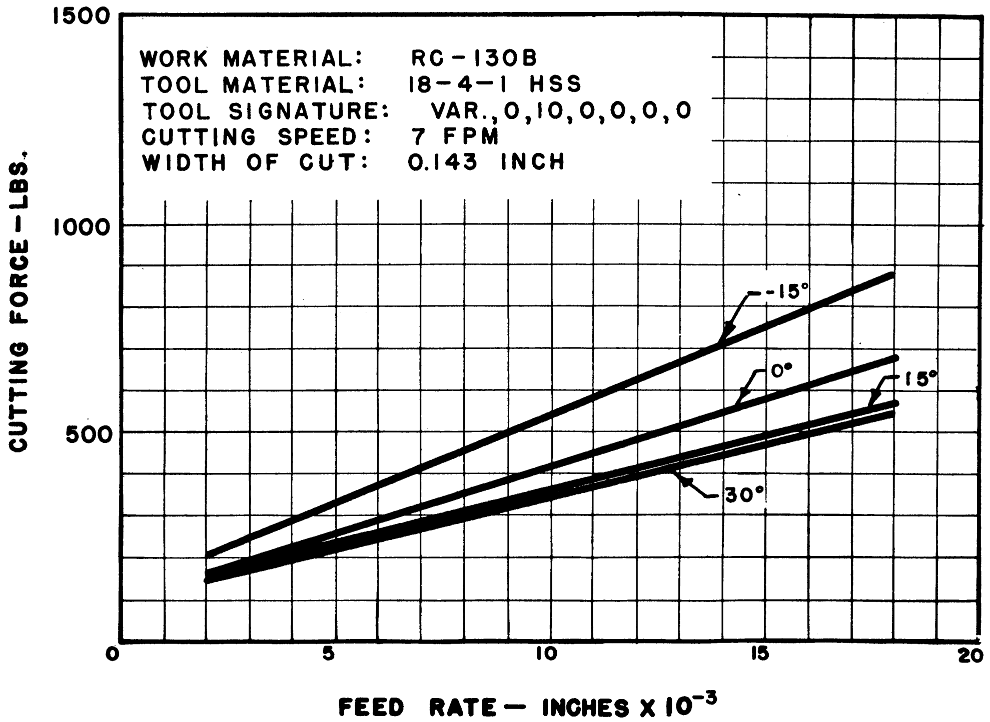



Fig. III-11. Cutting force for a titanium alloy when cutting at the same conditions as for steel shown in Fig. III-9. Note that force is generally lower, but larger rake angles fail to reduce force as much as in steel.

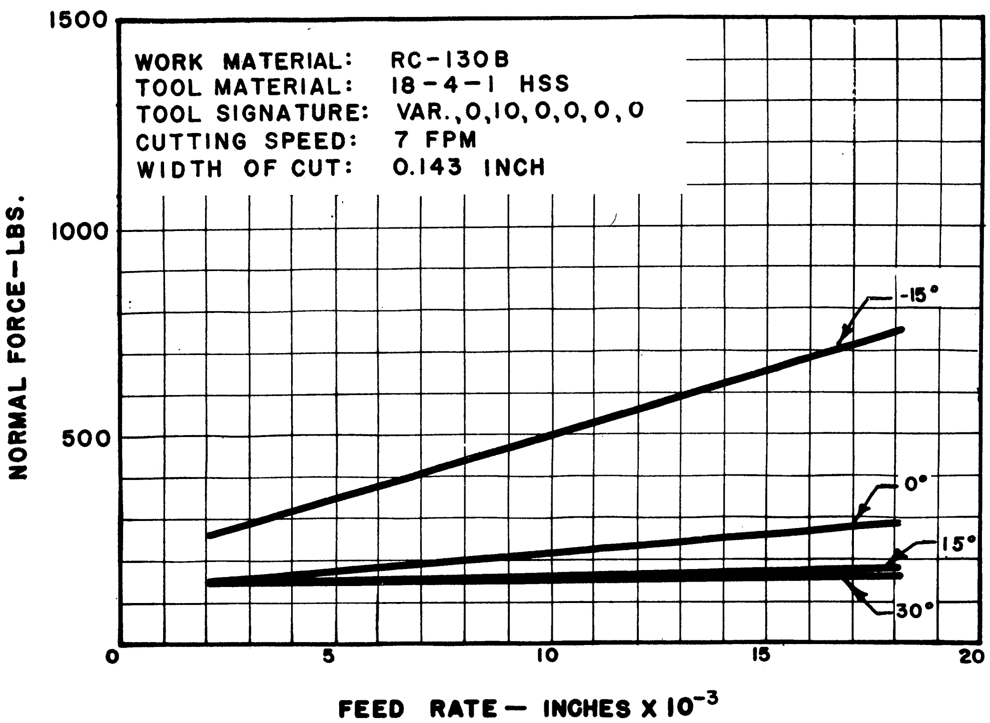



Fig. III-12. Normal or thrust force for a titanium alloy showing that the thrust force with medium-to-large rake angles are substantially greater than for steel.

the machining setup. Consequently, somewhat more favorable results can be obtained at high rake angles in a conventional and more rigid machine setup.

It will be pointed out in later chapters that for some small-chip operations like bandsawing, the feeding component of force exceeds the cutting component. This is due to the smallness of the chip and abnormal sensitivity of titanium to any dullness of a cutting edge. All cutting tools must be thought of as being relatively dull even after resharpening. This inherent or residual dullness will assume greater significance where the thickness of chip is small as in the case of sawing, reaming, etc. This also explains why the normal or thrust force builds up so much more rapidly as the tools dull when cutting titanium than when cutting other materials. Rapid build-up of thrust force and small contact area between the chip and cutting tool are the factors which demand exceptional rigidity throughout the entire system. This combination is probably the most important and troublesome for production machining of titanium.

Effect of Size of Cut.—The four previous figures also illustrate the effect of thickness of chip or feed rate on cutting force. It can be seen that the force drop-off is almost linearly proportional to reduction in chip thickness for the medium to heavy feed range. This trend does not continue below chip thicknesses of about 0.003 inch. In general, depth of cut is directly proportional to the length of cutting edge engaged so that both components of cutting force will be substantially doubled for twice the depth of cut.

Effect of Cutting Fluids.—Production planners usually are concerned as to whether cutting force can be reduced by the use of cutting fluids. In general, it can be said that coolants will have little effect on cutting force, whereas good lubricants can have a pronounced effect for some operations.

Figures III-13 and III-14 illustrate this point in connection with tapping titanium. The bar diagram in Fig. III-13 indicates the torque requirements for tapping commercially pure titanium with different lubricating conditions, including dry cutting. The open or white bars represent the cutting torque, while the black or solid bars represent the torque required to back the tap out of the threaded hole. The back-out torque was frequently higher and occasionally several times greater than that required to cut. This unusual condition is explained by the fact that the metal in the wall of the threaded hole yields away from the tap during cutting. The yielding is relaxed when cutting is stopped and this causes seizure on the flank of the thread. This behavior can be reduced by increasing the number of flutes and the eccentric relief of the tap. However, the tendency still persists and can be greatly improved by the use of an effective lubricant. The lubricant might even require mechanical separators such as the zinc sulphide and barium sulfate powders which make up the lithopone-in-oil combination used during the investigation. It is possible

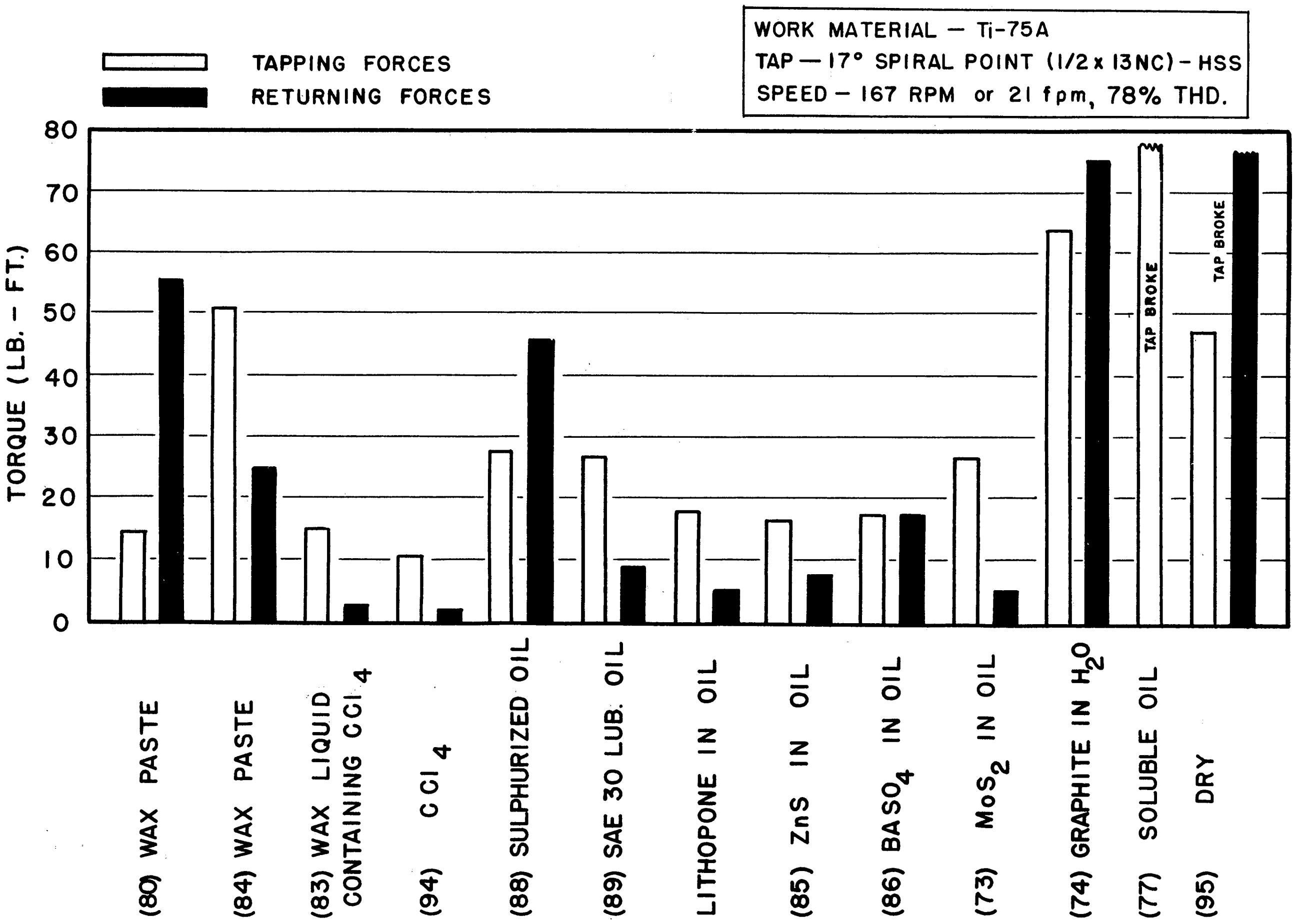



Fig. III-13. Effect of lubricants on torque requirements when tapping commercially pure titanium. Note that back-out or returning torque occasionally is greater than cutting torque.

that effective coolants without good lubricating properties would be even worse than dry cutting in this situation.

Figure III-14 illustrates another reason for good lubricants in tapping titanium. This figure shows the torque requirements over a wide range of cutting speeds. It will be noted that the torque required for tapping 1045 steel is unaffected by cutting speed. By contrast, all titanium alloys in addition to commercially pure titanium demonstrated the property of having a critical terminal velocity beyond which the torque increases very rapidly. This occurred despite the use of a very good lubricant. Failure to use the lubricant lowers the critical terminal cutting speed in each case.

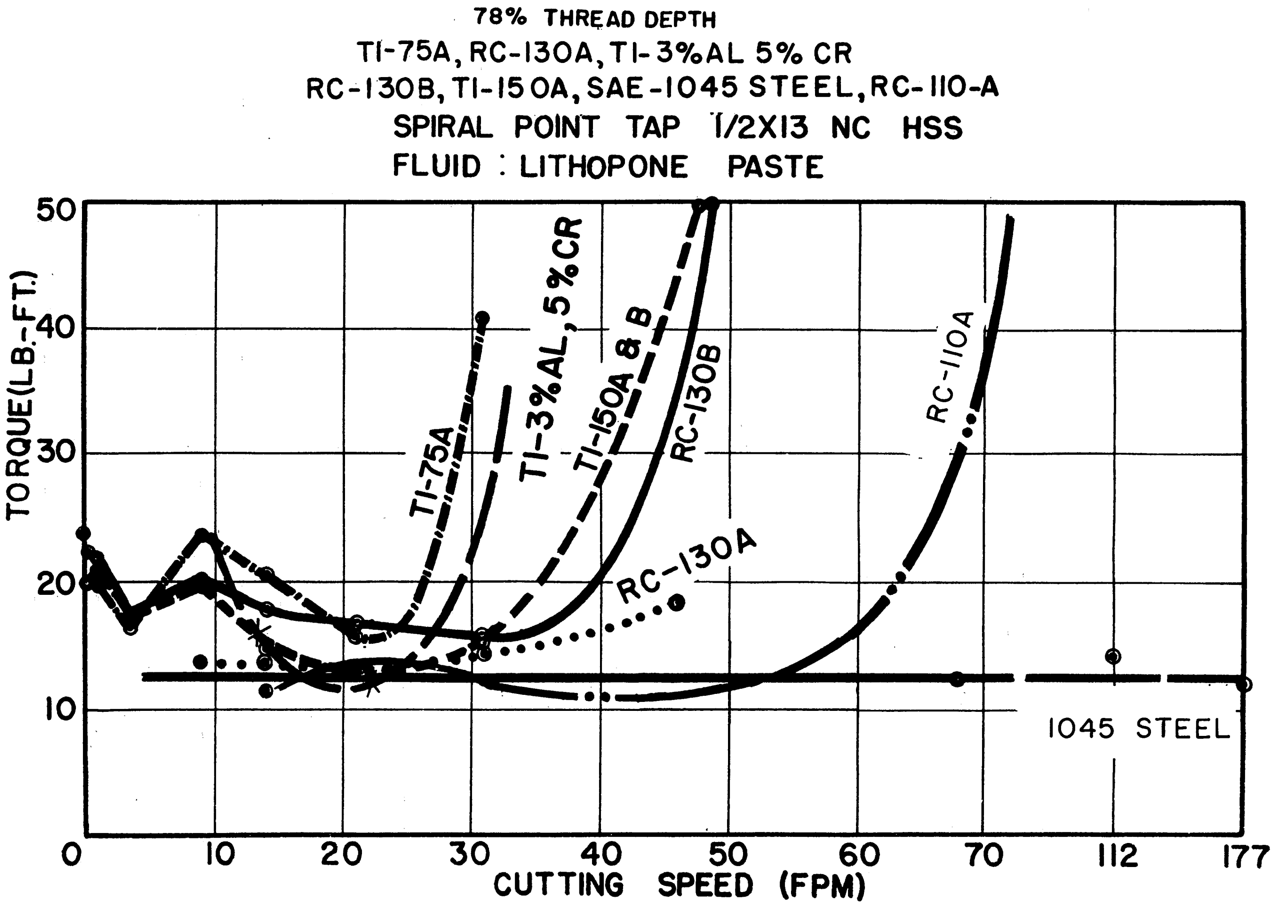



Fig. III-14. Titanium alloys exhibit the property of terminal cutting speed above which the torque requirements increase so rapidly that tap breakage may result.

POWER

As a general rule, cutting forces do not vary with changes in cutting speed. The preceding example for tapping titanium is rare. When the general rule applies, power is doubled for a cutting speed twice as large. Furthermore, the rate of metal removal is linearly proportional to the cutting speed for the same size of cut. It has been found that if the horsepower required to make a given cut is divided by the rate of metal removal in cubic inches per minute, the result is the same for all sizes of cut and all speeds for a given work material. The result is known as unit horsepower, $HP_u$, and it is substantially the same value for such operations as turning, milling, drilling, broaching, shaping, planing, etc., where the chip thicknesses are comparable.

If the unit horsepower, $HP_u$, is multiplied by 33,000, the result is the number of foot-pounds of energy required to cut a cubic inch of metal into chips. This number could be called "the specific energy" required for cutting. For most metals, $HP_u$ is equal to or less than 1.0. If $HP_u$ for a given metal is 1.0, then 10.0 HP will be required to cut 10.0 cubic inches per minute and 25.0 HP will be required to cut 25.0 cubic inches per minute. Generally, more than 99 percent of the power required to cut is used to overcome the cutting force component "$F_c$", so the cutting power is related to $F_c$ by the equation

$$HP = \frac{F_c V}{33,000}$$

where "V" is the cutting speed in feet per minute and "$F_c$" is the cutting force in pounds. In addition, the horsepower HP is obtained from unit horsepower $HP_u$ as follows:

$$HP = HP_u \text{ x rate of metal removal (cu in.).}$$

From the foregoing discussion it can be seen that both cutting power and cutting force "$F_c$" can be determined from $HP_u$ for any machining operation and for any metal for which this quantity has been determined. The other component of cutting force "$F_n$" is usually about one-half $F_c$, but for titanium it may be equal to or greater than $F_c$.

The following table lists average values of $HP_u$ for several titanium alloys in addition to SAE-1045 steel and 18-8 stainless steel. These values can be used for estimating forces and power requirements in turning, milling, drilling, broaching, etc.

Unit Horsepower, $HP_u$, for Various Metals

| Metal | $HP_u$ |
|---|---|
| SAE-1045 steel | 0.86 |
| 18-8 Stainless steel | 0.88 |
| Ti-75A titanium | 0.71 |
| RC-130B " | 0.71 |
| RC-130A " | 0.70 |
| Ti-150A " | 1.03 |
| RC-110A " | 0.63 |
| 3Al-5Cr " | 0.64 |

TOOL LIFE

No way has yet been found for determining tool life except by actual test; this method was used in the titanium investigation. The principal factors affecting tool life are cutting speed, tool material, tool shape, size of cut, cutting fluids, and material cut.

Tool life is more sensitive to cutting speed than to any other factor. This is illustrated in Fig. III-15, which shows the effect of speed on tool life for three different sizes of cut when turning a 3Al-5Cr alloy of titanium. Similar relationships have been obtained for steel and many other metals. The test data are plotted on logarithmic coordinates so that the relationship between cutting speed V-fpm and tool life T-minutes is expressed by an equation of the type

$$VT^n = C ,$$

where "C" is a constant representing the size of cut, tool shape, tool material, work material, etc. Performance curves of this type are no different for titanium than for steel.

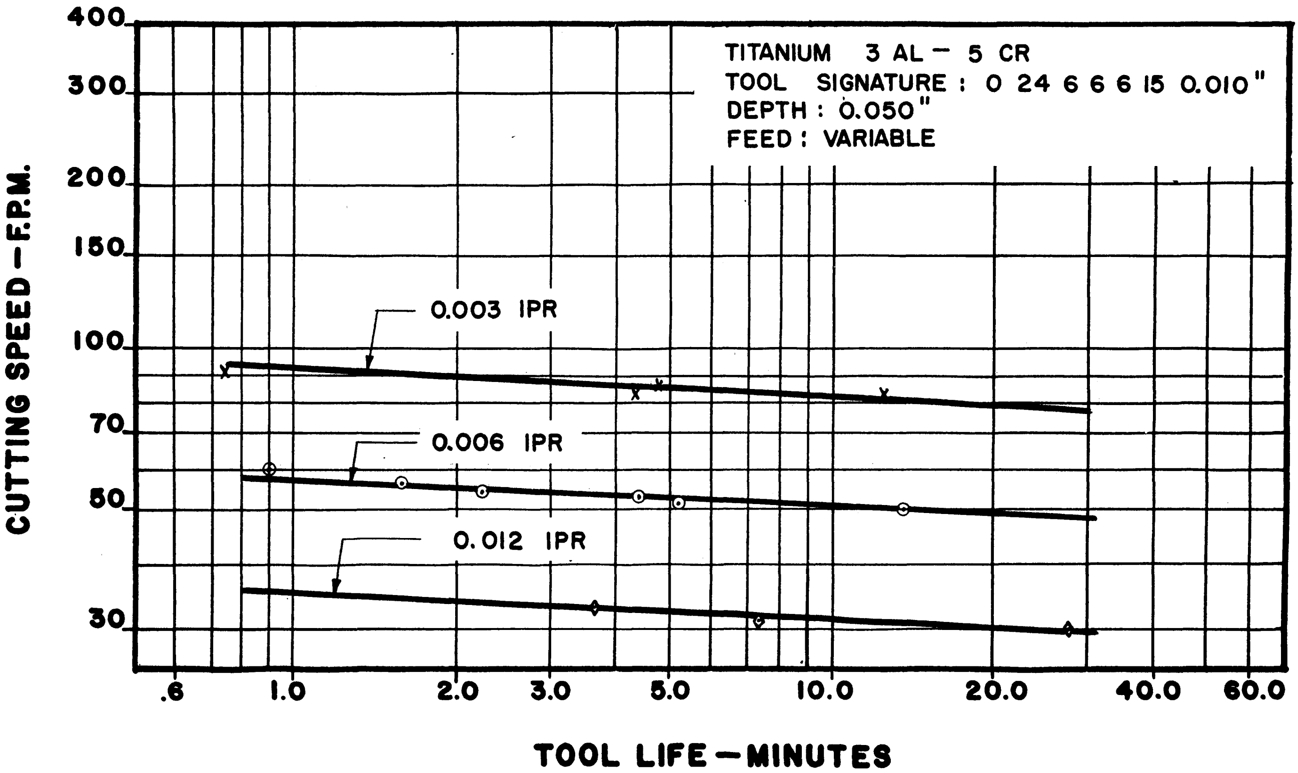



Fig. III-15. Typical cutting speed tool life lines for three different sizes of cut when turning the titanium alloy. The dependency of tool life on cutting speed is orderly and predictable.

In Fig. III-15 it is shown that the speed level drops with increase in feed rate as with steel cutting. However, this drop is orderly and predictable, as shown by Fig. III-16 where the cutting speed for a one-hour tool life, "$V_{60}$," is plotted against feed rate. The equation for this relationship is:

$$V_{60} = Kf^{a} .$$

Similarly, the depth of cut produces a relationship which can be expressed by an equation such as

$$V_{60} = Cd^{b} .$$

In this respect, titanium behaves no differently from any other metal, which is to say that its performance is orderly and predictable as affected by cutting speed, size of cut, and tool shape. Appropriate consideration is given to each of these factors in subsequent chapters.

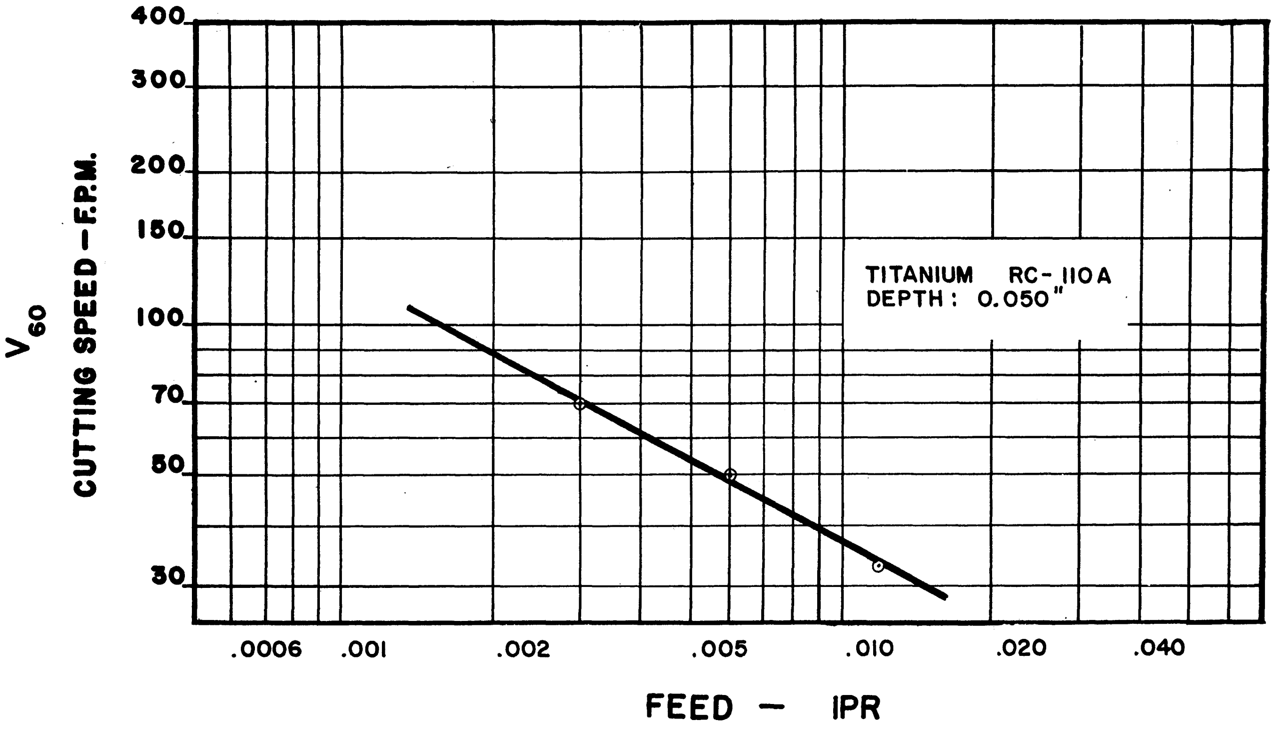



Fig. III-16. Effect of chip thickness or feed rate on the cutting speed required to produce constant tool life at all speed rates. This relationship is predictable.

Tool shape and cutting fluids also have significant effect on tool life. Rake angle is more important than any other factor of tool shape. Its effect is illustrated in Fig. III-17. Most common metals are represented by a similar curve showing an optimum rake angle at about 26° to 28°. The drop-off in tool life with increases beyond the optimum rake angle appear to be due to spalling of the cutting edge. Consequently, the optimum itself is sensitive to the rigidity of the machining setup so that a less rigid arrangement could cause the optimum to shift toward smaller rake angles with a loss in useful tool life at the same cutting speed. The specific effects of tool shape on each machining operation are discussed in later chapters.

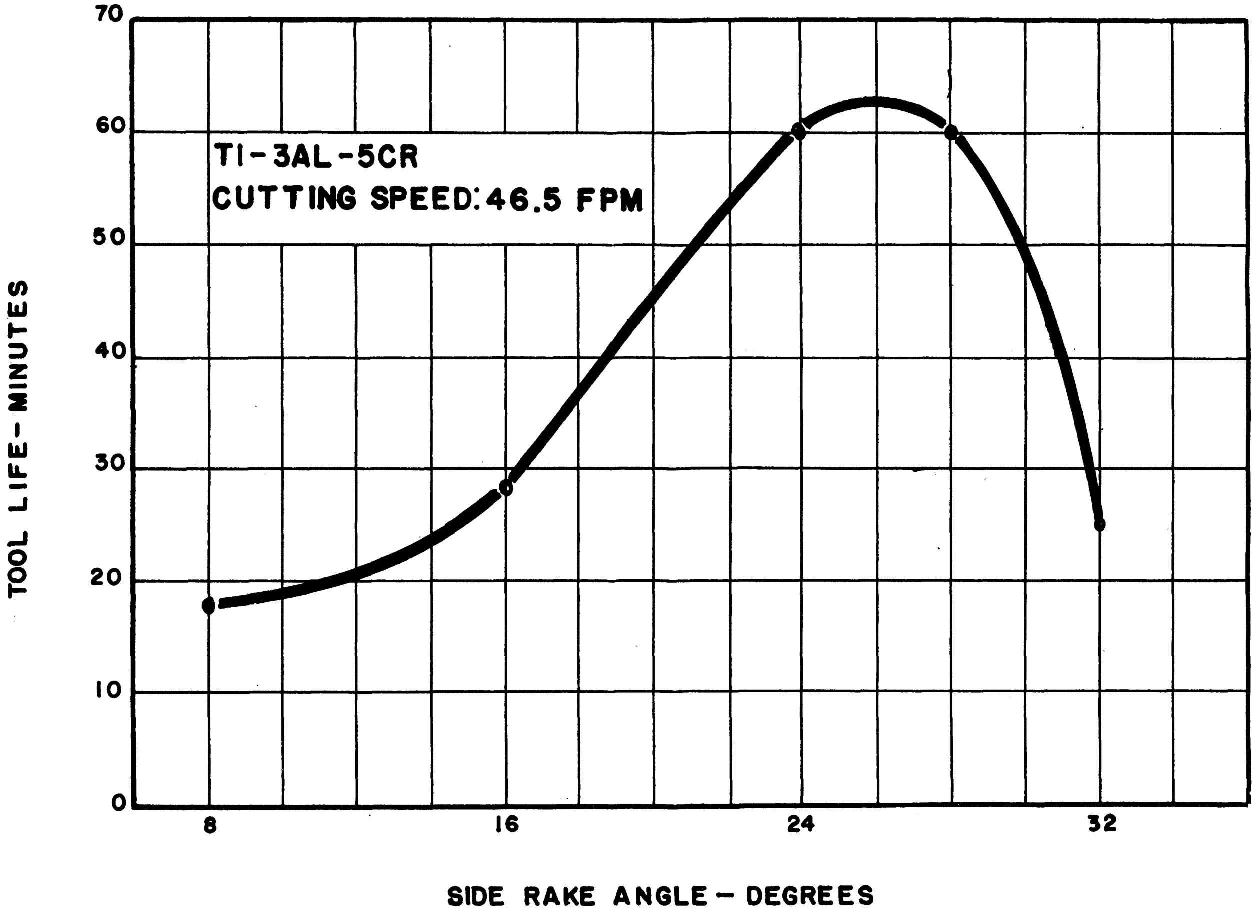



Fig. III-17. The effect of tool rake angle on tool life. The optimum will be shifted to smaller angles with less rigidity and to larger angles with greater rigidity.

Effect of Coolants.—When tool life is expressed as the time to complete "breakdown" tool failure rather than the time for some significant deterioration in control over surface roughness or size, then the length of tool life is determined by cutting temperature, and any improvement through the use of cutting fluids is derived primarily from their ability to reduce the temperature by cooling. One of the more effective coolants for machining titanium is a solution of 5% sodium nitrite ($N_aNO_2$) in water. This solution is also a good corrosion inhibitor.

Figure III-18 compares the use of a sodium nitrite solution with dry cutting when turning a titanium alloy. It is apparent that cutting speeds can be increased approximately 50 percent for the same tool life. This is unusual since similar fluids seldom increase cutting speed more than from 25 to 30 percent for steel cutting. However, the result should not be surprising since other indications point to unusually high temperatures in titanium machining.

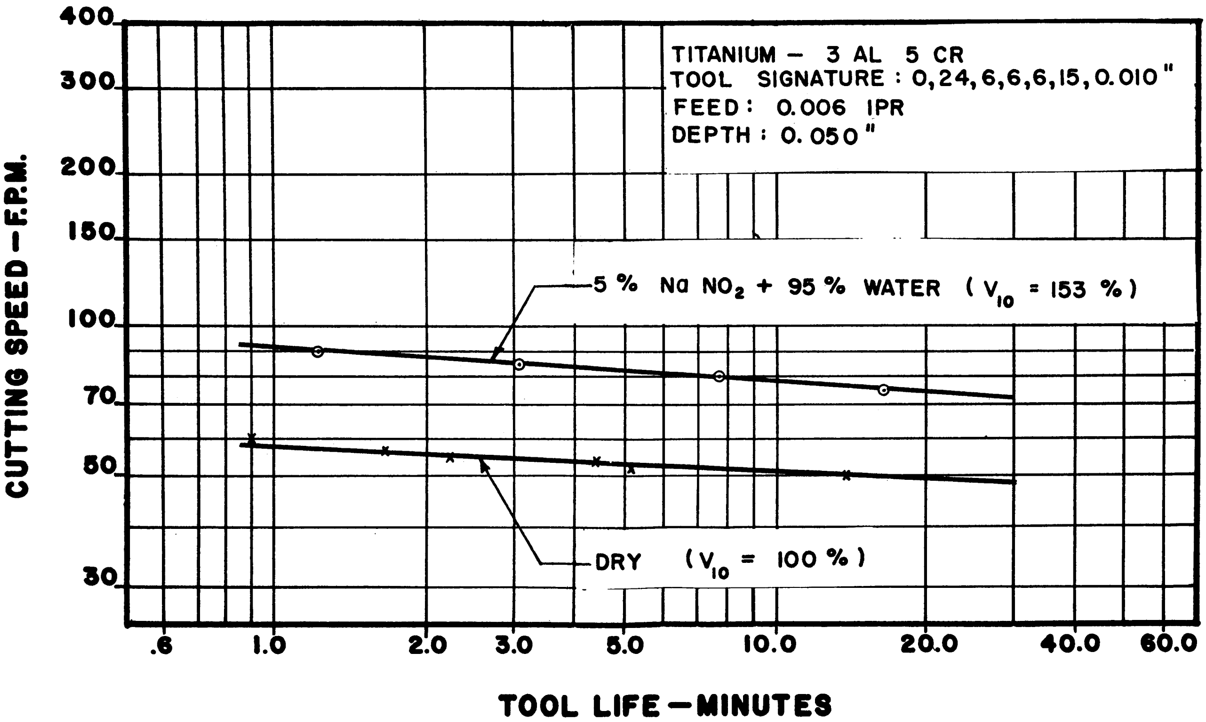



Fig. III-18. A typical example of the increase in cutting speed made possible by the use of effective coolants.

SURFACE FINISH

Surface finish is expressed in numbers as the roughness of a surface. Smoothness, the desired result, is the absence of roughness just as cold is the absence of heat; heat level or temperature can be measured; cold cannot be measured. Similarly, roughness can be measured but smoothness cannot.

Roughness of a machined surface is determined primarily by:

1. tool shape,
2. tool sharpness,
3. size of cut,
4. size of built-up edge.

It is more sensitive to built-up edge than to any other factor. A built-up edge produces a poorer finish since it separates the cutting edge from the work surface and sustains a condition of continuous or pulsating seizure between the tool and the machined surface. It was pointed out previously that a built-up edge does not occur in the machining of titanium; therefore, surface roughness in machining these alloys can readily be controlled since it is the result of selection of tool shape, size of cut, and limiting of tool dullness.

Figure III-19 shows the results of a study of surface roughness in a turning operation made with a constant tool shape over a range of feed rates.

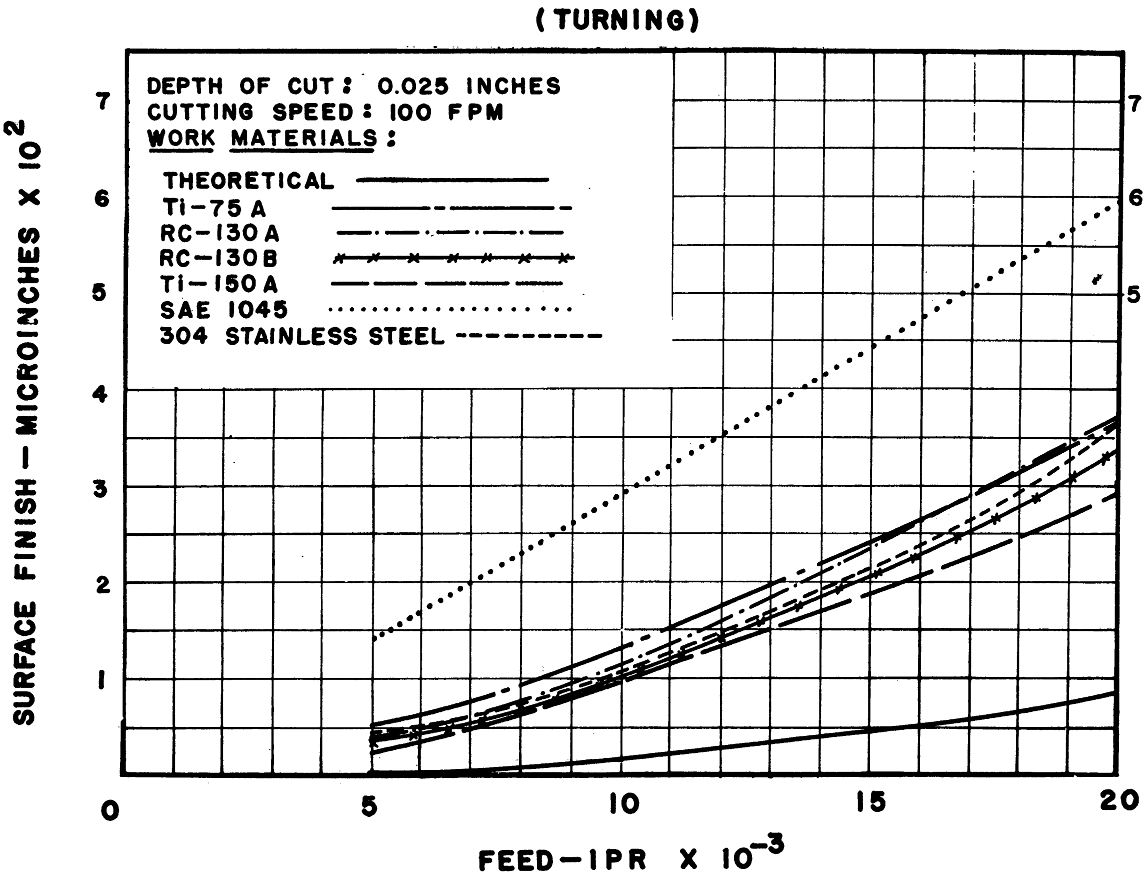



Fig. III-19. Surface finish in machining titanium is seldom a problem, since measured values of surface roughness seldom exceed half that of steel.

The solid black line represents the minimum-roughness reading for a perfectly sharp cutting edge with absolute smoothness between the feed marks. The dotted line represents measured roughness of SAE-1045 steel machined at the test conditions. It is significant that the titanium alloys were not more than half as rough as the steel. The studies made to date indicate that the principal causes of poor surface finish in machining titanium are:

1. tool chatter,
2. small relief angles on cutting tools.

The solutions to these problems are obvious; greater rigidity, and larger relief angles or more effective lubricants.

SIZE CONTROL

Some sacrifices or compromises can be tolerated in regard to tool life, surface finish, and even cost in machining, but a product is either accepted or rejected on the basis of meeting size specifications. Unusual difficulties are encountered in meeting size specifications in the machining of titanium; these difficulties stem from two principal causes:

1. abnormally large thrust forces in cutting,
2. relatively low stiffness of titanium.

The forces reacting between the flank of a cutting tool and the workpiece are unusually high for titanium, particularly as the cutting tool becomes more or less dull. These forces deflect the work away from the tool, causing loss of depth of cut and variation in dimension. The resistance of a material to applied force is expressed as the "modulus of elasticity"; the higher the modulus, the greater the resistance and the less the deflection for a given force. The "modulus of elasticity" of titanium is only slightly more than one-half that of steel, yet the normal or "thrust" component of cutting force may be substantially greater than for steel. Consequently, both properties add to the difficulties encountered in meeting size specifications. Three steps may be taken to meet this problem:

1. increase rigidity of the machine setup,
2. increase rake angles,
3. limit the wear of cutting tools to substantially less than that permitted in steel-cutting practice.

# CHAPTER IV

# LATHE OPERATIONS

## REVIEW OF IMPORTANT FACTORS

In any metal cutting operation one of the more important factors to be considered is the useful life of the cutting tool. Other criteria such as surface finish and power consumption must also be regarded, but of the factors involved, tool life might be considered to be of prime importance. It is sometimes defined as the volume of metal removed per regrind of the tool; however, in many cases it is simpler to talk of tool life in terms of the elapsed time to failure, usually expressed in minutes. This latter definition applies in this work.

Several variables have a decided influence on tool life, regardless of work material. Among them are the feed rate, depth of cut, cutting speed, tool shape, tool material, and cutting fluid, but all do not contribute equally. To determine the influence on tool life of each of these factors the most practical approach is to isolate each for individual study; in effect, one is varied while the others are held constant. Such a study can lead to the determination of near optimum conditions for each factor; however, it is impossible to predict the absolute best single set of conditions. The recommendations included in this chapter represent conditions that have been used for successful machining of titanium and its alloys. It is expected that individual industrial cases may require deviations from the exact suggestions, and several illustrations are included to show the probable effect on tool life, if such deviations are made.

## SUMMARY OF TEST RESULTS

The findings from this test program were the result of laboratory work, and alterations to more conservative conditions might be required in industrial applications. This is a distinct possibility since test conditions were checked with extreme care because of the nature of the work. Tool grinding and rigidity of the setup, for example, might not be controlled with as much emphasis as that exercised in the laboratory. The suggestions are based upon trends or tendencies that result when machining titanium, and exact duplication of the laboratory results may not be forthcoming.

Rake angles, defined as the slope of the tool face in the direction of chip flow, should be in the range of 16° to 20° when turning titanium and its alloys with high-speed-steel tools. Variations in the feed or depth of cut cause an orderly effect on tool life which may be predicted reliably. Tool life is very sensitive to changes in cutting speed but shows little reaction to changes in the nose radius of the tool.

Turning tests with carbide tools indicated that rake angles of approximately 16° worked well at light feed rates, while negative rake angles performed best at heavy feed rates. Hard, wear-resistant grades of carbides were most effective, and solid inserts were superior to the tipped form. In general, it appeared that carbides would find their most favorable application where rapid tool changing and low-cost regrinding does not lead to excessive cost. This conclusion is based on the finding that long tool life is difficult to attain with carbides. The above conclusions are discussed fully in the following sections, where necessary qualifications and explanations are included.

## RECOMMENDED PRACTICE

### A. Tool Design

#### 1. Turning

##### a) High-speed-steel tools

The slope of the tool face in the direction of chip flow, referred to hereafter as "rake angle," was an important factor in tool life. Figures IV-1 and IV-2 are typical of the findings. For all materials the optimum rake angles were in the range of 24° to 32°; however, angles from 16° to 20° are recommended to prevent premature chipping or spalling of the cutting edge. Figure IV-3 is a composite of the type of curves shown in the preceding figures. The titanium alloys RC-110A and 3Al-5Cr are not included in the third figure as they were tested at a later date, but the results were comparable to those shown.

Curves of rake angle versus tool life were derived from tool-life curves, of which a typical example is shown in Fig. IV-4. Since the tool-life curves were relatively flat, it is possible to get an exaggerated impression

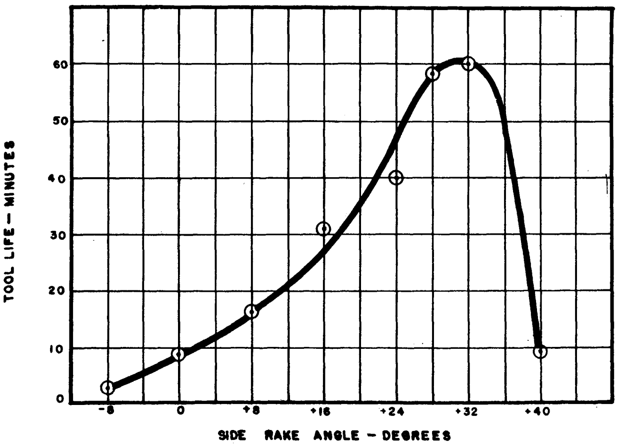



Fig. IV-1. The effect of rake angle on tool life when turning titanium RC-130B at 48 fpm.

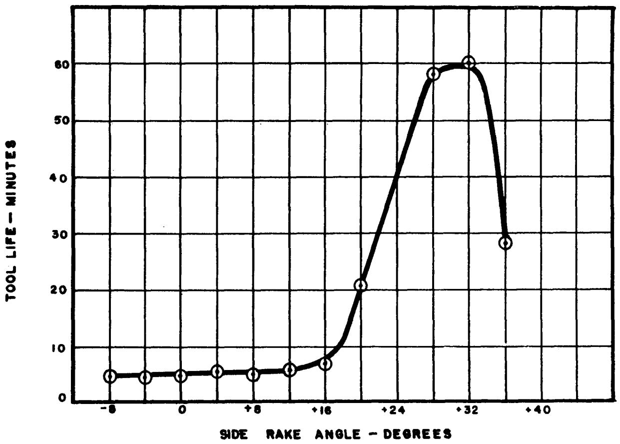



Fig. IV-2. The effect of rake angle on tool life when turning titanium Ti-150A at 74 fpm.

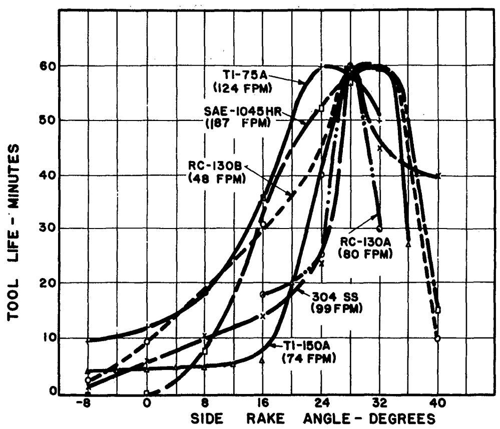



Fig. IV-3. A summary of the effect of rake angle when turning several grades of titanium and steel.

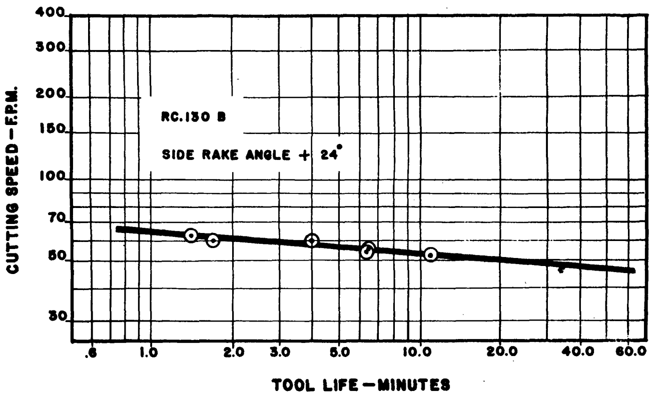



Fig. IV-4. A typical tool-life line obtained when turning titanium RC-130B with a tool having a rake angle of 24°.

from the first three figures. Therefore, the cutting speed for a one-hour tool life was plotted against rake angle, and a typical result can be seen in Fig. IV-5. The broad optimum indicates that lower rake angles may be used with only a small sacrifice in production rate as compared to the optimum condition.

Table IV-1 shows a comparison of cutting speeds that produced a one-hour tool life, $V_{60}$, for all work materials tested using the optimum rake angle for each material. Actual and relative speeds are listed with the speed for SAE-1045 steel being considered as a base value of 100 percent for the relative comparison.

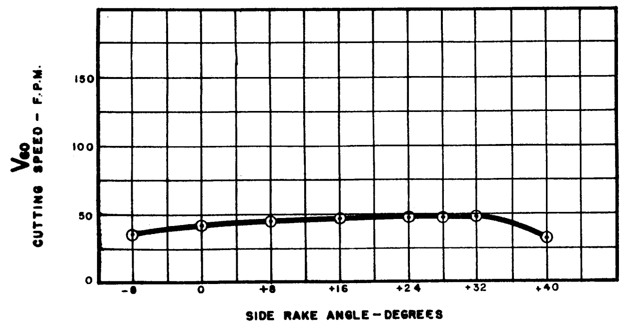



Fig. IV-5. The effect of side rake angle on the cutting speed for a one-hour tool life when turning titanium RC-130B.

TABLE IV-1

CUTTING SPEED FOR A ONE-HOUR TOOL LIFE*

| Material | Optimum Rake Angle, degrees | $V_{60}$ fpm | $V_{60}$ % |
|---|---|---|---|
| SAE-1045 steel | 32 | 187 | 100 |
| Ti-75A | 24 | 124 | 66 |
| 304 Stainless steel | 28 | 99 | 53 |
| RC-130A | 28 | 80 | 43 |
| Ti-150A | 32 | 74 | 39 |
| RC-110A | 24 | 50 | 27 |
| RC-130B | 32 | 48 | 26 |
| 3Al-5Cr | 24 | 46.5 | 25 |

*Feed of 0.006 ipr and depth of cut of 0.050 inch.

The optimum nose radius was approximately 0.025 inch when the size of cut consisted of a 0.006 ipr feed and 0.050 inch depth of cut. In general, the nose radius appeared to have little effect on tool life; this was somewhat unexpected since increased nose radii usually improve heat transfer characteristics, which leads to increased tool life. This advantage was undoubtedly offset by less favorable rake angle in the direction of chip flow. Figure IV-6 illustrates the effect of nose radius on the cutting speed for a one-hour tool life.

Since the influence of relief angles and cutting-edge angles was not investigated, it is recommended that the values used throughout this study be

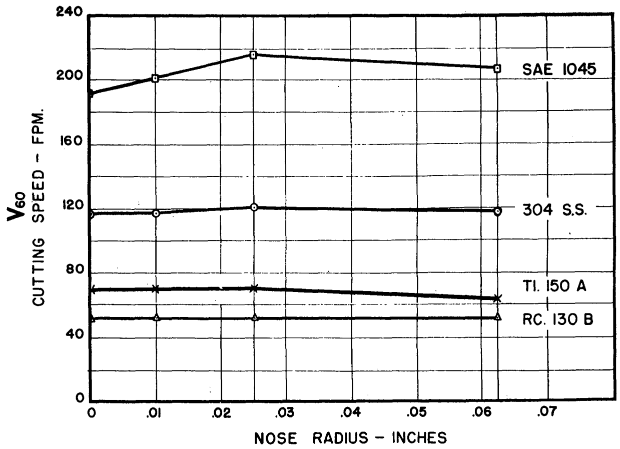



Fig. IV-6. The effect of nose radius on cutting speed for a one-hour tool life.

employed. Both end- and side-relief angles were six degrees; smaller relief angles are discouraged. A 6° end-cutting-edge angle and 15° side-cutting-edge angle performed satisfactorily. Smaller side-cutting-edge angles would probably be disadvantageous because of poorer heat transfer characteristics.

b) Carbides

Rake angle was the only component of the tool signature that was studied, since it was considered to be of primary importance. For feeds in the vicinity of 0.006 ipr, positive rake angles in the region of 16 degrees performed most efficiently, but at heavier feeds, 0.015 ipr, negative rake angles of about -5 degrees were superior. In general, the negative angles were less sensitive to changes in size of cut and appear to be most practical from a production viewpoint since heavier feeds are employed.

Figures IV-7 and IV-8 show the effect of rake angle when turning with a carbide tool at a feed of 0.015 ipr. Both relief angles and the end-cutting-edge angle were 6°, the side-cutting-edge angle was 0°, and the nose radius was 1/32 inch for all tests. These values can be used as a start, but should be altered where subsequent experience indicates the need.

Figure IV-9 illustrates the effect of carbide tool material on tool life. Grade 999 produced by the Carboloy Division of the General Electric Company and grade HA produced by the Firth-Sterling Steel Company performed most efficiently, and as a result it was concluded that the harder, more wear-resistant types of carbide are more desirable. Subsequent tests indicated that the 999 grade was superior to the HA grade; Fig. IV-10 illustrates such a comparison.

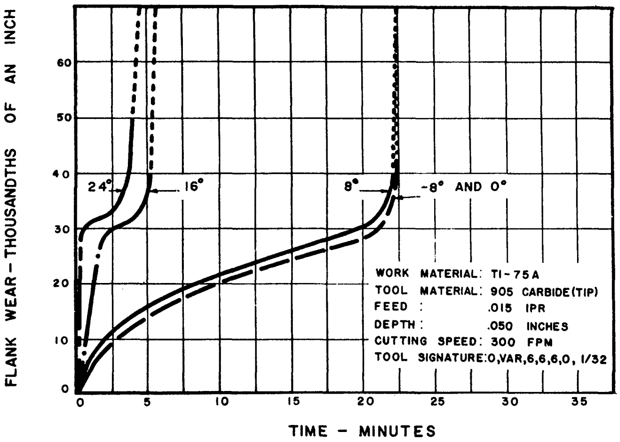



Fig. IV-7. Typical wear curves showing the influence of rake angle when turning Ti-75A with a carbide tool.

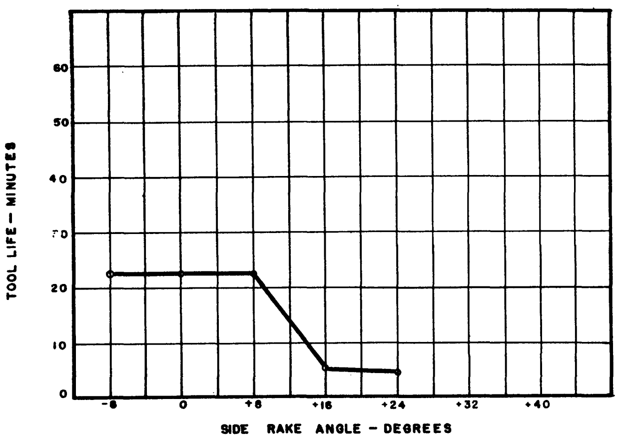



Fig. IV-8. A summary of Fig. IV-7 showing the influence of rake angle on tool life.

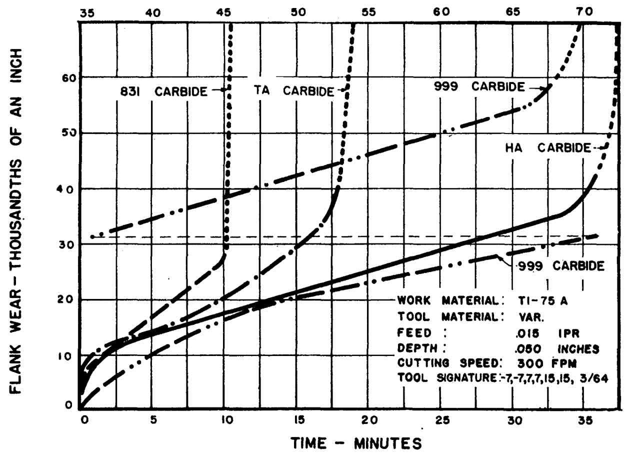



Fig. IV-9. Effect of carbide tool material when turning titanium.

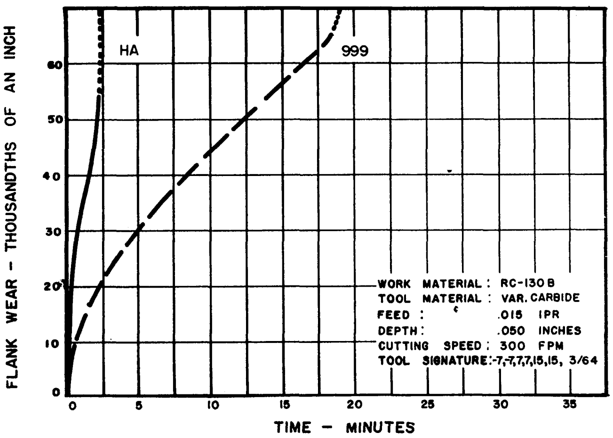



Fig. IV-10. Typical comparison of two grades of carbide tool material.

Because of the rapid increase in wear in the vicinity of tool failure, it can be concluded that carbides will not tolerate as much wear in the machining of titanium as is ordinarily permitted with steel. This differs from the ASA standard procedure, which designates 1/32-inch flank wear as carbide tool failure. Decreasing the cutting speed from 300 to 225 fpm did not yield appreciably longer tool life; thus, it is suggested that carbides be used in situations where lengthy tool life is not a definite requirement. The superiority of solid tools over the tipped variety may be the result of better heat transfer conditions that exist with the solid type.

2. Forming

High-speed-steel tools are recommended for forming cuts, and it would seem that rake angles smaller than those suggested for turning should be used to prevent chipping of the cutting edge. Relief angles must not be too small since the tendency for pickup might occur, as evidenced on other operations. A minimum of 6° is advised, and 10° is preferable.

3. Boring

Either high-speed steel or carbide tools should function effectively, and the suggestions made with regard to turning should be considered.

4. Cut-off or grooving

High-speed-steel tools should perform satisfactorily if a rake angle from 8° to 10° is used. Relief angles between 6° and 10°, and side clearance angles from 6° to 8° are recommended. Caution is again advised, to avoid clearance and relief angles that are too small, or increased material pickup may result.

Since the above suggestions cannot cover all problems that may arise, it is advisable to follow practices that prove satisfactory when machining steel unless specific recommendations indicate otherwise. Boring, forming, and grooving operations were not actually performed, so the suggestions given are not confirmed.

B. Size of Cut

1. Roughing

a) High-speed steel

Optimum rake angles were used during this entire study and conclusions drawn from the following recommendations must be based upon that condition. Any variations in rake angle will therefore necessitate qualification of suggested procedures. For rake angles from 0° to 15°, cutting speeds should be reduced 20 to 25 percent from the speeds used with optimum rake angles.

A feed of 0.006 to 0.010 inch per revolution and a depth of cut from 0.050 to 0.100 constitute a roughing cut. Increasing either of these variables will require a corresponding reduction in the cutting speed if tool life is to be maintained. Since both the feed and depth affected the cutting speed for a particular tool life in an orderly manner, it is possible to make reliable predictions of cutting-speed — tool-life combinations for various sizes of cut. Table IV-2 illustrates the effect of three sizes of cut on the cutting speed for a one-hour tool life, $V_{60}$, the values being derived from the aforementioned equations. It can be seen that the cutting speed is more sensitive to changes in feed than it is to depth; this trend existed for all grades of titanium and is a common property in all metal cutting.

TABLE IV-2

$V_{60}$ VERSUS FEED AND DEPTH OF CUT FOR RC-130B

| Feed ipr | Depth of Cut in. | $V_{60}$ fpm | $V_{60}$ Based on Case 1 as 100% |
|---|---|---|---|
| .010 | .100 | 36 | 100 |
| .020 | .100 | 24 | 67 |
| .010 | .200 | 33 | 92 |

It can be seen in the above table that cutting speed is more sensitive to feed than depth. For the same tool life, the speed must be reduced 33 percent if the feed is doubled, while only an 8 percent reduction is required when the depth of cut is doubled.

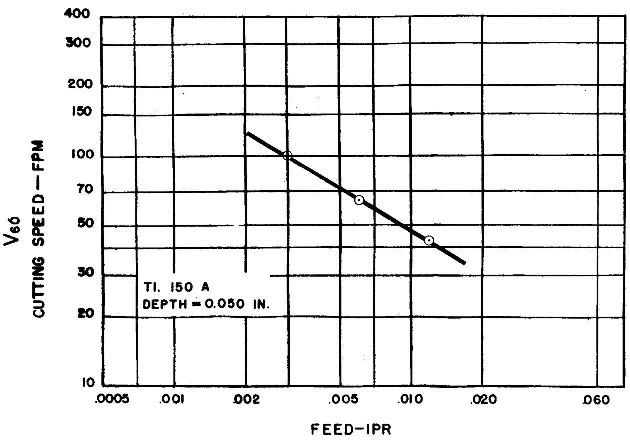



Fig. IV-11. The effect of feed on the cutting speed for a one-hour tool life.

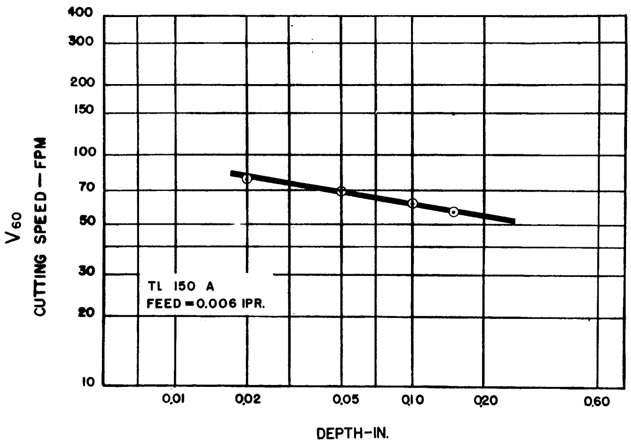



Fig. IV-12. The effect of depth of cut on the cutting speed for a one-hour tool life.

Figures IV-11 and IV-12 are typical summary curves that indicate the effect of feed and depth of cut on cutting velocity. The points on these curves are obtained from individual tool-life lines similar to those shown in Fig. IV-13.

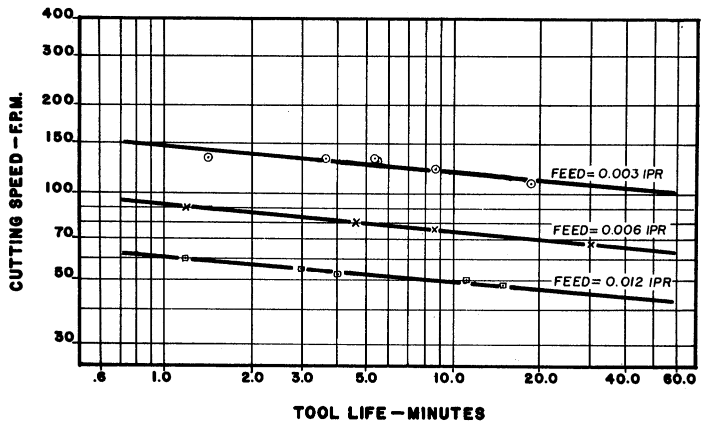



Fig. IV-13. Family of tool-life lines for different feed rates.

b) Carbides

A feed rate in the region of 0.015 ipr and a depth of cut from 0.050 to 0.100 inch should constitute a satisfactory size of cut for rough turning. Negative rake angles are preferred for cuts of this size.

2. Finishing

a) High-speed steel

This type of turning cut should consist of a 0.003 ipr feed rate and a depth of cut between 0.005 and 0.015 inch. The magnitude of cutting speed accompanying such a cut will depend upon the work material and desired tool life. Means for predicting such speeds have been discussed previously.

b) Carbides

Finish-turning with carbides may be done by using a feed of 0.003 to 0.005 ipr and depth of cut of 0.015 to 0.025 inch. Positive rake angles, about 16°, should be used with a cut of this size.

C. Cutting Speed

1. High-speed steel

As shown in Tables IV-1 and IV-2, differences in work material and size of cut have a pronounced influence on the cutting speed for a given tool life; therefore, no single speed can be recommended to cover all situations. The values listed in Table IV-1 may be used as a guide, but more precise values for any given set of cutting conditions may be derived from the equations.

2. Carbides

A cutting speed of 300 fpm, in conjunction with the size of cut recommended previously, can be used on the commercially pure grade of titanium. This should be reduced to the vicinity of 225 fpm for the alloys. Reducing the speed below these values did not increase tool life considerably, so it appears that these are the best suggestions available. Future experience with other grades of carbide and size of cut will probably require alterations in these speeds; therefore, they should be interpreted as an initial condition.

D. Cutting Fluids

The material on this topic is discussed at length in Chapter XII and only the conclusions will be repeated in this section. High cutting temperatures associated with titanium required an effective coolant. A water-base solution of 5% sodium nitrite and 95% water proved most satisfactory. Where lathe operations are conducted at low speeds and the need for lubrication becomes apparent, a sulfochlorinated mineral oil should be used.

It can be concluded that substantially the same improvement in tool life will result from the use of cutting fluids when machining titanium as that which occurs with steel and, in many cases, the improvement will be greater.

Reports 3, 4, 7, 12, 13, 14, 26, and 29 contain all the information regarding the basic studies pertaining to lathe operations and should be consulted for a complete analysis of any specific recommendation given in this chapter.

# CHAPTER V

# MILLING

## REVIEW OF IMPORTANT FACTORS

The milling of titanium-base alloys presented the problem of selection of types of cutters, cutting-tool material, and conditions of operation (speed, feed, and depth of cut). With the advancement in the use of carbide cutting tools during World War II, work had been done for the War Production Board on the milling of cast iron with high-speed-steel and sintered-carbide face milling cutters and this background of information provided an immediate index for evaluating the same process on titanium materials.

High-speed-steel and sintered-carbide milling cutters were used in comparing the results of tests on the titanium materials with those previously obtained on the various cast irons. The same cutting conditions that were found to be satisfactory for the milling of cast iron (cutter material, type, and geometry) and conditions of operation (speed, feed, and depth of cut) were used for milling titanium alloys to determine if normal designs of cutters and conditions of cut are applicable to the milling of titanium.

In general, it was found that the cutting conditions normally recommended for cast iron were not satisfactory in the machining of titanium materials because of (1) excessive chipping on the carbide tools, (2) reduced speeds required on high-speed-steel cutters, (3) required changes in feed rates, and (4) required changes in tool geometry.

## SUMMARY OF TEST RESULTS

### A. High-Speed-Steel Tools

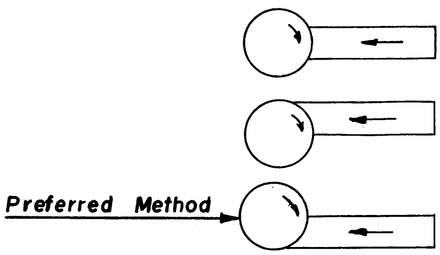
A comparison of results of the various titanium alloys with the 20,000 psi cast iron, in the velocities for a 60-minute tool life and where the feed was .010 per tooth and the depth of cut was .100 inch, would indicate the following:

| Material | 60-Minute Tool Life fpm |
|---|---|
| 20,000 psi cast iron | 140 |
| Ti-75A | 95 |
| Ti-110A | 38.5 |
| Ti-150A | 38.0 |
| 3Al-5Cr | 33.5 |
| RC-130B | 27 |
| Ti-150B | 20 |

This shows that high-speed-steel tools must be operated at greatly reduced speeds in the machining of titanium alloys to maintain a reasonable tool life.

B. Sintered-Carbide Tools

An 883-Carboloy tool ground to 7, 7, 6, 6, 2, 0, .070 - 45° in a 9-inch-diameter face cutter gave very poor results in the machining of the titanium materials. This type of cutter had given excellent results previously on the 20,000 psi cast iron at 143 Bhn and Meehanite cast iron at 197 Bhn, but now reacted unfavorably because of excessive chipping. Immediate changes were made in the position of the cutter relative to the work and it was found that thin-exit chips, obtained by in-milling with the chip thickness approaching zero at the exit side of the cut, would reduce the amount of chipping and improve the tool life of cutting tools. Following are examples of the types of cuts made in this investigation:




| Type of Cut | Type of Chip |
|---|---|
| Centerline | Uniform |
| Out-milling (conventional) | Thick at exit |
| In-milling (climb) | Thin at exit |

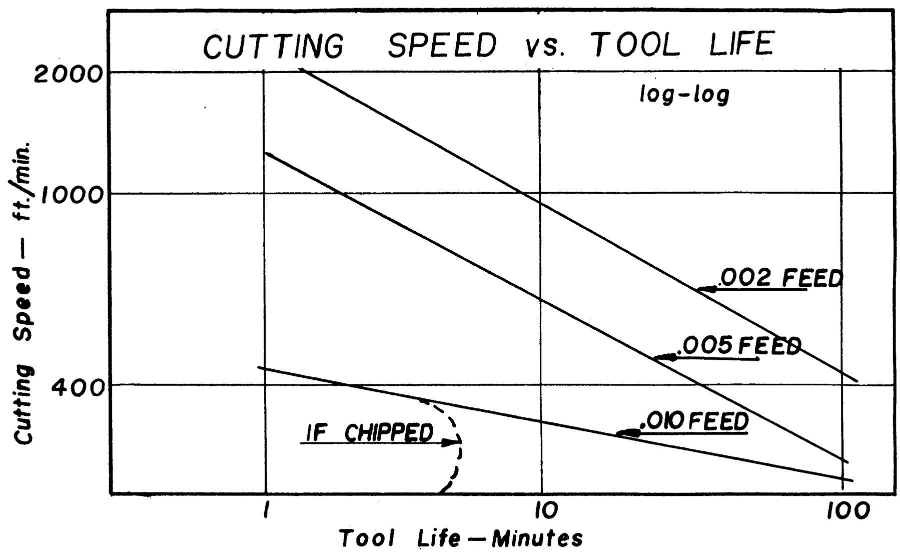
Tool signature was studied to determine the effects of the variables, and the following results are indicated:

Relief angles: At lower speeds, a higher relief angle of 12° gives longer tool life than the standard reliefs of 6° or 7°. If chipping occurs, the reliefs should be reduced toward a standard value.

Rake angles: Side rake angles of -7° to +7° gave the most consistent performance, and extreme negative rake appeared to be beneficial only when using high speeds with the 883-Carboloy tool in the lower-strength materials.

Cutting edge angles: The longer cutting edge obtained by a 45° chamfer on the milling cutter gave better performance than the 0° cutting edge, even if it included a small chamfer. The cutting-edge angle provides a wider and thinner chip on the cutting tool and thus reduces the amount of welding that is inherent with the titanium materials on carbide tools.

Work feed in inches per tooth seems to be of considerable importance in the satisfactory machining of titanium with carbide tools. Normally, because of the high-compressive strength of carbides, the feed loads are increased and higher production rates are attained; but in the milling of titanium, it was found that a reduction in feed increment would reduce the welding tendencies of the titanium on the carbide and thus reduce the chipping which is ruinous to tools of this type. The figure below shows the effect of feed rate on the cutting speed for a given tool life or, conversely, the increase in tool life for a given cutting speed, as a result of decreasing the feed rate in inches per tooth from .010, which is considered normal for most materials, to .005 and to .002 inch per tooth of the milling cutter.



The lower line also shows what commonly happened to the carbide tools where chipping occurred near the beginning of the test. If tools fail by chipping rather than abrasive wear, the data points will not fall on a straight-line curve and the lower speeds may show as short a tool life as the higher speeds.

The power required in milling of the titanium materials can be determined from a simple form equation in which:

$$hp_{cutter} = C\ d\ w\ n\ f\ N$$

where d = depth of cut, inches
w = width of cut, inches
n = number of teeth in cutter
f = feed in inches per tooth
N = revolutions per minute
C = constant for titanium = .80 .

As an example, assume a total machine and motor efficiency of 60 percent and a titanium material being milled at 150 rpm with a 12-tooth cutter, depth of cut .250 inch, feed of .005 inch per tooth, and a bar width of 3 inches. If the motor horsepower is to be determined, then:

$$\frac{\text{hp cutter}}{\text{efficiency}} = \text{hp motor}$$

$$\text{hp cutter} = C\ d\ w\ n\ f\ N$$

$$= .80 \times 250 \times 3 \times 12 \times .005 \times 150$$

$$= 5.4 \text{ hp cutter.}$$

If $$\frac{\text{hp cutter}}{\text{mach. eff.}} = \text{hp motor,}$$

then $$\frac{5.4}{.60} = 9.0 \text{ hp motor.}$$

Therefore, a machine powered with a 10-hp motor would be required for the above condition.

RECOMMENDED PRACTICE

A. Tool Design

1. Face milling

The use of high-speed-steel tools in this type of operation definitely limit the production rate because of the speed and feed limitations that have been found inherent in the titanium materials. With the speed limitations that are imposed, it is recommended that the axial and radial rakes should be +7°, relief angles 6°, face cutting-edge angle 2°, and a peripheral cutting-edge angle up to 45°. The increased peripheral cutting-edge angle provides a longer cutting edge per given depth of cut and a thinner chip. The wider and thinner chips increase the tool life for a given cutting speed or, conversely, allow higher cutting speeds for a given tool life. The carbide face mills should have 0° to -7° rake, 6° to 17° normal relief, 2° face cutting-edge angle, and up to 45° peripheral cutting-edge angle. The harder grades of carbide give better tool life on the harder titanium alloys than is obtained by using the softer grades of carbide. At the higher cutting speeds the 883-grade carbide gave the best results with negative rake angles of -22°.

The face mounting of either high-speed-steel or carbide milling cutters is good from the standpoint of inherent rigidity. However, the successful face milling of titanium will depend, as well, on the rigidity of the work-holding device and the condition of the milling machine. In general, the cutter diameter should be as small as possible and consistent with the largest possible number of teeth. The larger number of teeth insures higher metal removal per minute and the smaller size of cutter provides less deflection and greater stability.

2. Arbor milling

The arbor-mount cutters should be ground with approximately the same tool geometry as recommended for the face cutters. On the profile, saw, or slab types of cutters the helical type of tooth design provides wider and thinner chips for a given feed rate than the standard, straight-tooth design. In this type of setup, the arbor should be of largest possible diameter to reduce the tendency toward windup and it should be supported on each side of the cutter with overarm supports. It is of utmost importance that the cutter is ground and mounted to run dead-true to make the best use of the light feed increments that are recommended.

B. Size of Cut

Light feed loads in the range of .002 inch per tooth have shown definite improvement over the more conventional feeds of .005 and .010 inch per tooth used on other types of materials. The finer feed load reduces the area of contact of the titanium materials on the face of the milling cutter tooth and thus reduces the tendency toward premature failure on the high-speed-steel tools and chipping on the carbide tools.

Depth of cut is normally defined by the specifications and the desired production rate in milling. Normal recommendations would be from .100 to .150 inch. Larger depths of cut are permissible if there is sufficient power available, since power increases directly with an increase in depth or width of cut. More important than this, however, is the position of the cutter in relation to the work, as in face milling. The cutter should be positioned relative to the work to provide a thin (approaching zero) exit chip. This is accomplished by (1) positioning the cutter so the work approaches as a tangent and (2) using the in-milling method of milling to insure a thick chip at the beginning of contact of a tooth and a thin chip at the tooth exit on the work. The in-milling method gives longer tool life for a given cutting speed and more efficient power consumption, but care must be exercised in the type of application and the machine condition. All gibs must be tightened and any inherent looseness in the machine eliminated.

C. Cutting Speeds

The cutting speeds for high-speed-steel tools should be in the range of 27 fpm for the RC-130B material and 95 fpm for the Ti-75A to provide a tool life of 60 minutes at a feed of .010 inch per tooth and a depth of cut of .100 inch. If the feed is reduced to .002 inch per tooth, as previously recommended, the cutting speed could be increased, as a function of the effect of feed on the cutting speed for a given tool life.

The recommended cutting speeds and feeds for the various titanium materials when using carbide-tooth milling cutters are as follows:

| Material | Feed, ipt | Speed, Fpm for a 100-Minute Tool Life |
|---|---|---|
| Ti-75A | .005 | 540 |
| RC-130B | .002 | 390 |
| Ti-150A | .002 | 310 |
| Ti-3Al-5Cr | .002 | 315 |
| Ti-110A | .002 | 324 |
| Ti-150B | .002 | 140 |

The speeds recommended showed practically no chipping at the light feed rates and are thus recommended as practical values for commercial application. If it is desirable to obtain a longer tool life than 100 minutes, reference may be made to Report 23D for the values of slopes of the cutting-speed — tool-life curves and the value of cutting speed for a given tool life can be computed.

D. Cutting Fluids

The addition of a cutting fluid to the milling operation would cause thermal cracking of the carbide tool bits so dry cutting is recommended for the carbide milling of titanium.

If high-speed milling cutters are being used, the addition of an emulsion or aqueous-type solution should give sufficient cooling effects to allow an increase of from 20 to 25 percent in the cutting speeds for a given tool life.

# CHAPTER VI

# DRILLING

## REVIEW OF IMPORTANT FACTORS

The important factors in drilling are the production of acceptable holes with respect to surface finish, straightness, and size. This should be accomplished with a minimum of power consumption and a maximum tool life.

Certain inherent properties make drilling titanium and its alloys different from drilling steel. These properties have to be recognized when selecting the proper feed, speeds, and drill design.

Due to the relatively high shear angle of titanium in comparison to steel, the chips do not foreshorten. This means that the chip itself is thinner and travels faster than a steel chip under the same cutting conditions. This property gives the titanium chips a tendency to fold and clog in the flutes of a drill. Correct feeds and large flutes, preferably surface treated to facilitate chip flow, will overcome this difficulty. Also related to the high shear angle is the concentration of the tool forces on a small area on the cutting edge. High forces and high speeds produce a large amount of heat. This heat produces premature failure of the cutting edges and has to be carried off by the proper application of a coolant. The previously mentioned packing of the chips might very well interfere with the application of the coolant and result in failure.

Titanium also has a tendency to work harden. From Figs. VI-1 and VI-2 it can be seen that the depth of work hardening is mainly a function of cutting speed and tool sharpness. If proper care is not taken, the work-hardening effect might become so severe that subsequent operations such as reaming and tapping become extremely difficult.

All cutting tests on titanium have shown that rigidity is of major importance. Rigidity of the setup in general, and of the drill in particular,

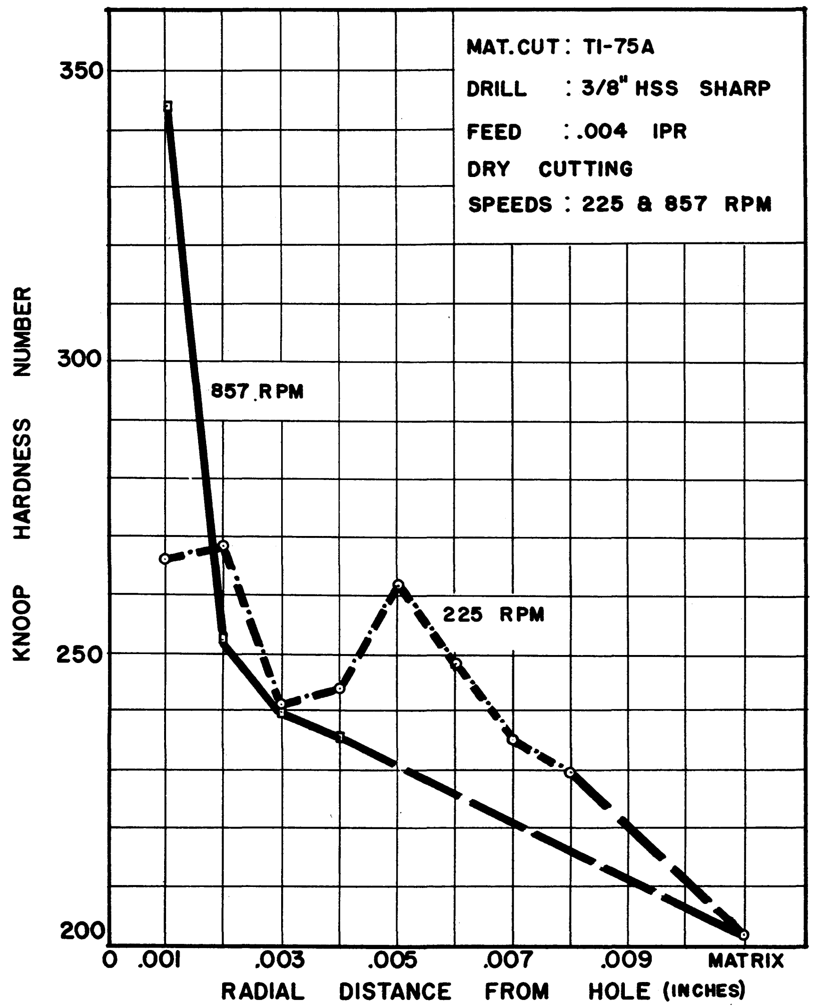



Fig. VI-1. The effect of cutting speed on the depth of work hardening for titanium 75-A at a feed of .004 ipr.

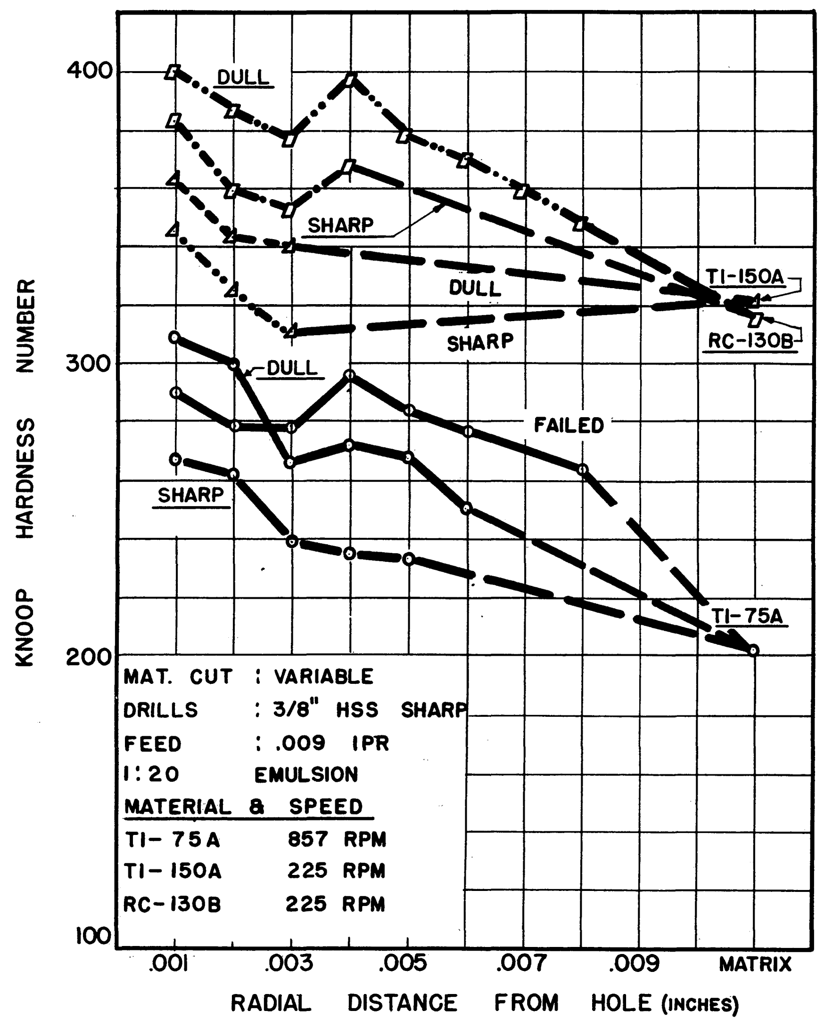



Fig. VI-2. The effect of drill sharpness on the depth of work hardening for Ti-75A, Ti-150A, and RC-130B.

will result in less chipping of the cutting edges, longer tool life, and better holes. The factor of drill rigidity can best be controlled by choosing the proper drill length. A study by Mr. Carl Oxford, Jr. of the National Twist Drill and Tool Company, Rochester, Michigan has shown that the number of holes drilled per grind is a direct function of drill length. Figure VI-3 shows the result of these studies.

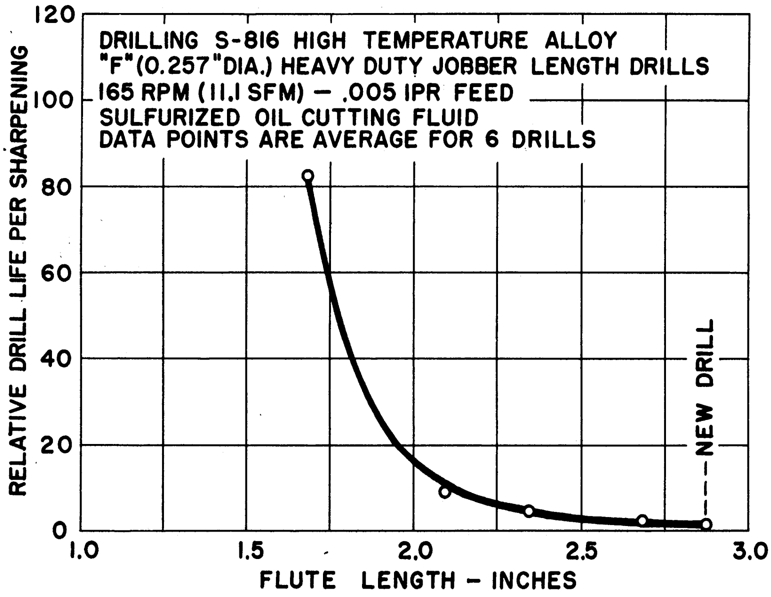



Fig. VI-3. Short drills are more rigid and can be expected to give longer life when drilling titanium. (By courtesy of the National Twist Drill and Tool Company of Rochester, Michigan.)

SUMMARY OF TEST RESULTS

A considerable amount of work has been performed on the machining of titanium. Some of the most useful information obtained is summarized in the following paragraphs.

Figure VI-4 shows the relative power requirements for drilling various titanium alloys and SAE-1045. The power is given as unit hp or the horsepower necessary to remove one cubic inch of material per minute. The table also shows the relative thrust forces and torque required to drill the various alloys.

| MATERIAL | TORQUE (1) | | | THRUST (2) | | | 1/2"HSS DRILL,225 RPM,.009IPR | | |
|---|---|---|---|---|---|---|---|---|---|
| | a | b | C | z | y | K | TORQUE LB.FT. | THRUST LBS. | HP/in³/min |
| TI-75A | 0.84 | 1.73 | 1900 | 0.42 | 0.84 | 6300 | 10.9 | 480 | 1.18 |
| TI-150A | 0.87 | 1.73 | 2550 | 0.96 | 0.78 | 101000 | 13.2 | 642 | 1.42 |
| RC-130B | 1.43 | 1.73 | 65000 | 0.81 | 1.60 | 105000 | 23.4 | 732 | 2.52 |
| RC-130A | 0.84 | 1.73 | 1680 | 0.82 | 1.00 | 63800 | 9.2 | 665 | 0.99 |
| TI-3AL-5CR | 0.97 | 1.68 | 4150 | 0.55 | 0.945 | 17950 | 13.5 | 700 | 1.45 |
| RC-110A | 0.78 | 1.80 | 1635 | 0.55 | 1.36 | 24900 | 12.0 | 725 | 1.29 |
| SAE 1045 | 0.85 | 1.73 | 2310 | 0.90 | 1.00 | 75500 | 13.0 | 532 | 1.40 |

(1) TORQUE = $T = C f^{a} D^{b}$

(2) THRUST = $B = K f^{z} D^{y}$

Fig. VI-4. Exponents and constants for the torque and thrust formulas as obtained in drilling pure titanium and various alloys. Actual torque, thrust, and unit horsepower values obtained when drilling these same materials with a 1/2-inch high-speed-steel drill at 225 rpm at 0.009 ipr feed.

Figure VI-5 gives a graphic representation of the torque and thrust forces encountered when drilling various alloys with a 1/2-inch drill at a cutting speed of 29.4 fpm and feeds of 0.009, 0.006, and 0.004 ipr without the use of cutting fluid. Figures VI-6 and VI-7 show the influence of feed and drill diameter, respectively, on torque and thrust for the titanium alloys tested.

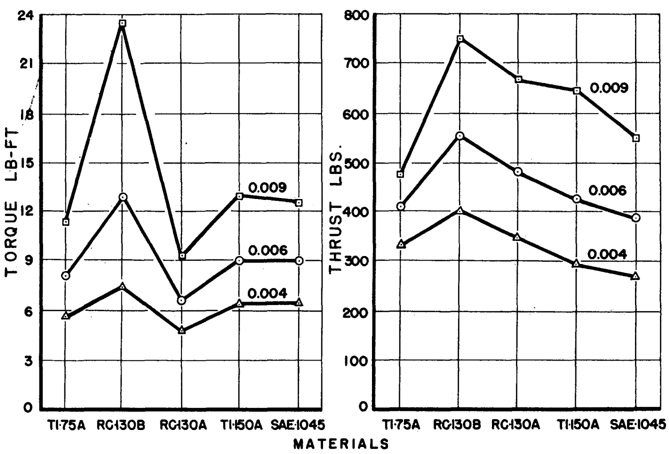



Fig. VI-5. Graphic representation of the torque and thrust values obtained when drilling titanium alloys with a 1/2-inch-diameter standard high-speed-steel drill at 29.4 fpm and various feeds.

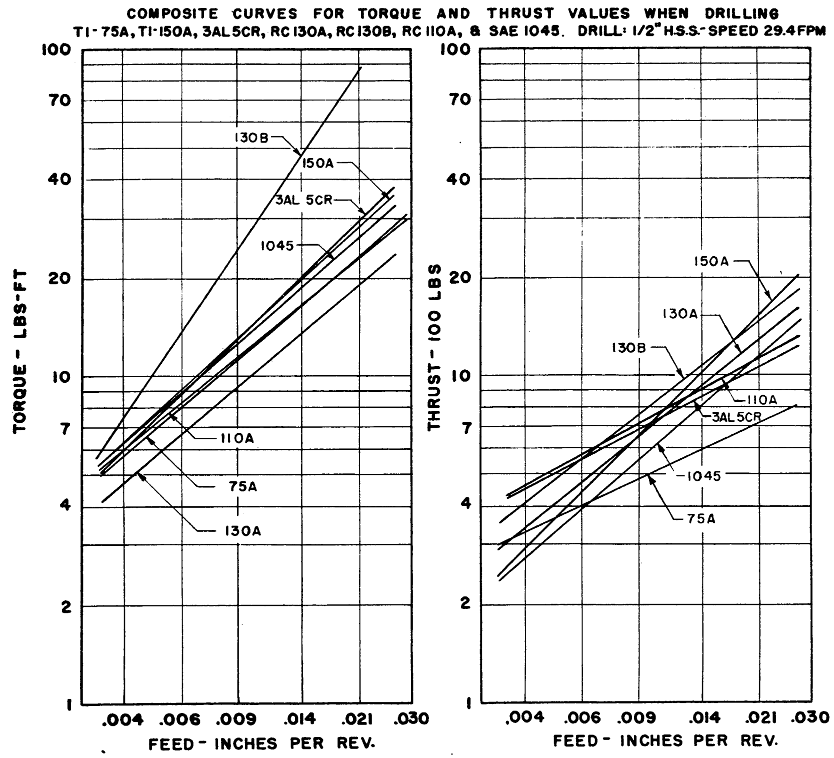



Fig. VI-6. Torque and thrust curves versus feed for SAE-1045 and various titanium alloys.

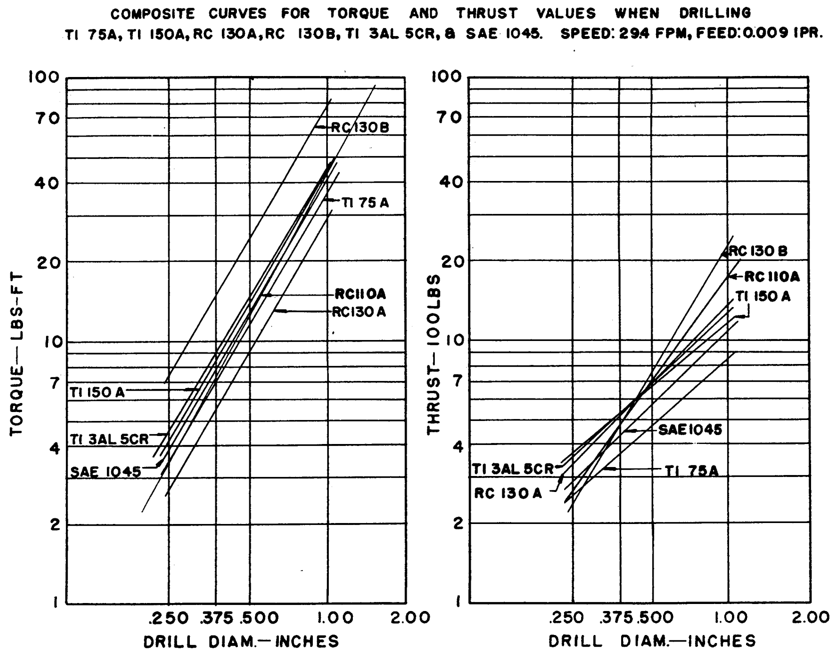



Fig. VI-7. Torque and thrust curves versus drill diameter for SAE-1045 and various titanium alloys.

The effect of drill sharpness and cutting speed on work hardening has already been shown in Figs. VI-1 and VI-2. Other tests have been performed to evaluate different variables. They show that the drills should be surface treated, e.g., nitrided, oxide treated, or some other commercial variant, to facilitate chip disposal. Cutting-fluid tests indicate that at higher speeds cooling is of greater importance than lubrication. At low speeds highly chlorinated and sulfurized mineral oils were found to perform satisfactorily.

From a variety of tests in all types of cutting, it has been found that the relief angles on tools used on titanium are of extreme importance. Small relief angles tend to cause excessive pickup and, ultimately, heat and wear. Too-large relief angles weaken the cutting edges to such an extent that they cannot stand up under the high forces. Relief angles of about 8° to 10° are recommended.

## RECOMMENDED PRACTICE

For the best drilling results the following practice is recommended:

The tools should be standard 30° Helix angle drills with a surface treatment to improve chip removal. The length of the drill should be kept as short as feasible to increase rigidity and decrease "windup," which will cause chatter and chipping. A standard 118° point angle with 120° chisel edge angle and 8° to 10° relief will give adequate results. Web thinning will reduce the thrust required, but care should be taken not to alter the effective rake angle when thinning. The speeds should be under 25 and preferably under 20 fpm with feeds from .006 to .014 ipr. The tool material for which the above values apply is high-speed steel. Carbon tool steel will not stand up at all. The cutting fluid used should be a good coolant for the higher speeds and a highly chlorinated sulfurized mineral oil for the lower speeds.

## DEEP-HOLE DRILLING

Deep-hole drilling tests have indicated that titanium alloys can be drilled satisfactorily by using the proper precautions. The same factors indicated previously will, in general, have a bearing on the successful drilling of deep holes. Single-lip gun drills of standard commercial design can be used satisfactorily if run at proper speeds and feeds. The feeds should be at about 0.0005 ipr. Heavier feeds will result in clogging of the flutes because of chip folding. Finer feeds will cause chipping of the carbide cutting edges due to high stress concentration.

The speeds vary from 220 fpm for commercially pure titanium to 150 fpm for the tougher alloys. The harder grades of cast-iron-grade carbides perform the best. Both the standard centercut and the trepaning or target-drill type of gun drills perform satisfactorily, with perhaps the target drill showing a slight superiority on the tougher alloys. The relief angles on the single-lip drills should be from 6° to 8° to avoid pickup.

All tests were satisfactorily run with the use of a mineral oil with rust and oxidation inhibitors added.

# CHAPTER VII

# BROACHING

## REVIEW OF IMPORTANT FACTORS

Broaching as a means of machining flat, formed, and round surfaces lends itself directly to successful operation on commercially pure titanium and its alloys. Broaching provides inherent rigidity due to the self-locking action derived from cutter motion against the work-holding device or fixture.

Tool design was considered one of the most important factors in obtaining performance in the broaching operation; thus, rise per tooth, rake angle, and relief angle were investigated under the dry cutting condition, with measurements of surface quality and cutting force recorded as criteria to be used in evaluating the variables.

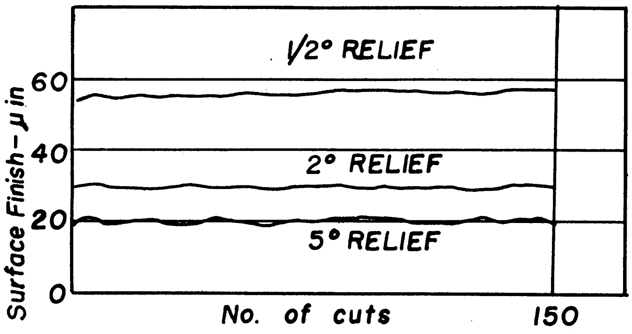
One type of high-speed-steel tool material was used in all broaching tests, and the tooth shape consisting of pitch, depth of tooth, and land width was adapted according to general recommendations of the Broaching Tool Institute.

Standard cutting speeds of from 20 to 30 fpm are normal for the broaching operation, and the lower value (20 fpm) was used during the testing program.

The standard test for each material was established as 150 cuts — 1 inch wide by 2 inches long — or fewer if a material did not respond properly because of excessive forces or poor surface quality.

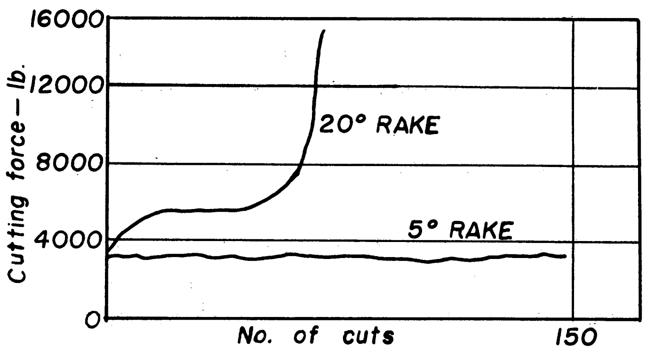
## SUMMARY OF RESULTS

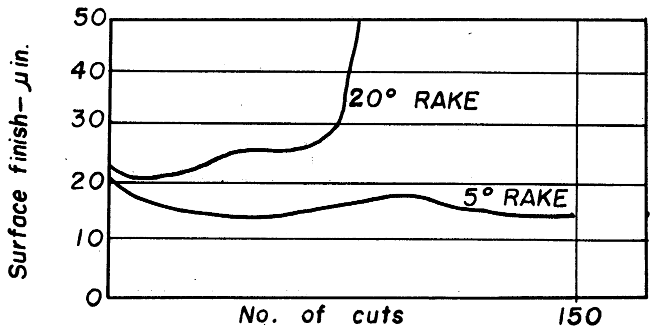
Results of tests on the effect of relief or back-off angles indicate that titanium materials require a higher relief—5° as compared to the normal practice of 1/2° to 2°. Relief angle seems to have little or no effect on the




cutting force and power requirements in machining titanium, but the surface finish is directly affected by the amount of relief angle. Metal pickup on the land relief, in the case of 1/2° to 2°, can seriously affect the resulting surface quality.

A rake or hook angle of 20° is normally recommended for the broaching operation, but with the titanium materials a considerable reduction from 20° to 5° showed a marked difference in performance, as illustrated.




The higher rake angles allow less metal at the cutting edge to absorb and resist the wear characteristics of this type of material, and as a result of this characteristic the high-rake tools perform poorly as compared to the low-rake designation.

The normal recommendation for the rise per tooth in broaching steel is .0005 to .003 inch, depending on type of cut, material hardness, etc. All the titanium materials, with the exception of Ti-150B, were machinable by the broaching process at .002- to .005-inch rise per tooth, but the .002-inch rise gave better results in magnitude of cutting forces and lower value of surface finish (microinches, rms) than the .005-inch rise per tooth. The results obtained on the various alloys at .002 inch per tooth rise indicated that the RC-130B gave the best quality of surface finish, with the other materials listed in descending order as follows: Ti-150B, Ti-75A, Ti-110A, 3Al-5Cr, and Ti-150A. All the titanium materials gave surface finishes that were superior to the SAE-1045 steel as dry cut.

The geometric combinations of the several tools that appeared best in the surface-broaching tests were applied to the design of a bore-broaching tool, and this was compared directly with a tool that was designed according to standard industrial practice. The tool designed as a result of surface-broaching tests outperformed the tool with lesser relief, larger rake, and smaller rise per tooth.

RECOMMENDED PRACTICE

A. Tool Design

1. Broaching tools that are to be used in the machining of titanium and its alloys should have 5° of relief angle instead of 1/2° to 3°, as normally recommended for other materials. This seems to be one of the most important aspects of tool design for these materials.

2. The tools should be kept always at maximum sharpness so that the tendency to "smear" the land will be reduced.

3. A rake angle of 5° is preferred to one of 15° to 20° normally recommended for other materials, to give greater support to the cutting edge and a greater volume of metal for heat transfer.

4. The titanium materials provide great resistance to penetration of a cutting tool, so rigid support of the work piece is of utmost importance in eliminating the effect of "stepping" or producing a series of "flat surfaces" on the work piece.

5. The use of shear angles or lengthening of the cutting edge should eliminate the effect mentioned in No. 4 above but, in any case, the rigidity of the work piece is of utmost importance.

6. Hole broaching presents no problem in any of the materials that can be surface broached. The centering action of a bore-broaching tool and localization of forces on the cutting tool reduce the problem of work-holding that is prevalent on other types of operations.

7. Any type of high-speed steel should work reasonably well in a broaching tool. The standard types T-1, M-2, and M-10 should give good performance in the speed ranges common to this operation.

B. Size of Cut

1. Size of cut, as defined by a particular job requirement and the type of operation to be performed, does not seem to be critical for the broaching operation. On the basis of observed reactions, one should expect Ti-75A to be similar to SAE-1045 in the magnitude of power requirement, and the titanium alloys,

Ti-110A, 3Al-5Cr, Ti-130A, RC-130B, and Ti-150A will require approximately 25 percent more power when other variables are held constant.

2. Size of cut (rise per tooth) seems to be directly related to power requirement. The area of cut, together with the number of teeth in contact, is used in determining the required power for a given operation. A value of 1.0 to 1.8 unit hp (hp/cu in. per min) can be used for determination of actual forces and power requirement. The range represents various types of titanium alloy materials.

3. A rise per tooth of .002 inch gives better surface quality than higher values normally associated with roughing operations. A range of 6 to 28 microinches, rms, should be expected from the titanium alloys if tool design is consistent with the recommendations herein.

C. Cutting Speed

Cutting speed for the titanium materials should be restricted to the range of from 20 to 30 fpm when using high-speed-steel tools. Some of the alloys have shown marked tendencies toward critical response to slight changes in cutting speed, and thus it would appear reasonable to recommend a low speed for this type of operation.

D. Cutting Fluids

1. The introduction of a cutting fluid such as a sulfurized-mineral oil to the broaching operation should (1) improve the surface finish slightly, (2) reduce the wear rate resulting from the abrasiveness of the material, (3) minimize the heat resulting from the cutting action, (4) provide an opportunity to increase the cutting speed by 10 to 15 percent of the dry cutting condition, and (5) reduce the power requirement slightly.

2. The introduction of an emulsion or aqueous-type cutting fluid should (1) have little or no effect on the surface quality, (2) provide greater cooling than the oil-base materials, and (3) show little or no effect on a reduction in power requirements.

CHAPTER VIII

SHAPING

IMPORTANT FACTORS

One of the most important factors to be considered in the successful machining of titanium and its alloys by the shaping operation is the inherent rigidity of the machine, together with the rigidity gained by proper tool setup

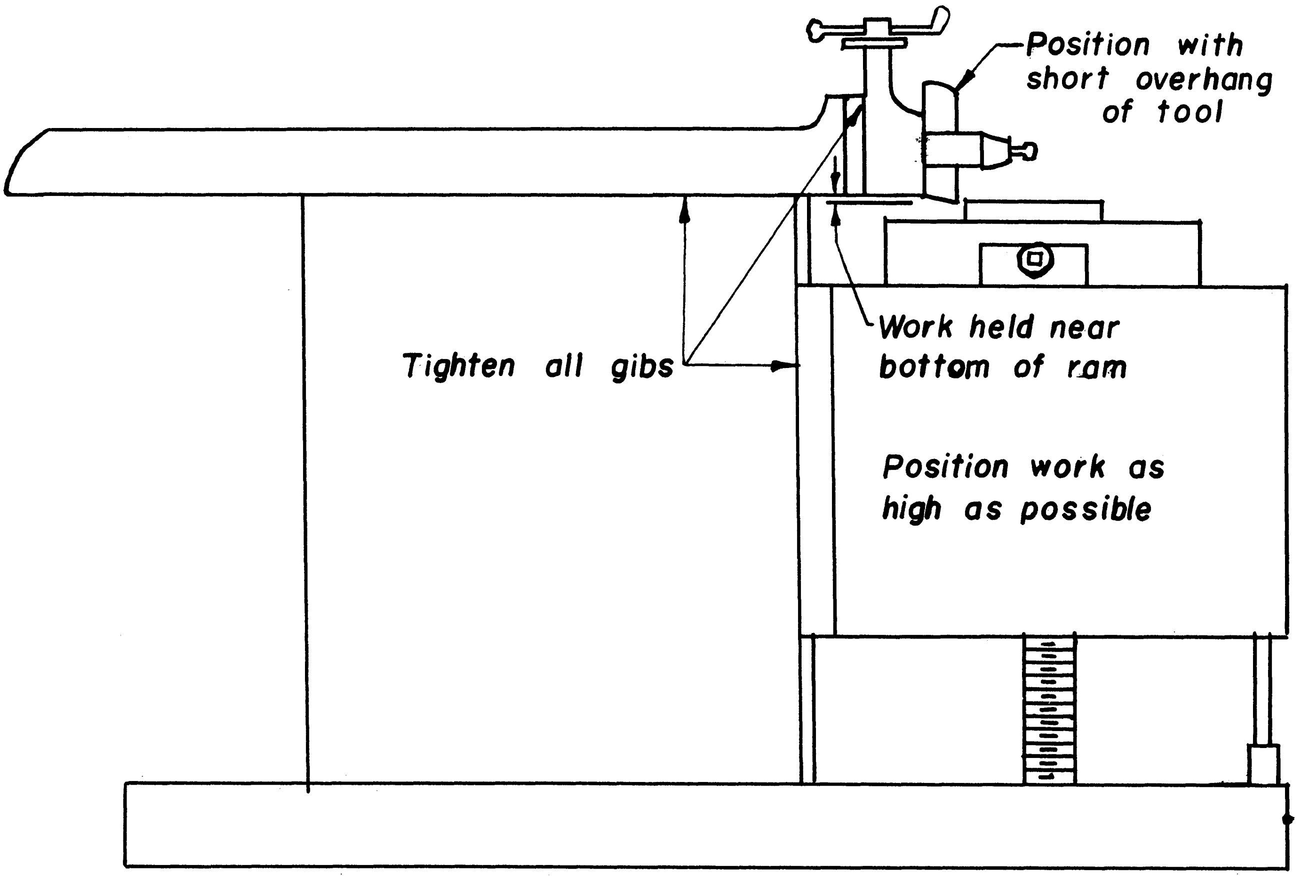



Fig. VIII-1. Machine requirements for shaping titanium.

and work position. At the beginning of the studies on this type of operation, it was discovered that the machining of titanium alloys by shaping was virtually impossible with the normal setup that would be common to the machining practice on ferrous and nonferrous materials. Tool life on some of the alloys was practically zero, regardless of the value of cutting speed that was used. As the result of these observations, the gibs on all sliding and positioning ways were adjusted to a maximum, allowable tightness, the cutting tool was positioned in the clapper box to allow a minimum overhang (i.e., an amount slightly larger than the depth of cut), and the box table was adjusted vertically upward to position the work almost directly in front of the ram of the machine.

The significant considerations in the shaper setup are indicated above. It is important that the tool and work deflections should be minimized.

The factors that were evaluated in the shaping of titanium were cutting speed—tool life, cutting speed for a given tool life versus work-feed rate, and cutting speed for a given tool life versus depth of cut. Since most of the shaping operations are performed under dry cutting conditions, cutting fluid studies were deleted from this survey.

The geometry of the high-speed-steel cutting tools was identical to that used in the turning operations, and carbide tools were not considered for this operation since their use in shaping operations is restricted because of the machine-speed limitations.

SUMMARY OF TESTS

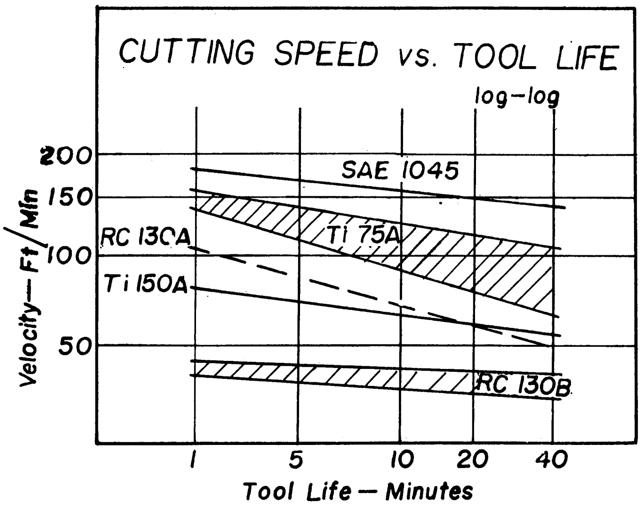



Fig. VIII-2. Effect of cutting speed on tool life. Titanium oxide scale reduces tool life erratically.

Cutting-speed — tool-life tests (Fig. VIII-2) indicate that Ti-75A is somewhat similar in performance to SAE-1045 steel, but the cutting speeds for a given tool life must be reduced somewhat over that of the latter. Ti-75A materials gave results indicating a range of cutting speeds for a given tool life, due to the material variation and the position of cut in respect to the original scale condition on the test specimens. Ti-150A, RC-130A, and RC-130B show correspondingly lower values of cutting speed for a given tool life in descending order. On the basis of these results, the cutting speed for a given tool life of RC-130B should be 25 to 30 percent of the Ti-75A and 22 to 25 percent of the SAE-1045 steel. The RC-130A and Ti-150A are similar in performance, except that the RC-130A shows a higher wear rate both on the cutting tool and as indicated by the steeper slope of the curve. The cutting speed for a given tool life versus feed rate of the work against the tool (Fig. VIII-3) shows very predictable performance in the shaping of titanium. The SAE-1045 steel and Ti-75A are very similar in performance, with the Ti-75A showing slightly higher cutting speed for a given tool life at the higher feed rates than the SAE-1045 steel. This is shown in Fig. VIII-3 by the difference in slopes of the two curves. The RC-130A and Ti-150A curves are nearly identical in height and in slope, so the response of these two materials is nearly the same as the result of feed variation. The RC-130B material is again the lowest of all materials, and a change in feed rate produces the same reaction in cutting speed for a given tool life.

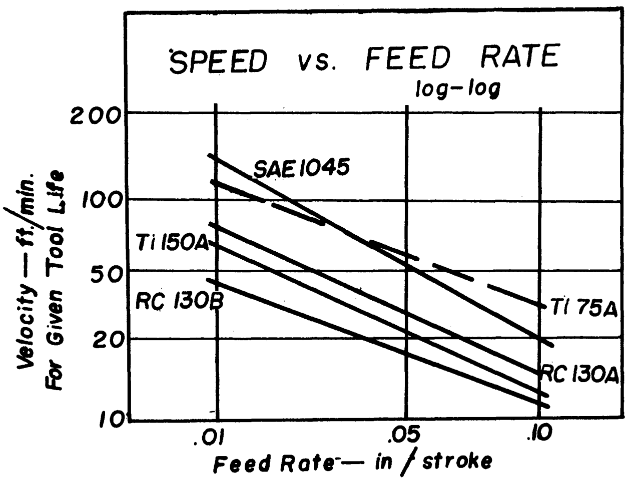



Fig. VIII-3. Effect of feed rate on cutting speed for constant tool life.

The results obtained in varying depth of cut (Fig. VIII-4) show that Ti-75A is more susceptible to effects of increase than SAE-1045 steel (the opposite of the effect of feed rate change). A range of speeds is shown for given values of tool life as a function of the position of the cut relative to the original cast surface of the test bar. RC-130A and Ti-150A show similar levels of cutting speed but, as indicated by the slopes of the curves, the RC-130A shows greater reactions to an increase in depth of cut than does the Ti-150A material. The RC-130B material should be machined at lower speeds than any of the other materials and produces similar curve characteristics to the other titanium alloys.

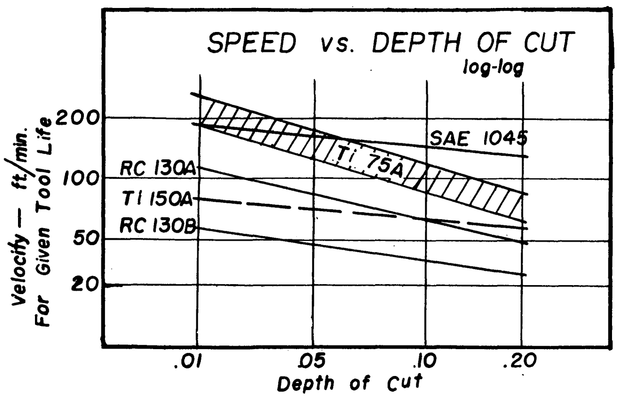



Fig. VIII-4. Effect of depth of cut on cutting speed for constant tool life.

RECOMMENDED PRACTICE

A. Machine Setup

A shaper that is to be used in the machining of titanium and its alloys should be checked for looseness of ways and gibs and adjusted for maximum tightness to insure minimum deflections. The work-holding device should be positioned to retain the work as close as possible to the bottom of the ram. The tool and the head should be positioned with a minimum overhang to insure a limited deflection of the cutting tool. Maximum rigidity in all machine tool, cutting tool, and work-holding components should be the objective of any shaping operation in these materials.

B. Tool Design

High-speed-steel tools of the T-1, M-2, and M-10 types give satisfactory performance in the shaping of titanium and its alloys. A signature of 0° back rake, 28° side rake, 6° reliefs, 6° end-cutting angle, 15° side-cutting angle, and 0.030-inch nose radius gives very good results in the shaping of titanium. Variations in the amount of nose radius should be within the limits of 0.010-inch minimum to 1/16-inch maximum. Larger nose radii are likely to produce chatter on the work piece. The side rake angle on shaping tools is of considerable importance in obtaining maximum performance on titanium materials, and it appears that this angle should be larger on tools used on titanium than on those that are commonly used on steel and cast iron.

C. Cutting Speed

The machining of titanium and its alloys can be successfully performed in the shaping operation, provided that proper levels of cutting speed are recognized for each material. The cutting-speed — tool-life relationships are orderly and predictable, and the following speed ranges with high-speed-steel tools should produce reasonable results at a feed of 0.010 inch per stroke and a depth of cut of 0.050 inch:

Ti-75A - 75 to 160 ft/min, depending on the proximity to the scale surface and the length of actual tool contact time of 1 to 40 min (tool life).

RC-130A - 60 to 105 ft/min for the same tool life, 1 to 40 min.
Ti-150A - 60 to 80 ft/min.
RC-130B - 34 to 45 ft/min, depending on the proximity of the cut to the scale surface.

D. Size of Cut

Results from tests for the effect of feed rate on the cutting speed indicate that increasing the feed from 0.010 inch to 0.020 inch would require reducing speed to the percentage values shown below:

| Material Cut | Speed Used for 0.010 Feed % | Range of Cutting Speed for 1- to 40-Min Tool Life ft/min |
|---|---|---|
| Ti-75A | 70 | 52 - 112 |
| RC-130A | 62 | 37 - 65 |
| Ti-150A | 60 | 36 - 48 |
| RC-130B | 58 | 20 - 26 |

Depth of cut on titanium materials has a lesser effect on a reduction in cutting speed for a given tool life than does feed rate. The effect of doubling the depth of cut from 0.050 inch to 0.100 inch is illustrated for each material as follows:

| Material Cut | Speed Used for 0.050-in. Depth of Cut % | Range of Cutting Speed for 1- to 40-Min Tool Life ft/min |
|---|---|---|
| Ti-75A | 81 | 61 - 130 |
| RC-130A | 86 | 51 - 90 |
| Ti-150A | 91 | 55 - 73 |
| RC-130B | 90 | 30 - 40 |

In general, titanium and its alloys can be machined successfully by the shaping operation if the machine, cutting tool, cutting speed, and size of cut are given significant consideration and application. If cutting fluids are considered essential for the operation, the same general recommendations that are given for turning operations will hold for the shaping of titanium materials.

# CHAPTER IX

# TAPPING

## UNIQUE FACTORS

Tapping titanium and its alloys has presented a problem because of excessive seizure and resulting tap breakage. In selecting the proper taps and cutting fluids, the important characteristics of the titanium alloys should be considered.

Due to the high shear angle in titanium, the chips do not foreshorten as much as they do in steel. This calls for a larger chip space and a design which will guide the chips away from the cutting edges and out of the hole. The high shear angle is also responsible for a very concentrated cutting force on the cutting edge. This situation is inducive to chipping. The tendency to cause seizure calls for the careful selection of a suitable tapping fluid, paste, or compound.

## SUMMARY OF TESTS

During the tapping tests, the performance of both the tap design and the cutting fluids was based on the torque required to tap a 1/2-13 thread. It was found that both the cutting and the reversing torque were of importance in judging performance. Figure III-13 illustrates the effectiveness of the various cutting fluids tested. From this graph it can be seen that pure carbon tetrachloride gave the best results and that a wax containing $CCl_4$ gave the next best performance. The use of carbon tetrachloride is, however, objectionable and in some cases even prohibited by law for commercial practice. The fluids which performed best and were at the same time commercially feasible were lithopone and ZnS in oil. Both compounds are powders and were mixed with lubricating oil to produce a paste. This paste was then applied to the tap with a brush or similar instrument.

Figure IX-1 shows torque vs cutting speed for various titanium alloys. From this graph it can be seen that most of the alloys have their lowest torque requirements at approximately 22 fpm cutting speed. If the optimum cutting speed is exceeded, the torque increases rather rapidly and will then cause tap failure.

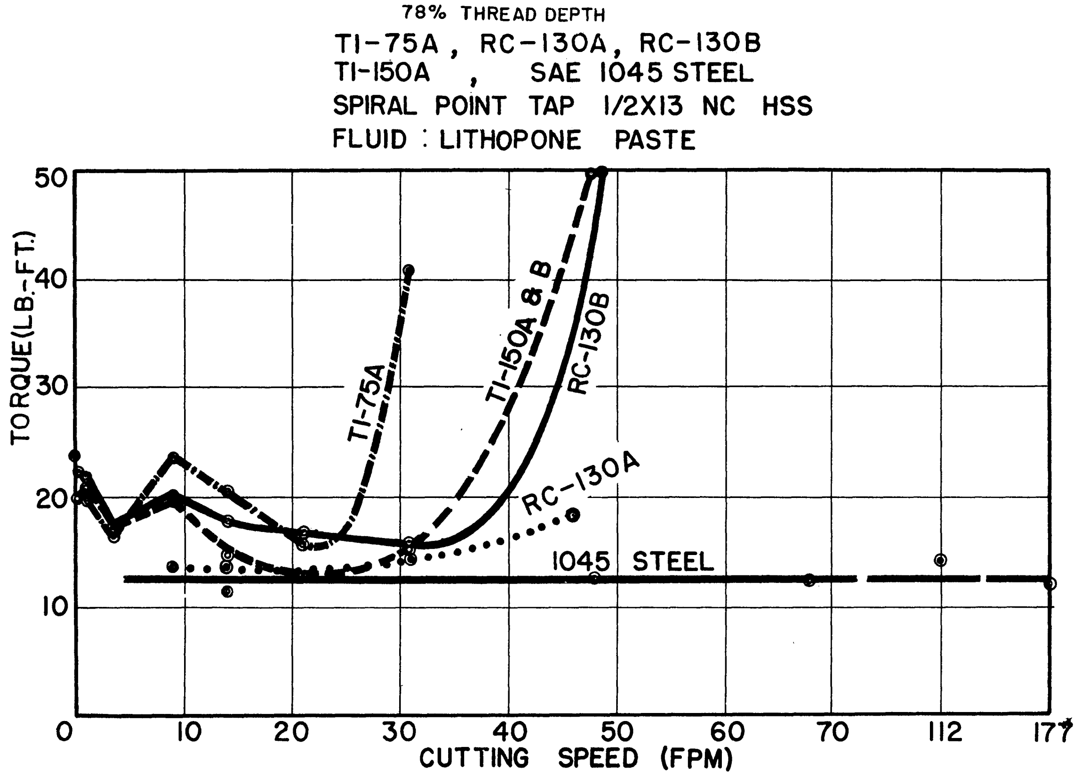



Fig. IX-1. The effect of cutting speed on torque for various titanium alloys.

The tests indicated that most tapping difficulties could be eliminated if the thread depth was reduced to 50 to 60 percent. Hand tapping presents problems due to the lack of rigidity. It was virtually impossible to tap a 1/2-13 thread with 78 percent thread depth without breaking or badly chipping the tap.

RECOMMENDED PRACTICE

A. Tap Design

A satisfactory tap for power-tapping titanium would be a high-speed-steel tap of the following design:

A three-fluted tap with a 10° to 17° spiral point angle, plug chamfer commercially ground with either regular or interrupted threads. The rake on the cutting side should be from 5° to 10°. The rake on the reverse side is not critical. The threads should have some relief, enough to prevent seizure but not enough to cause mechanical jamming of the chips on backing out. The jamming of the thin chips is of greater consequence than the seizure as far as relief is concerned. The relief should therefore be from 2° to 4°. To further prevent seizure, the taps should be oxide coated. The spiral point angle has a definite bearing on the flow of a continuous chip. With too low an angle the chips do not flow out of the hole ahead of the tap and thus cause breakage.

Although the angle on the reverse side is not too critical, it should be kept around -3°. If this angle is increased too much—say to -11°—the chips will show a tendency to jam on backing out of the hole.

The normal chamfer angle of about 5 threads will give satisfactory results. A short chamfer will result in high torque, causing breakage, and a long chamfer will produce thin, long, stringy chips which will have a tendency to jam on backing out.

Of the special taps, the only type recommended is the interrupted-thread-type tap with a 10° to 17° spiral point angle.

B. Cutting Speed

From Fig. IX-1 it can be seen that the cutting speed should be around 20 fpm. Increasing this speed will result in much higher torque values, which will cause breakage.

C. Cutting Fluids

The paste type of cutting fluids, lithopone or ZnS in oil, will give the best results. They seem to lubricate well and, in addition, help control the chips in backing out. In the event that the application of the lithopone paste onto the tap is difficult or impossible, the next best cutting fluid in liquid form would be a heavily chlorinated and sulfurized mineral oil. The cutting torque required for the fluid oil would, however, be about 50 percent higher and the back-out torque about 200 to 400 percent higher.

# CHAPTER X

# REAMING

## UNIQUE FACTORS

Several criteria should be used to consider whether a reaming practice is satisfactory. These include a smooth surface finish and proper size of the reamed hole, low torque requirements, and the avoidance of excessive tool regrinding. In many cases there is a tendency for the reamer to be subjected to extensive material pickup or seizure, with the result that one or several of the above standards are not attained. Proper tool design and operating conditions will reduce this adverse occurrence considerably, and acceptable holes result. The presence of chatter during the cut also proves detrimental, but this, too, can be eliminated by alterations in the tool design, size of cut, and cutting speed.

A single set of cutting conditions which will satisfy all the criteria in an optimum sense is the exception. Higher speeds, for example, may improve surface finish, but invariably lead to shorter tool life. The most logical solution is to select a set of conditions that yield satisfactory results from all viewpoints.

## TEST RESULTS

Three grades of titanium, Ti-75A, RC-130B, and Ti-150A, were studied in this work, and high-speed-steel reamers were used throughout. Any attempt to investigate the large number of combinations of test variables on all work materials would prove impractical in view of the excessive time and cost required. For that reason, titanium Ti-75A was used to analyze the variables that led to the selection of a satisfactory reamer design and effective cutting fluid. These findings were then applied directly to studies conducted on the titanium alloys, thus eliminating a repetition of these tests. Subsequent work bore out the supposition that the reamer design and cutting fluid that worked satisfactorily on the commercially pure titanium would function effectively when reaming the alloys.

An analysis of cutting speeds and feeds was made on all three subject materials. This was necessary since the properties of the materials were different. Also, other machining operations had indicated wide variation in the magnitude of cutting forces and temperatures that prevailed when each of these grades of titanium was machined. It was found that the cutting speeds to be used with the alloys were lower than the speeds that could be used with the pure grade.

Since the alloys RC-130A, RC-110A, and 3Al-5Cr were not subjected to reaming tests, the recommendations given with regard to these materials are based upon a correlation of the results found in this study and the comparative behavior of these alloys as evidenced in other machining operations.

RECOMMENDED PRACTICE

A. Tool Design

1. Width of margin

It was found that a small margin width was necessary to prevent seizure and scoring; it is recommended that the width be about 0.010 inch. Acceptable holes resulted with this condition. Figure X-1 illustrates the effect of margin width, and it might be concluded from the figure that the 0.005-inch width would produce superior results. This width introduced a condition of excessive chatter and is not recommended on that basis. Figure X-2 illustrates the result of this condition.

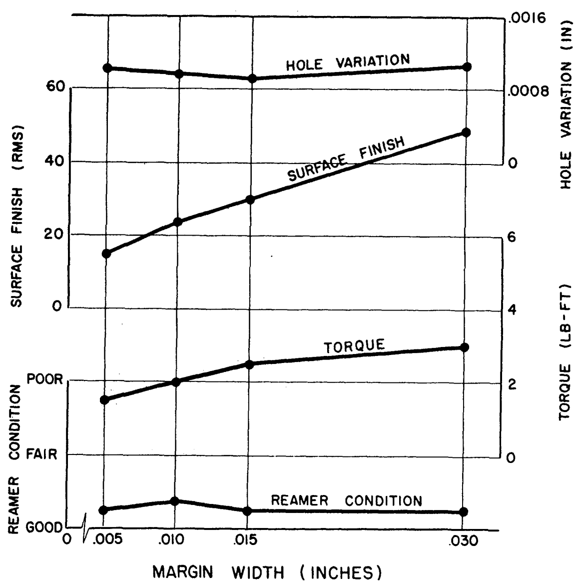



Fig. X-1. The influence of margin width when reaming titanium Ti-75A.

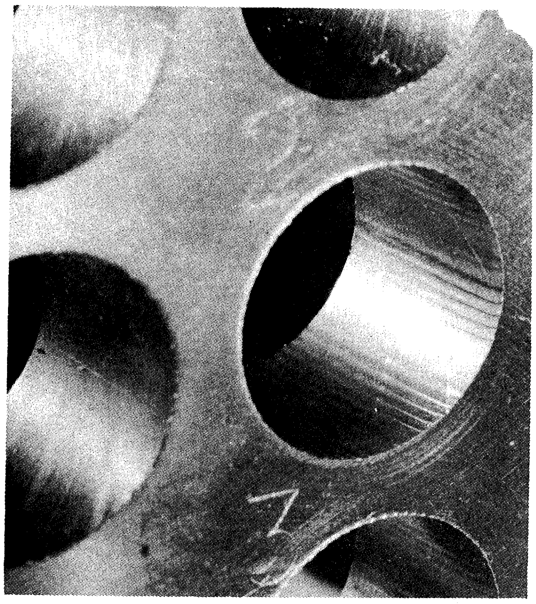


Fig. X-2. This shows the effect of chatter due to having too small a margin width.

2. Chamfer angle, axial rake angle, and normal relief angle

Each of these items was investigated over a substantial range of variation, and none showed any pronounced effect. A qualification should be made regarding the relief angle. Experience on other operations indicates that poor results occur if this angle is too small, and this study showed that chatter occurs when this angle exceeds 10°; therefore, it should be held between 5° and 10°. Figure X-3 illustrates the effect of a chamfer relief angle that is too large.

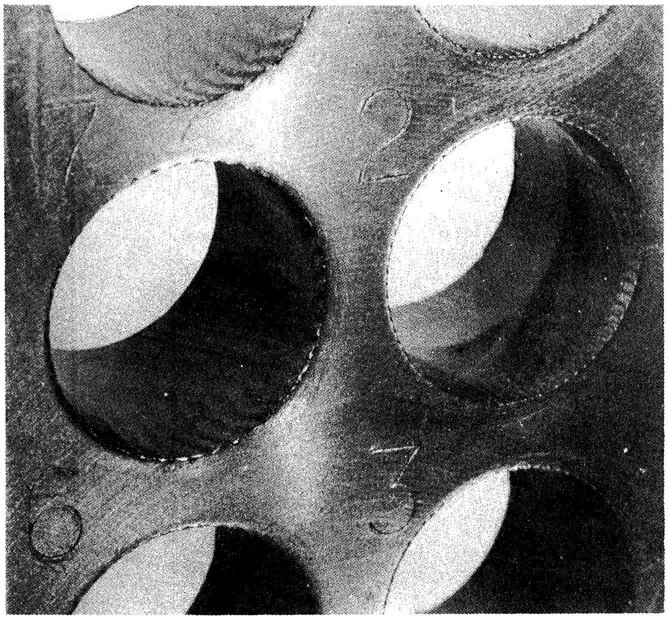


Fig. X-3. The effect of chatter at the entry of the hole, as caused by an excessive chamfer relief angle.

B. Feed, Speed, and Depth of Cut

1. Feed

Low feeds were required to produce acceptable holes, and a rate of 0.0007 inch per tooth is recommended. Higher feeds led to excessive pickup that resulted in scarred holes. Figure X-4 shows such a result. Figure X-5 typifies the effect of feed rate on the factors that are used to judge reaming performance.

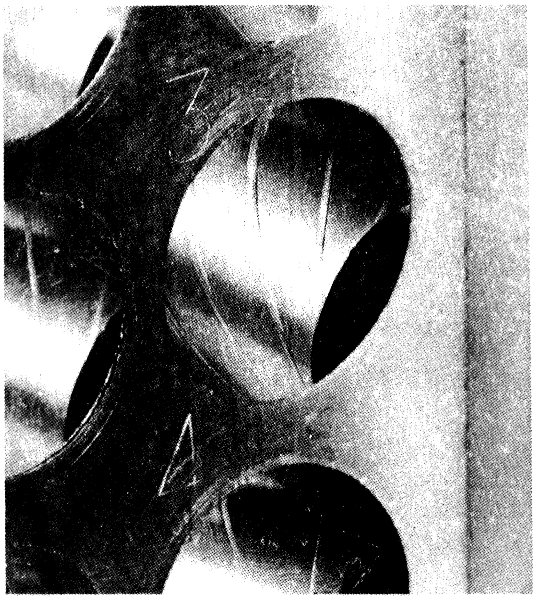


Fig. X-4. A scarred hole caused by excessive pickup of work material on the margin of the reamer.

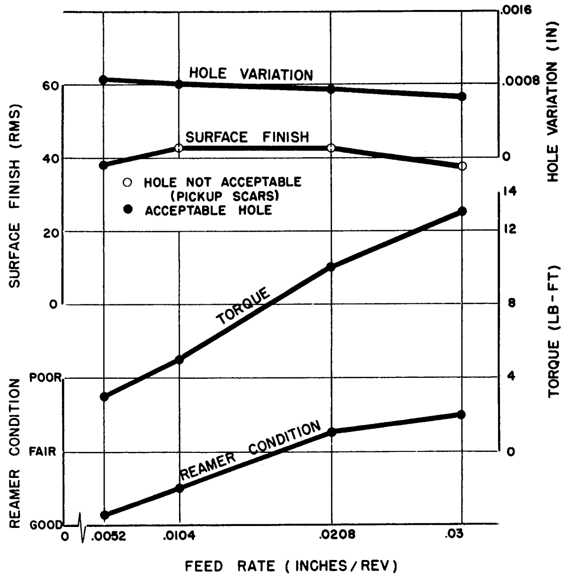



Fig. X-5. The effect of feed when reaming titanium Ti-75A.

2. Cutting speed

The optimum cutting speed at which the alloys of titanium were reamed successfully was between 20 and 30 fpm; for the commercially pure titanium it can be increased to 40 to 50 fpm. At these speeds the feed rate should be approximately 0.0007 inch per tooth. The cutting speed used with alloys RC-110A and 3Al-5Cr was similar to that used with the RC-130B on other machining operations, while the grade RC-130A usually fell between the types Ti-150A and Ti-75A. Therefore, it is recommended that speeds of 20 to 30 fpm be used for all alloys. When the speed and feed combination is excessive, results such as those shown in Fig. X-6 occur.

3. Depth of cut

This item was varied between .002 and .016 inch (on the radius) and showed no pronounced effect except for an increase in torque with increasing depths of cut. It should be merely large enough to allow complete "cleanup" of the hole.

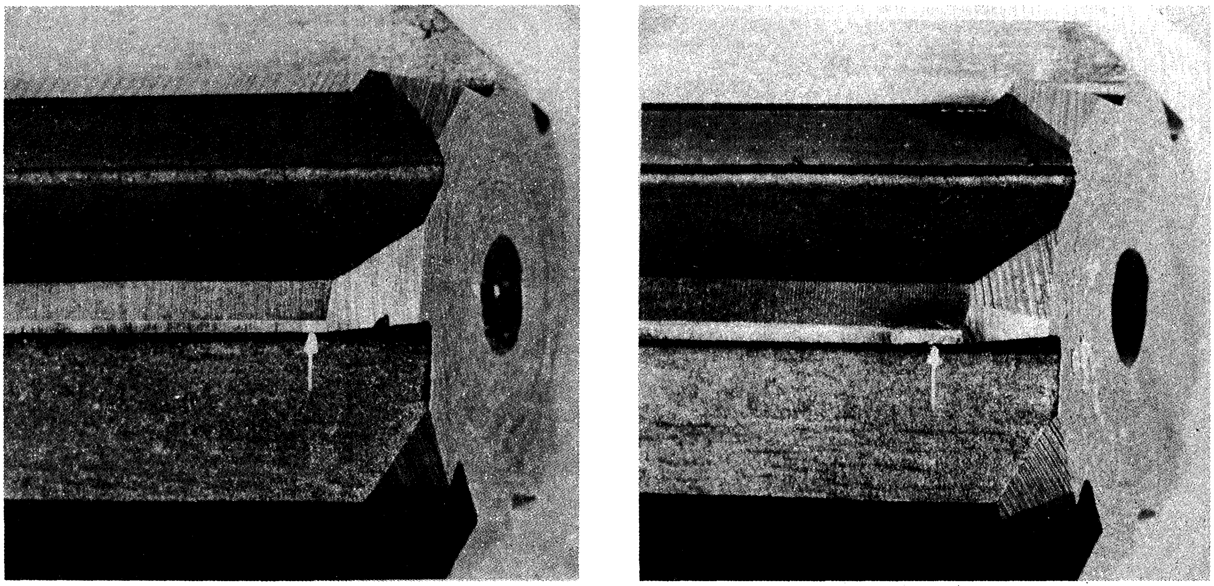


Fig. X-6. Typical examples of reamers run at excessive speeds and feeds.

C. Cutting Fluids

From a practical viewpoint, the most effective fluid was found to be a sulfochlorinated mineral oil. This topic is covered extensively in Chapter XII and does not warrant repetition. Figure XII-6 shows the comparison of the fluids that were used.

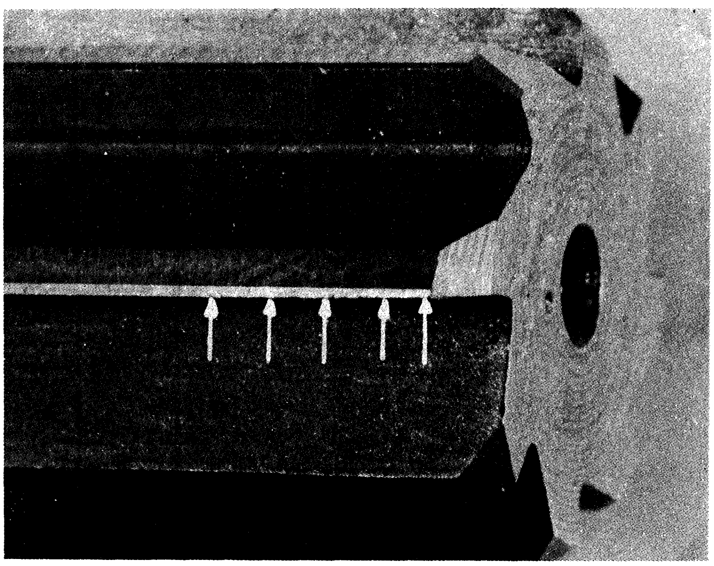


Fig. X-7. Typical example of a reamer that picked up work material during reaming of a hole as shown in Fig. X-4.

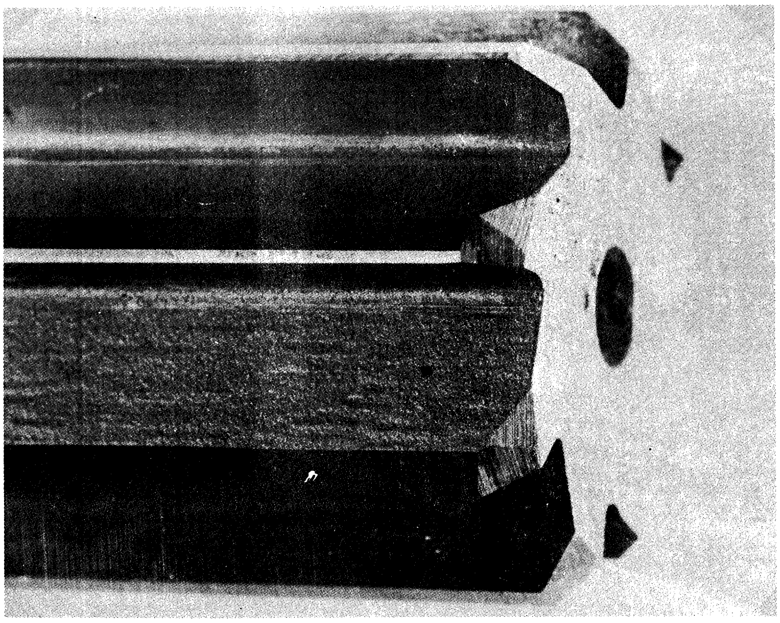


Fig. X-8. Typical example of a reamer free from pickup after reaming a hole as shown in Fig. X-9.

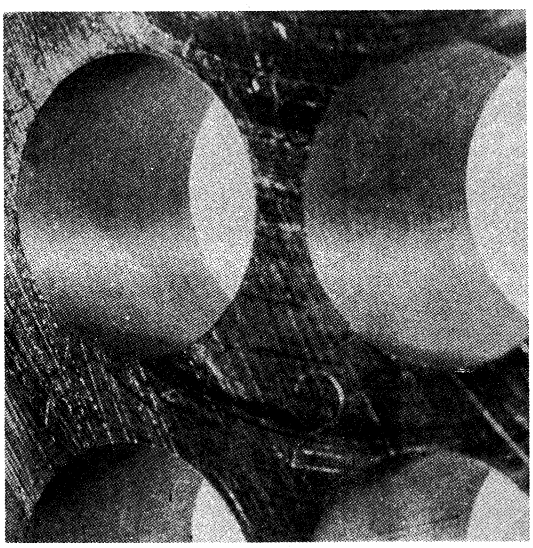
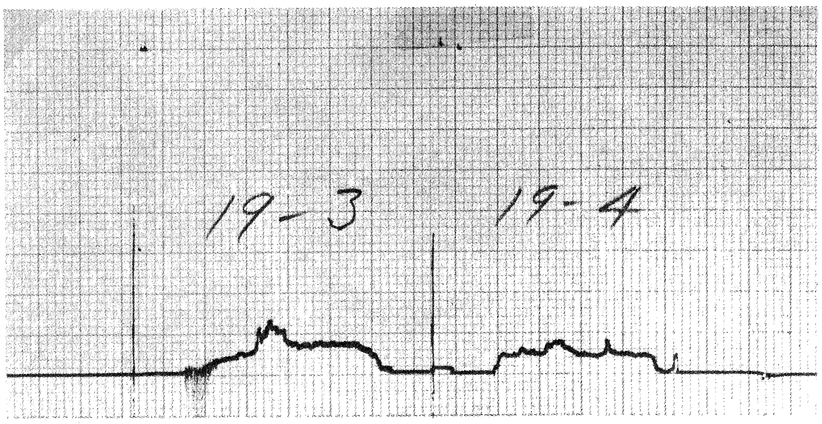
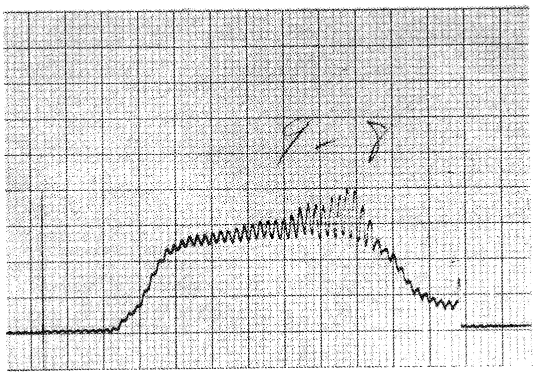


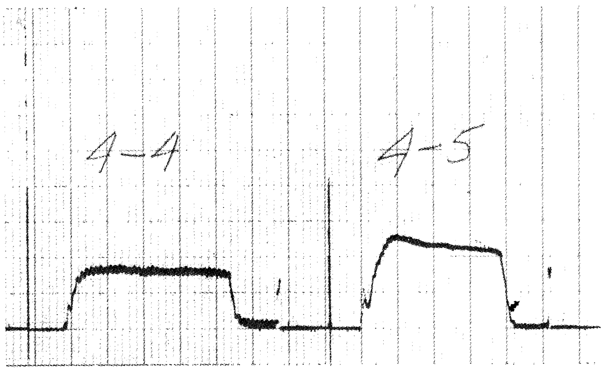
Fig. X-9. Example of a reamed hole that has a good surface finish and is free from chatter, scars, and other defects.




a. Erratic torque indicating non-uniform cutting conditions.




b. Oscillating torque curve indicative of increasing chatter throughout hole.




c. Normal torque curve under good operating conditions.

Fig. X-10. Typical torque curves recorded by Sanborn equipment.

All the work conducted on the reaming of titanium and its alloys is covered in Report No. 19.

# CHAPTER XI

# SAWING

## UNIQUE FACTORS

The hacksawing and bandsawing of commercially pure titanium and its alloys can be successfully accomplished under controlled conditions of machine, saw blade, cutting speed, feed rate, and use of cutting fluid. The problems encountered in these operations are not too different from those of other machining operations. The condition of material (surface and alloy) can directly affect the results obtained in either operation.

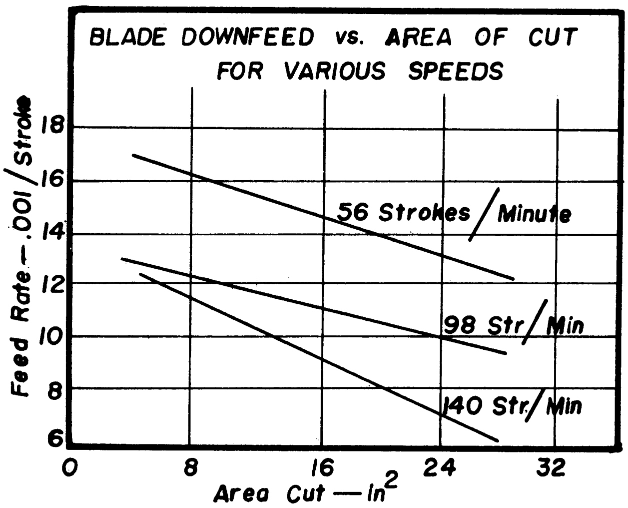
At the beginning of the research on sawing, it was found that many sawing operations were practically impossible because of excessive blade wear (rapid dulling) and consequent lack of penetration of the cutting teeth into the material. It was discovered that heavy feed pressures in hacksawing and positive feed load in bandsawing were essential requirements in these operations. These requirements would necessarily eliminate some of the machines that are commonly used by industry, wherein only the hand-feed or gravity-feed mechanisms are employed. Cutting speed is an important aspect in the successful sawing of titanium alloys and, in general, it must be reduced somewhat from the range normally used on ferrous and other nonferrous materials.

## TEST RESULTS

### A. Hacksawing

The tests on the hacksawing of titanium and its alloys were made on a Peerless, hydracut hacksaw with a 6-inch stroke. The full feed pressure of 400+ pounds was used on all tests and under this condition, satisfactory results were obtained.

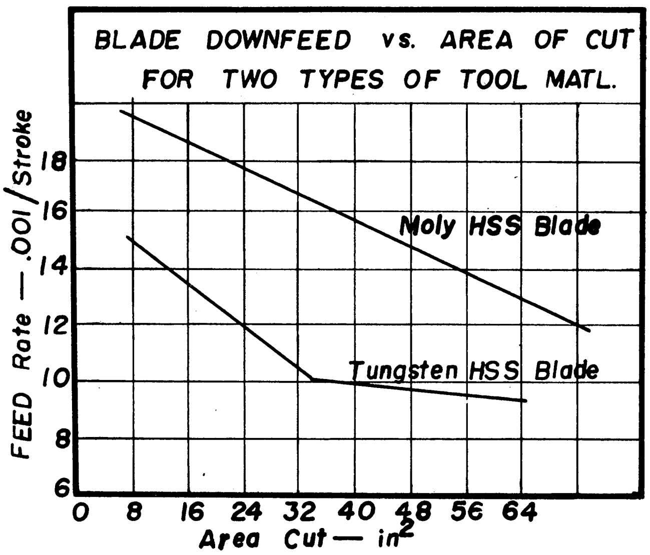
Results of cutting-speed tests indicate that the low setting of 56 strokes per minute on the machine, as compared to the others available (98 and




140), gave the lowest wear rate and the longest tool life on all materials, where tool life is defined by total square inches of cut (measured on the cross section of the piece). The figure shows data that are representative of results on Ti-75A.

The two higher speeds, 98 and 140 strokes per minute, should be eliminated from use on the various titanium alloys with the type of cutting tool material now available in saw blades.

Tests were made on moly high-speed-steel versus tungsten high-speed-steel blades and it was determined that the moly-type blade gave longer blade life than the latter, as shown in the figure. Most types of high-speed-steel blades now available on the market should give results similar to those shown, provided other important variables are properly controlled.




Tests on dry cut versus cutting fluid indicated that an emulsion-type material (1 part soluble oil to 20 parts of water) should be satisfactory in reducing the effects of heat and adherence of chips in the tooth space.

The results of cutting-speed tests showed that the various materials can be sawed satisfactorily at the following ranges of speeds available on the Peerless hacksaw:

Ti-75A - 56, 98, or 140 strokes per minute,  
Ti-150A - 56 or 98 strokes per minute,  
RC-130B - 56 strokes per minute only.

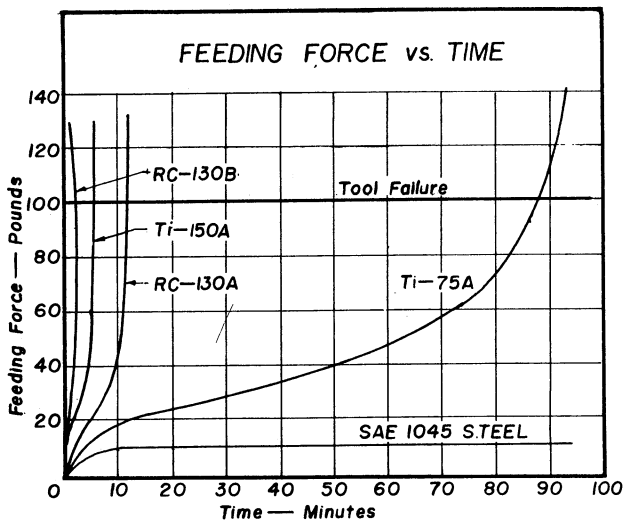
Any speeds less than the maximum for each material should give greater tool life as a result of lesser rates of wear. The 3Al-5Cr and Ti-110A alloys should be sawed at speeds of 98 strokes per minute or less, as indicated by the relations established for cutting-speed — tool-life tests on other operations.

B. Bandsawing

The bandsawing of titanium alloys was accomplished by designing a mechanical, screw-feed mechanism to impart a positive feed of the work against the saw blade. This was found necessary during preliminary tests on hand and dead-weight feeds and the resulting failures therefrom.

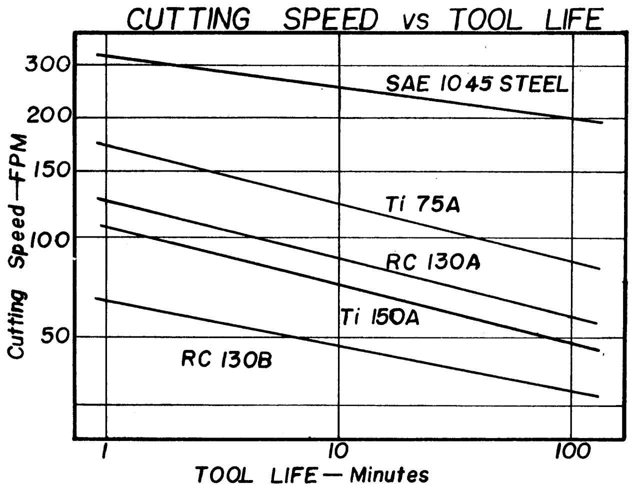
The factors that were considered important in the study of the bandsawing of titanium were tool life and forces. Tool life is interpreted as a function of cutting speed but, in the case of bandsawing, was defined by a maximum value of feeding force.

In normal metal-cutting operations, the cutting force (force in the direction of cut) exceeds the feeding force (force at a right angle to the direction of cutting tool), but the Ti-75A showed the forces to be equal, and the various alloys gave results in which the feeding forces exceeded the cutting forces. This resulted from the abrasive characteristics of the materials and the glazing tendencies encountered with these materials.



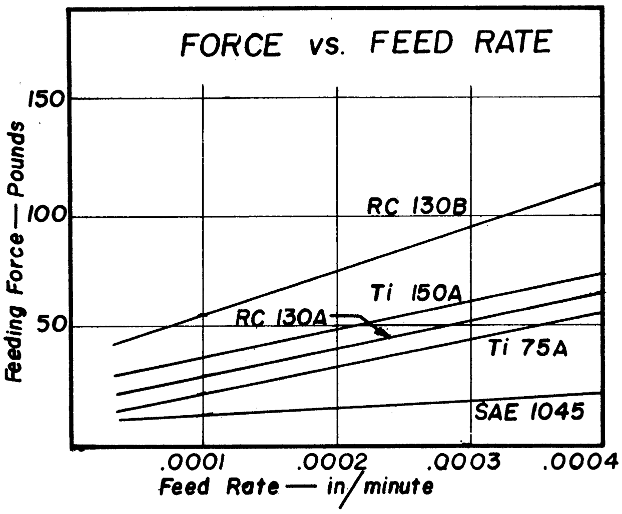

While determining the increase in feeding forces as a function of cutting time in minutes, it was discovered that 100 pounds of feeding force represented a reasonable tool failure, as the forces would rise precipitously beyond this value. As a result, the tool life was determined as that time at which the feeding force equalled 100 pounds.

The figure at the left shows the variation in feeding forces for the various materials and the definition of tool life at 100 pounds force increment. These data obtained for a speed of 78 fpm and feed of .000120 inch per tooth feed were combined with other data from speed and feed variations to determine the cutting-speed — tool-life relations shown in the next figure.




All the titanium materials including the Ti-75A are somewhat below the SAE-1045 steel in the height of the tool life curves (velocity for a given tool life). Of the titanium materials, the Ti-75A can be bandsawed at the highest speed for a given tool life, and the RC-130B should be cut at the lowest speed with the other alloys somewhat intermediate between the two.

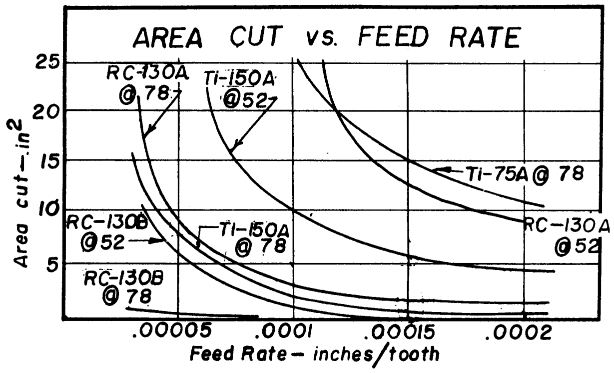
The feeding force in pounds will increase as a function of an increase in the feeding rate in inches per tooth, as shown on the figure below. The forces for the titanium materials are considerably higher than for SAE-1045 steel; this helps to explain the necessity for positive feeding action to insure successful cutting of these materials. A feed rate of 100 x $10^{-6}$ per tooth equals .0001 inch per tooth. The number of teeth per minute is easily determined from the product of the velocity in feet per minute and the number of cutting teeth per foot of blade. Thus, the feed in inches per minute can readily be determined as the product of the feed in inches per tooth and the number of teeth per minute. As an example, consider a 6-pitch (6 teeth per inch) blade cutting at 50 fpm and a feed of 100 x $10^{-6}$ per tooth.



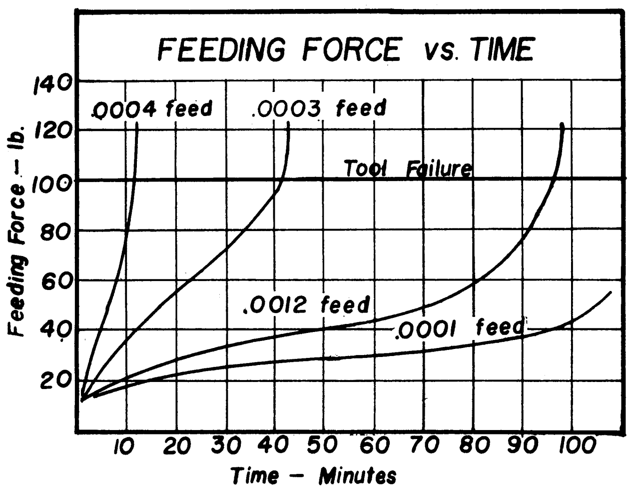

6 teeth/inch x 12 in./ft = 72 teeth/ft,
72 teeth/ft x 50 ft/min = 3600 teeth/min,
3600 teeth/min x .0001 in/tooth = .36 in./min.

Therefore, the work should feed against the saw blade at the rate of .36 inch per minute to maintain 100 x $10^{-6}$ inch per tooth feed.

The square inches of material cut can be used as a factor in determining the performance of saw blades in the various materials, and the proper speed and feed selections can be chosen for various shapes of parts.




A figure such as that shown at the left provides a ready index to the performance of saw blades on the various types of materials. The proper use of this information would be the determination of the total square inches of cut per saw blade and the proper selection of speed and feed of the sawing operation. An example might be 20 square inches of cut on an RC-130A material. If a speed of 52 fpm is used, the feed rate can be .000120 inch per tooth, whereas if 78 fpm cutting speed is desired, the feed should be reduced to .000038 inch per tooth.




The feed rate in inches per tooth is very important in the sawing operation. The chip that is cut by the hack or bandsaw tooth should be in the range of .0001 to .0003 inch thick as shown on the figure at the left. These results on Ti-75A indicate that feed rate is very critical on the tool life in minutes and the success of the sawing operation is a direct function of the metal cut per blade life.

RECOMMENDED PRACTICE

A. Hacksawing

1. Machine

The machine should be a heavy-duty type that is capable of producing heavy feeding pressure on the work. A well-designed work-holding device is an essential requirement of the machine that is to be used with heavy feeding loads.

The motor should have a minimum of 3-hp rating and as high as 5 available for the sawing operation.

2. Saws

Standard high-speed-steel saw blades 18 to 24 inches in length, 6-pitch or less, .100 to .110 inch kerf (set), and a right, left, raker set should give reasonable performance on hacksawing. The pitch must be consistent with the bar width and a minimum of three teeth should contact the bar at all times. The lowest number pitch or least number of teeth per inch consistent with proper number of teeth in contact will provide the largest possible tooth space and the least amount of chip-packing between the teeth.

Moly high-speed-steel blades show better performance than the tungsten high-speed-steel material in the sawing of titanium materials.

Blade tensioning is very important in the installation of a new saw blade, and recommended practice would include the use of a tension meter to establish a preload of 12,000 to 15,000 pounds per square inch on the saw blade. Blades that have not been properly pre-tensioned will suffer excessive wear on the sides of the teeth, and the side wear directly affects "skew" or run-out.

3. Feeds and speeds

The feed load should be computed to provide up to .0005 inch per tooth and not less than .0001 inch per tooth for economic operation on the saw blade and the best tool life of the blade. This can be determined by timing the down-feed in inches per minute, calculating the feed in inches per stroke, and, as a function of the number of teeth in contact per stroke, defining the chip load per tooth.

The scale condition of the titanium might increase the wear significantly at the beginning of a saw cut. It might be considered expeditious to remove the scale by milling or shaping prior to the sawing operation if difficulties are encountered in cutting through the scale with a saw blade.

Cutting speeds are of utmost importance in the successful hacksawing of titanium and its alloys. The following recommendations are based on the performance reported in preceding reports:

| Material | Cutting Speed ft/min |
|---|---|
| Ti-75A | 50 to 150 |
| Ti-150A | 50 to 100 |
| RC-130A | 50 to 100 |
| 3Al-5Cr | 70 or less |
| Ti-110A | 60 or less |
| RC-130B | 60 or less |

It should be remembered that blade life is a function of cutting speed and the wear rates will be reduced at the lower speeds.

4. Cutting fluids

Most commercial emulsion-type and aqueous-type materials should lend themselves to the hacksawing operation. A recommended concentration of 5% by volume (1 in 20) in water should give the desirable cooling and lubrication of the saw blade. Friction from rubbing on the sides of the saw blade adds to the total heat resulting from the operation, and cooling is considered of prime importance under normal conditions of operation.

B. Bandsawing

1. Machine

The bandsawing machine should be of good, rigid design. It should have not less than a 2-hp motor for driving the band and an auxiliary power for providing positive feed to the work. Hand and gravity feeds will not provide satisfactory results in the bandsawing of titanium alloys. A positive-pressure system will work satisfactorily, provided sufficient force is available for driving the work against the bandsaw blade.

2. Saw blades

The saw blade should be of a right, left, raker tooth design and preferably 3/4 inch wide. The greater width of blade provides greater stability when the saw is properly pre-tensioned. It should have 6 or fewer teeth per inch to provide proper chip clearance in the teeth.

The blade should be pre-tensioned and checked with a tension meter to approximately 12,000 pounds per square inch to minimize unnecessary bending of the blade in the cut.

3. Speeds and feeds

The speeds for sawing titanium and its alloys range from 50 to 120 fpm, depending on the desired feed rate and the resulting tool life. Results obtained in cutting-speed — tool-life studies indicate the following ranges of cutting speed for a 60-minute tool life at feeds of .00008 and .000120 inch per tooth:

| Material | Speeds ft/min |
|---|---|
| Ti-75A | 85 to 100 |
| RC-130A | 60 to 70 |
| Ti-150A | 50 to 65 |
| 3Al-5Cr | 40 to 45 |
| Ti-110A | 42 to 47 |
| RC-130B | 35 to 45 |

The feeds should be in a range of .00004 to .00012 inch per tooth for bandsawing, and the lower feeds will definitely give the best tool life. The higher feed rates might be needed to satisfy the economic aspect of the situation, but the resulting blade life will be shortened.

4. Cutting fluids

The only cutting-fluid application that could be recommended for bandsawing would be a spray mist of an aqueous solution. The rubber tires on the bandsaw wheels would be subject to reaction to oil-base materials, and the flooding of coolant on this type of operation would be questionable. A spray mist application at the point of tool-work contact might provide sufficient cooling to justify its use.

# CHAPTER XII

# CUTTING FLUIDS

## CLASSIFICATIONS AND FUNCTIONS

For most machining operations the application of a fluid to the region where the cutting action is being effected has led to improved cutting performance. Various criteria are used in defining such improvement, some of these being improved surface finish, longer tool life, better control of dimensional stability of the finished work surface, and less power consumption. In broad terms, such fluids are often referred to as coolants or lubricants, but these classifications fail to explain the differences that exist among the many varieties that fall into either broad category. Many commercial fluids are recommended for specific purposes; thus, all lubricants would not perform equally when subjected to the same cutting operation. To promote a clearer understanding of differences among the many available fluids, and to aid in the selection of the proper type of fluid for particular situations, more refined distinctions of the classes of cutting fluids are made. The following list is now widely used and accepted in the field of metal cutting.

1. Water base - usually composed of water and an additive that acts as a rust inhibitor.

2. Emulsions - mixtures of water and soluble oils.

3. Straight oils - straight mineral oils or straight fixed or fatty oils.

4. Mixed oils - combinations of a straight mineral oil and a straight fatty oil.

5. Sulfurized or chlorinated oils - usually a straight or mixed oil to which sulphur or chlorine compounds have been added.

6. Dry - an atmosphere of air, sometimes as a blast or suction.

Various combinations for each of the above classifications are obviously too numerous to list, since the proportion of the ingredients in any classification may be altered in an almost infinite number of ways.

The purpose in using a cutting fluid for a specific job will usually dictate the type of fluid that should be employed. It follows that different fluids are used for different reasons, and it should not be interpreted that all fluids will perform all of the functions listed below. The purposes for which such fluids are used may be summarized as follows:

a. To conduct heat away from the cutting zone. This tends to cool the work and the cutting tool. It is desirable to cool the work to aid in controlling dimensional stability, while cooling the tool helps to prolong tool life.

b. To act as a lubricant, thereby reducing the heat that is caused by friction between the chip and top of the tool. This also improved tool life and may lower the power required to perform the cutting process.

c. To improve surface finish by reducing the tendency of the metal to form a built-up edge on the cutting tool.

d. To wash chips away from the tool. This function finds greatest use in deep-hole drilling, hacksawing, and milling.

Those fluids that have the ability to absorb and conduct heat readily are usually called coolants and show the most pronounced effect for increasing tool life. Lubricants are used for improving surface finish and on operations where the tendency of the chip welding to the cutting tool proves detrimental. Such a case is milling with carbide cutters.

## REVIEW OF TEST RESULTS

Regardless of the type of machining operation conducted on commercially pure titanium or the alloys studied in this work, the use of cutting fluids invariably led to improved conditions of machining. In some instances the advantage derived was increased tool life, while other cases indicated an increase in the ability to maintain the desired dimension. Since it has been learned that the temperatures which result when cutting titanium are noticeably higher than those for more widely used materials such as SAE-1045 hot-rolled steel, the improvement that results by using a cutting fluid on titanium, as compared to cutting dry, may be greater than generally expected.

Some of the operations that follow were not actually investigated with respect to the effect of cutting fluids; therefore, the recommendations made are based upon a correlation with the results found in the remainder of the study and a reliance upon past experience that has pointed out any noticeable differences among the various types of cutting operations as influenced by the use of fluids. It should be realized, therefore, that the operations not actually investigated contain recommendations based upon what should be expected rather than what was found through an actual test program.

It seems proper to assume at this time that the cutting fluids suggested for use with the grades of titanium included in this study would prove satisfactory if used on future alloys. In any event, they should provide an appropriate beginning.

## RECOMMENDED PRACTICE

### A. Coolants

The operations that are included in this section are usually conducted at relatively high cutting speeds which in turn lead to high cutting temperatures. Since this heat effect must be controlled for satisfactory machining, the use of coolants proves more beneficial than lubricants. This conclusion is supported by experience with other metals, the reason being that coolants possess a greater ability to absorb and conduct heat away from the cutting zone.

#### 1. Turning and boring

A water-base solution consisting of 95% water and 5% sodium nitrite, by weight, has been found to be an extremely effective fluid when turning all grades of titanium used in this study. The benefit derived from this fluid is quite pronounced at higher levels of cutting speed and, although the degree of improvement over dry cutting lessens somewhat as the cutting speed is decreased, it was still the most effective fluid tested. Effectiveness in this case is based upon the ability of a fluid to improve tool life.

Dry cutting, a sulfochlorinated oil, and a common emulsion constituted the other types of fluid conditions that were used. Figure XII-1 provides a picture of the relative effect of these various fluids as compared to dry cutting. These results occurred when turning the commercially pure grade of titanium. It may be seen that the water-base solution provides the greatest increase in tool life, while the emulsion was next in order of effectiveness. This fluid consisted of twenty parts water and one part soluble oil. Results such as these verified the premise that coolants would be more effective than lubricants where high cutting temperatures were encountered.

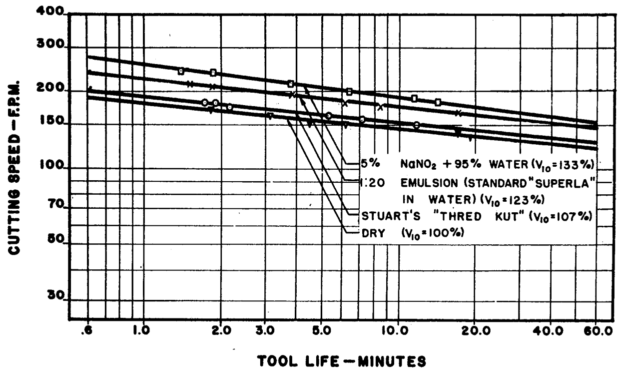



Fig. XII-1. A summary of experimental data showing the relative effectiveness of various cutting fluids on tool life when turning commercially pure titanium (Ti-75A).

Figure XII-2 is typical of the findings that resulted when turning alloys of titanium. Again, the improvement that occurs with the water-base fluid as compared to cutting dry is quite pronounced.

The relative effectiveness of cutting fluids may be evaluated in several ways, but the method used most frequently is the one which indicated the percent increase in cutting speed for a given tool life above the cutting speed which gave the same tool life when cutting dry. The latter condition is considered as a base value of 100 percent as shown on Fig. XII-2. A tool life of ten minutes, $V_{10}$, was selected as the standard tool life, since it was well within the test values obtained for all cutting fluids.

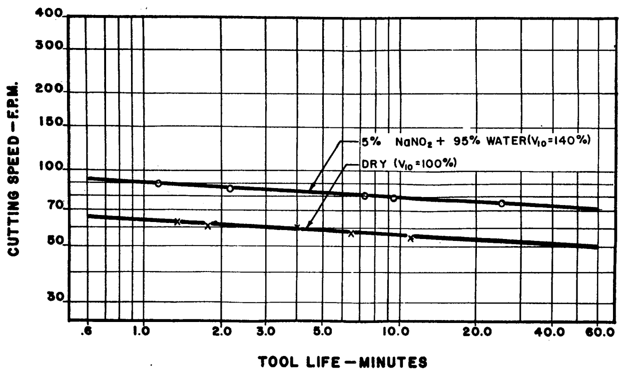



Fig. XII-2. A comparison of the results obtained when turning the titanium alloy RC-130B dry and with the water-base fluid. The use of this fluid indicated that the velocity for a ten-minute tool life, $V_{10}$, may be increased 40 percent above the velocity that would produce this same tool life when cutting dry.

Table XII-1 is a summary of the results found when turning all grades of titanium dry and with the water-base solution. Both the actual cutting speeds and percentage comparisons are listed. Conditions of feed, depth of cut, tool shape, and tool material were constant for all these tests. It can be seen that the absolute values of cutting speeds for the different grades of titanium vary considerably and provide a basis for comparison of these materials as to their relative machinability. For example, the grade Ti-75A shows a cutting speed of 146 fpm when cutting dry, while the RC-130B alloy shows 57 fpm. This indicates that the former may be turned more easily.

TABLE XII-1

EFFECTIVENESS OF SODIUM NITRITE CUTTING FLUID ON TITANIUM ALLOYS

| Work Material | Cutting Fluid | Fpm | % |
|---|---|---|---|
| SAE-1045 Steel (H.R.) | Dry | 200 | 100 |
| SAE-1045 Steel (H.R.) | $NaNO_2$ | 260 | 130 |
| Ti-75A | Dry | 146 | 100 |
| Ti-75A | $NaNO_2$ | 194 | 133 |
| RC-130A | Dry | 88 | 100 |
| RC-130A | $NaNO_2$ | 121 | 138 |
| Ti-150A | Dry | 78.5 | 100 |
| Ti-150A | $NaNO_2$ | 96 | 122 |
| RC-130B | Dry | 57 | 100 |
| RC-130B | $NaNO_2$ | 80 | 140 |
| RC-110A | Dry | 55 | 100 |
| RC-110A | $NaNO_2$ | 75.5 | 137 |
| 3Al-5Cr | Dry | 51 | 100 |
| 3Al-5Cr | $NaNO_2$ | 78 | 153 |

The water-base fluid consisting of 5% sodium nitrite and 95% water is also recommended for boring operations. This type of machining cut was not included in the study, so the conclusions drawn are not based upon actual test results. There are reasons, however, that should substantiate the recommendation made above. Turning and boring cuts are very similar in nature; hence, the practices that prove sound for one, regarding the use of cutting fluids, usually apply for the other. Both are conducted at relatively high cutting speeds where coolants are more beneficial than lubricants. Therefore, it seems probable that the water-base fluid would provide the necessary functions of heat absorption and conduction.

For a complete analysis of the results pertaining to the effect of cutting fluids when turning titanium, refer to Reports 12 and 29.

2. Milling

A study of the effect of fluids when milling titanium was not included in the scope of this phase of the program; therefore, the recommendations are not based upon actual test findings. In view of the other test results, it does seem that appropriate suggestions can be made. Where high-speed milling is performed, it again becomes necessary to control cutting temperatures, and the solution of 5% sodium nitrite and 95% water will perform this function. As a second choice, an emulsion consisting of twenty parts water to one part soluble oil should be considered.

If cutting conditions consist of low speeds and heavy cuts, the heat-conducting ability of a coolant becomes less important. It may become more imperative to prevent the chips from welding to the cutting teeth and, if such a tendency does persist, a lubricant should be used. A sulfochlorinated mineral oil is recommended since it has shown the ability to reduce chip pickup on other operations. Where carbide cutters are used, this lubricant is recommended regardless of cutting speed because intermittent cooling and heating of carbide tools may produce thermal cracks. This result has been noted on numerous occasions when coolants were used on high-speed milling.

Reports 23A through 23E cover the work conducted on milling titanium.

3. Drilling

It was found that the presence of a cutting fluid was essential to produce satisfactory drill performance. At high cutting speeds this was especially evident since the chips became plastic and jammed in the drill flutes. With this condition poor holes and poor drill life resulted, but when a cutting fluid was applied, the tendency toward chip jamming was reduced considerably. This led to improved drill life.

At high drill speeds adequate cooling must be provided, and an emulsion consisting of twenty parts water and one part soluble oil worked effectively. Although a water-base solution, such as the 5% sodium nitrite and 95% water, was not used it would seem that other test results warrant the use of such a fluid. This type of coolant should be at least as effective as an emulsion, and all indications lead to the conclusion that the water-base solution would be superior.

At lower cutting speeds the problem of cooling does not become so vital, and a highly chlorinated sulfurized mineral oil showed a tendency to reduce power requirements and drill pickup. Such a lubricant is recommended when cutting conditions consist of heavy feeds and low speeds.

Figures XII-3 and XII-4 show the relative effectiveness of several types of fluids for reducing torque and thrust requirements. Dry cutting required the least thrust, but would not be practical for production drilling because of an adverse effect on drill life. Considering all factors, the sulfochlorinated mineral oil gave the best all-round performance at low speeds. Reports 20 and 29 contain the complete results on drilling titanium and its alloys.

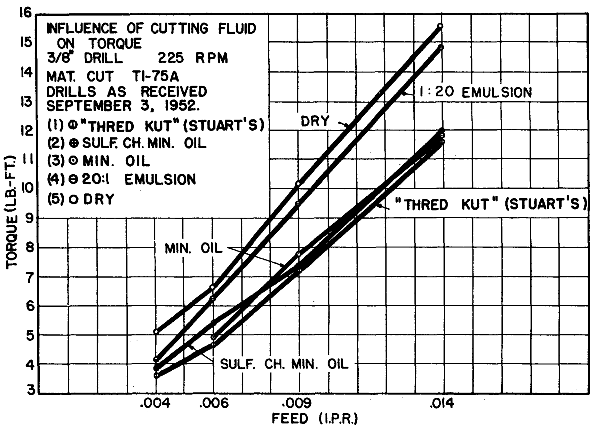



Fig. XII-3. Relative comparisons of various fluids showing the effect on torque when drilling titanium Ti-75A.

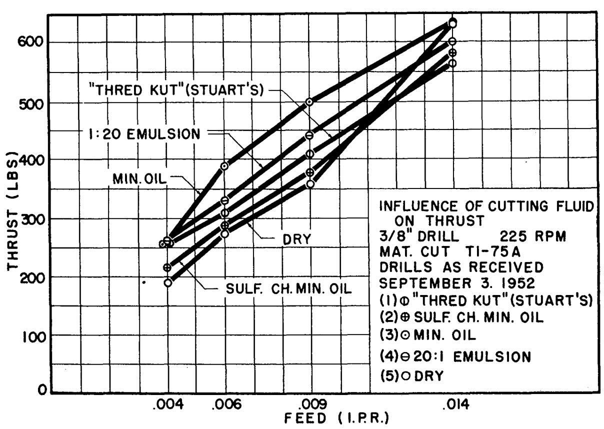



Fig. XII-4. Relative comparisons of various fluids showing the effect on thrust when drilling titanium Ti-75A.

Deep-hole drilling studies were made, and a mineral oil containing rust and oxidation inhibitors was used throughout. This performed satisfactorily and is recommended on that basis. Reports 20, 21, and 29 contain all the work conducted on deep-hole drilling.

4. Sawing

Hacksawing may be accomplished satisfactorily if a cutting fluid is used. Dry cutting resulted in rapid wear of the saw teeth, a high degree of chip seizure, and excessive chip clogging between teeth. The addition of a coolant reduced these adverse results considerably. An emulsion consisting of twenty parts water to one part soluble oil worked well, but it is suggested that the water-base solution of 5% sodium nitrite and 95% water be used, since it has proved superior to emulsions on other operations where a coolant was deemed necessary. This water-base solution was not used during these tests so this recommendation is not based upon actual results. Report 6 contains the complete study of hacksawing.

Bandsawing of titanium was conducted successfully without the use of a cutting fluid, but it is probable that improved performance would result if this operation were conducted in the presence of a coolant. Since the rubber band wheels that guide the blade might be adversely affected if subjected to excessive liquid, consideration should be given to a mist or spray application. Either a water-base solution or emulsion is recommended, with the former taking precedence because of previous comparisons of these two types of fluids.

Reports 11 and 29 cover the work done on bandsawing titanium.

B. Lubricants

1. Tapping

Tapping titanium dry produced extremely poor results because of excessive chip interference in the tap flutes, a high degree of seizure on the tap threads, and high torque requirements which caused tap breakage in several tests. Most of the fluids improved the cutting action considerably, with carbon tetrachloride showing the greatest effect. However, this fluid is toxic and is not recommended for commercial use. A mixture of 30% SAE-30 lubricating oil and 70% lithopone, by weight, showed a definite tendency toward improved tapping and is suggested for use where its application does not prove impractical. Since it is used in the form of a paste, it must be applied with a brush unless agitators are used to prevent settling of the pigment. In the event that this proves unhandy for production work, a highly chlorinated oil is recommended as it ranked next in performance.

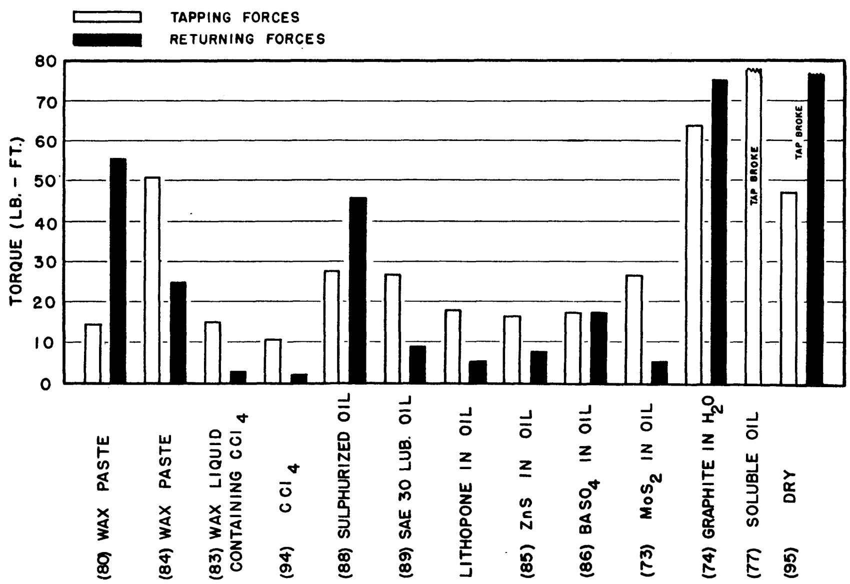



Fig. XII-5. A summary of tapping and back-out torques required when tapping titanium Ti-75A using various cutting fluids.

Figure XII-5 is a pictorial summary of the effect of tapping torques required when the various test fluids were used. Both tapping and back-out torques are shown, and the fluids previously mentioned indicate the lowest torque requirements. For a complete analysis of the results from the tapping tests, reference is made to Reports 18, 22, and 29.

2. Reaming

To ream titanium successfully, it was found that the use of a cutting fluid was a necessity. When reamed dry, an excessive amount of pickup occurred on the land of the reamer and this led to high torque requirements, poor surface finish of the reamed hole, oversize holes, and poor condition of the reamer after a few cuts.

Cooling proved to be of little consequence at these low speeds and, since lubrication decreased the tendency for pickup, the latter type of fluid was definitely superior. A sulfochlorinated mineral oil worked extremely well and is recommended for this operation.

Figure XII-6 shows a comparative summary of the test fluids as to their effect on torque, surface finish, hole variation, and reamer condition. No single fluid was superior from all viewpoints, but the sulfochlorinated mineral oil seemed to provide the best overall performance. For further reference regarding the scope of the reaming tests, Report 19 should be consulted.

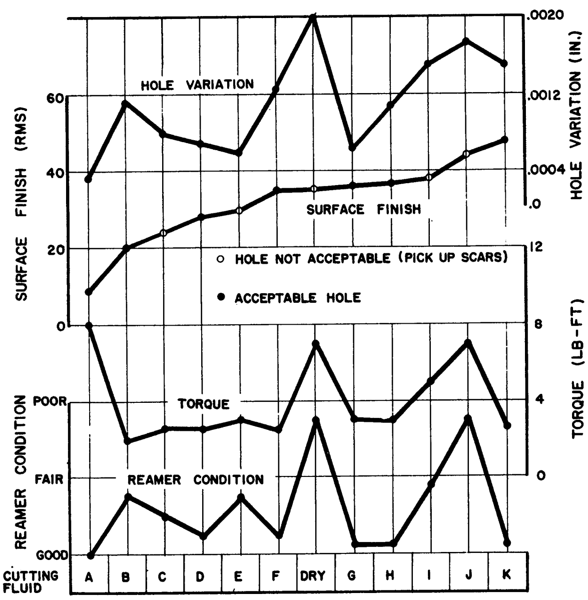



Fig. XII-6. The effect of cutting fluids when reaming titanium Ti-75A.

| Code | Cutting Fluid |
|---|---|
| A | Carbon tetrachloride |
| B | Oleic acid |
| C | Lard oil |
| D | Sulfochlorinated mineral oil |
| E | Mineral oil |
| F | Rust-Veto - 25% in water |
| G | Mineralized sulfur (a sulfur-base oil containing 40% sulfur) in 4% lubricating oil |
| H | Lithopone - 10% in lubricating oil |
| I | Emulsion - 5% in water |
| J | "Trim" - 5% in water |
| K | A base oil having 14% sulfur, 20% dichlorine, and 30% lard oil - 4% in lubricating oil |

3. Broaching

All broaching work was conducted dry, and the tendency for pickup and seizure to occur presented one of the main problems to overcome for successful machining. Since a sulfurized mineral oil showed a definite influence toward diminishing this tendency for other machining operations, it seems that such a lubricant would prove effective in this case. All the work conducted on broaching studies is covered in Reports 10, 24, 28, and 29.

DISTRIBUTION LIST

| No. of Copies | Agency |
|---|---|
| 2 | Chief of Ordnance<br>Department of Army<br>Washington 25, D. C.<br>Attn: ORDTB - Res. and Mtls. |
| 1 | Chief of Ordnance<br>Department of Army<br>Washington 25, D. C.<br>Attn: ORDTX-AR - Exec. Library |
| 2 | Chief of Ordnance<br>Department of Army<br>Washington 25, D. C.<br>Attn: ORDIX |
| 7 | Chief of Ordnance<br>Department of Army<br>Washington 25, D. C.<br>Attn: ORDGU-SE |
| 2 | Commanding General<br>Aberdeen Proving Ground<br>Aberdeen, Maryland<br>Attn: ORDBG - R. D. and E. Library |
| 1 | Commanding Officer<br>Detroit Arsenal<br>Center Line, Michigan |
| 1 | Commanding General<br>Frankford Arsenal<br>Bridesburg Station<br>Philadelphia 37, Pennsylvania |
| 1 | Commanding Officer<br>Picatinny Arsenal<br>Dover, New Jersey |
| 2 | Commanding General<br>Redstone Arsenal<br>Huntsville, Alabama |
| 1 | Commanding General<br>Rock Island Arsenal<br>Rock Island, Illinois |
| 1 | Commanding Officer<br>Springfield Armory<br>Springfield, Massachusetts |
| 1 | Commanding Officer<br>Watervliet Arsenal<br>Watervliet, New York |
| 5 | Armed Services Technical Information Agency<br>Documents Service Center<br>U. B. Building<br>Dayton 2, Ohio |
| 1 | Commanding Officer<br>Office of Ordnance Research<br>Box CM<br>Duke Station<br>Durham, North Carolina |
| 1 | Chief, Bureau of Aeronautics<br>Navy Department<br>Washington 25, D. C. |
| 1 | Chief, Bureau of Ordnance<br>Navy Department<br>Washington 25, D. C. |
| 1 | Chief, Bureau of Ships<br>Navy Department<br>Washington 25, D. C.<br>Attn: Code 324 |
| 1 | Chief<br>Engineering Experimental Station<br>Navy Department<br>Annapolis, Maryland |
| 1 | Commanding Officer<br>Naval Proving Ground<br>Dahlgren, Virginia<br>Attn: A. and P. Laboratory |
| 1 | Director, Naval Research Lab.<br>Anacostia Station<br>Washington, D. C. |

DISTRIBUTION LIST (concluded)

| No. of Copies | Agency |
|---|---|
| 1 | Chief, Office of Naval Research<br>Navy Department<br>Washington 25, D. C. |
| 1 | Commanding General<br>Wright Air Development Center<br>Wright-Patterson Air Force Base<br>Dayton 2, Ohio<br>Attn: WCRTO |
| 1 | Commanding General<br>Wright Air Development Center<br>Wright-Patterson Air Force Base<br>Dayton 2, Ohio<br>Attn: WCRRL |
| 1 | Commanding General<br>Wright Air Development Center<br>Wright-Patterson Air Force Base<br>Dayton 2, Ohio<br>Attn: MCPBIS-2 |
| 1 | Director<br>U. S. Department of Interior<br>Bureau of Mines<br>Washington 25, D. C. |
| 1 | Chief, Bureau of Mines<br>Eastern Experimental Station<br>College Park, Maryland |
| 1 | National Advisory Committee for Aeronautics<br>1724 F. Street, N.W.<br>Washington, D. C. |
| 1 | Office of the Chief of Engineers<br>Department of Army<br>Washington 25, D. C.<br>Attn: Eng. Res. and Dev. Div., Military Operations |
| 1 | Pontiac Division<br>General Motors Corporation<br>Pontiac 11, Michigan |
| 1 | U. S. Atomic Energy Commission<br>Technical Information Service<br>P. O. Box 62<br>Oak Ridge, Tennessee<br>Attn: Chief, Library |
| 5 | Commanding Officer<br>Watertown Arsenal<br>Watertown 72, Massachusetts<br>Attn: Laboratory |
| 1 | Commanding Officer<br>Watertown Arsenal<br>Watertown 72, Massachusetts<br>Attn: Ordnance Materials Research Office |
| 1 | Commanding Officer<br>Detroit Ordnance District<br>574 East Woodbridge Street<br>Detroit 31, Michigan |
| 1 | Rem-Cru Titanium, Inc.<br>Midland, Pennsylvania<br>Attn: Mr. D. W. Kaufmann<br>Assistant Sales Manager |
| 1 | Carboloy Department of General Electric Company<br>Detroit 32, Michigan<br>Attn: Mr. H. Jack Siekman,<br>Engineer, Design and Application |
| 1 | Norfolk Naval Shipyard<br>Norfolk, Virginia |
| 1 | Battelle Memorial Institute<br>505 King Avenue<br>Columbus 1, Ohio<br>Attn: Mr. Stuart Lyman |