GUIDE TO MACHINING CARPENTER SPECIALTY ALLOYS

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Carpenter Technology Corporation

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Guide to Machining
CARPENTER SPECIALTY ALLOYS

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Introduction

Carpenter Technology Corporation ("Carpenter") is a materials company making specialty alloys and engineered parts for dozens of industries with hundreds of applications. Specialty Alloys Operations, our specialty steel and alloy manufacturer and distributor, comprises the core business. Dynamet Incorporated, a Carpenter company, produces bar and coil products from titanium and other alloys. Carpenter Powder Products makes and sells tool and high speed steels and specialty alloy powder products. The Engineered Products Group is a consortium of companies that makes precision drawn products, complex ceramic parts, thin-wall tubing and other engineered materials.

Since 1928, when Carpenter introduced the world's first free-machining stainless steel, we have been concentrating on the business of making stainless and other specialty alloys more useful and more profitable to industry.

Our record of accomplishment in this endeavor has been gratifying. Through never-ending research, exacting quality controls and rigid production techniques, we have led the field in the introduction of new and improved specialty alloys and services to help industry improve product quality and reduce fabricating costs.

The Carpenter list of "firsts" is impressive. It includes the first free-machining stainless, Type 416 . . . the first free-machining chrome-nickel stainless, Type 303 . . . the first free-machining Invar, Free-Cut Invar "36"® alloy . . . and this evidence of leadership continues with the widespread acceptance of the Project 70® stainless and Project 7000® stainless grades and now Project 70+® stainless.

Through these constant efforts to improve specialty alloy quality, we have built every known production and performance advantage into every machining bar we produce. But no specialty steel can be so good that it will perform satisfactorily in the shop when it s mishandled or misunderstood.

The purpose of this book is to help you, the fabricator, get every benefit out of the Carpenter specialty alloys you machine. The machining tables are intended to provide you with suggested starting feeds and speeds. Machine setup, tooling and other factors beyond Carpenter's control will affect actual performance. A section on machining Carpenter tool steels, high temperature alloys, and electronic alloys is also included. These are tabbed together under "Other Specialty Metals."

If the answer to your particular machining problem cannot be found here, we hope you will call us at 1-800-654-6543 for help. Or, refer to our online technical information database at www.cartech.com. Registration is free.

General Stainless Material and Machining Characteristics

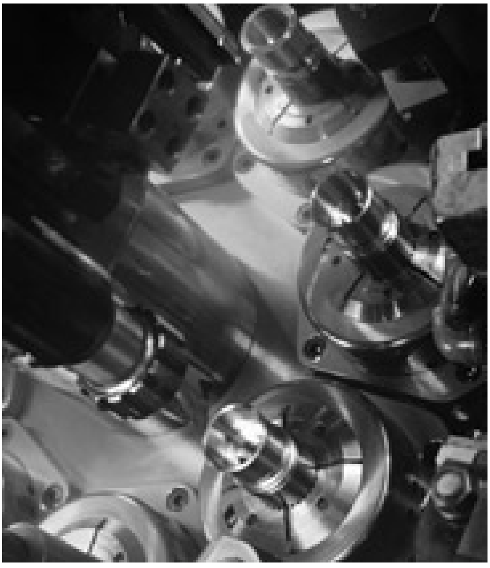
Stainless steels do not constitute a single, well-defined material; but, instead, consist of several families of alloys, each generally having its own characteristic microstructure, type of alloying and range of properties. To complicate the matter, further compositional differences within each family produce an often bewildering variety of alloys suited to a wide range of applications. The common thread among the alloys is the presence of a minimum of about 11 percent chromium to provide the excellent corrosion and oxidation resistance which is the chief characteristic of the materials.

Because of the wide variety of stainless steels available, a simple characterization of their machinability can be somewhat misleading. As shown in later sections of this booklet, the machinability of stainless steels varies from low to very high, depending on the final choice of alloy. In general, however, stainless steels are considered more difficult to machine than certain other materials, such as aluminum or low-carbon steels. Stainless steels have been characterized as "gummy" during cutting, showing a tendency to produce long, stringy chips, which seize or form a built-up edge (BUE) on the tool. Machine operators may cite reduced tool life and degraded surface finish as consequences. These broad observations are due to the following properties, which are possessed by stainless steels to different extents:

1.	high tensile strength
2.	large spread between yield strength and ultimate tensile strength
3.	high ductility and toughness
4.	high work-hardening rate
5.	low thermal conductivity

Despite these properties, stainless steels are machinable, as long as it is recognized that they behave differently from other materials, and, consequently, must be machined using different techniques.

In general, more power is required to machine stainless steels than carbon steels; cutting speeds must often be lower; a positive feed must be maintained; tooling and fixtures must be rigid; chip breakers or curlers may be needed on the tools; and care must be taken to ensure good lubrication and cooling during cutting.



Classification of Stainless Steels

Basic Families and Designations

Stainless steels can be divided into five families. Four are based on the characteristic microstructure of the alloys in the family: austenitic, ferritic, martensitic or duplex (austenitic plus ferritic). The fifth family, the precipitation-hardenable alloys, is based on the type of heat treatment used, rather than microstructure.

In addition, stainless steels may be divided into the non-free-machining alloys and the free-machining alloys. Free-machining alloys form a limited group that cuts across the basic families. Finally, both non-free-machining and free-machining alloys may be available in the Project 70+® stainless version having enhanced-machining properties compared to the standard alloys.

Because of the variety of stainless steels, it is usually possible to obtain an alloy possessing the desired set of attributes, unless they are mutually exclusive. This same wealth of alloys can create problems during the selection process, simply because of the number of alloys that must be considered and evaluated for their suitability. An invaluable aid in this process is Carpenter's Selectaloy® method, described later in this booklet. The following sections describe the basic characteristics which may be important during the selection process for a particular stainless steel.

Austenitic Alloys

Austenitic stainless steels have a face-centered cubic structure and are nonmagnetic in the annealed condition. The alloys can be subdivided into two categories: the standard alloys, such as Type 304, containing nickel to provide the austenitic structure;

and those containing instead a substantial quantity of manganese, usually with higher levels of nitrogen and in many cases nickel. Examples of the latter are 22Cr-13Ni-5Mn, 21Cr-6Ni-9Mn and 15-15LC® stainless. Nitrogen may also be used to provide strengthening in the chromium-nickel grades, as in Type 304HN. The standard chromium-nickel alloys with lower nitrogen levels have tensile yield strengths of 30-40 ksi (205-275 MPa) in the annealed condition, while alloys containing higher nitrogen have yield strengths up to about 70 ksi (480 MPa).

Austenitic stainless steels possess good ductility and toughness, even at cryogenic temperatures, and can be hardened substantially by cold working. The degree of work hardening depends on alloy content. Austenitic stainless steels with a lower alloy content may become magnetic due to transformation of austenite to martensite during cold working or even machining, if the surface is heavily deformed. A corrective anneal or the selection of an alloy with a lower work-hardening rate may be necessary if a low magnetic permeability is required for the intended application. Corrosion resistance of austenitic alloys varies from good to excellent, again depending on alloy content.

The most common austenitic stainless steel is Type 304, which contains approximately 18 percent chromium and 8 percent nickel. In addition to the alloying variations noted above, higher chromium, higher nickel, molybdenum or copper may be added to improve particular aspects of corrosion or oxidation resistance. Examples are Type 316, Type 309, Type 310 and 20Cb-3® stainless. Many of the more corrosion-resistant alloys, such as 20Cb-3 stainless, have nickel levels high enough to rate classification as nickel-base alloys. Titanium or columbium is added to stabilize carbon in alloys such as Type 321 or Type 347, in order to prevent intergranular corrosion after elevated-temperature exposure. Conversely, carbon levels are reduced to low levels during melting to produce the AISI "L" or "S" alloys, such as Type 304L, Type 316L or Type 309S.

Ferritic Alloys

Ferritic stainless steels have a body-centered cubic structure and are magnetic. In the annealed condition they have a tensile yield strength of about 40-50 ksi (275-345 MPa). They are generally hardenable only by cold working, but not to the same extent as the austenitic stainless steels. The alloys possess fairly good ductility in the annealed condition, but are not used where toughness is a concern. They have a broad range of corrosion resistance, depending on alloy content. However, as a class, they are considered less corrosion resistant than the austenitic alloys.

The most well-known alloy of this family is Type 430, which is an iron-base alloy with 16-18 percent chromium. Other alloys, such as Type 405 or Type 409, contain lower chromium. Higher levels of chromium are used in alloys such as Type 443 or Type 446 for improved corrosion or oxidation resistance. Molybdenum is added to certain alloys, such as Type 434, in order to improve corrosion resistance, particularly in chloride-containing solutions. Titanium or columbium is used to stabilize carbon and nitrogen in order to improve the as-welded properties of alloys like Type 409.

Martensitic Alloys

Martensitic stainless steels have a body-centered cubic/tetragonal structure and are magnetic. In the annealed condition they have a tensile yield strength of about 40 ksi (275 MPa) and, like the ferritic alloys, can be moderately hardened by cold working. However, martensitic alloys are normally heat treated by hardening plus tempering to yield strength levels up to about 280 ksi (1930 MPa), depending primarily on carbon level. The alloys exhibit good ductility and toughness, which decrease, however, as strength capability increases.

The most commonly used alloy of this family is Type 410, which contains about 12 percent chromium and 0.1 percent carbon to provide strengthening. Carbon level and, consequently, strength capability increase in the series Type 420, Type 440A, Type 440B, and Type 440C. Chromium is increased, particularly in the latter three alloys, to maintain corrosion resistance since chromium is removed from solution, forming carbides with increasing carbon level. Molybdenum may be added to improve mechanical properties or corrosion resistance, as in TrimRite® stainless. Nickel may be added for the same reasons, as in Type 414. Nickel also serves to maintain the desired microstructure, preventing excessive free ferrite, when higher chromium levels are used to improve corrosion resistance in a lower-carbon alloy like Type 431. The limitations on alloy content required to maintain the desired fully martensitic structure limit the corrosion resistance obtainable with martensitic alloys to only moderate levels.

Duplex Alloys

Duplex stainless steels contain a mixture of ferrite and austenite and are magnetic. They have tensile yield strengths of about 80 ksi (550 MPa) in the annealed condition, or about twice that of the standard austenitic alloys. Strength can be increased by cold working. The alloys have good ductility and toughness along with excellent corrosion resistance.

The original alloy in this classification was 7-Mo® stainless or Type 329, which contains chromium, molybdenum and sufficient nickel to provide the desired balance of ferrite and austenite. More recent alloys, such as 7-Mo PLUS® stainless, also contain nitrogen and a different austenite/ferrite balance.

Precipitation-Hardenable Alloys

Precipitation-hardenable stainless steels are categorized by their ability to be age hardened to various strength levels. The alloys can be subdivided into the austenitic (e.g., Pyromet® alloy A-286), martensitic (e.g., Custom 630, 17Cr-4Ni) or semi-austenitic classifications (e.g., Pyromet alloy 355). The latter alloys may have an austenitic structure for formability, but can be subsequently transformed to martensite and aged to the desired strength level. Depending on the type of alloy, precipitation-hardenable stainless steels can reach tensile yield strength levels of up to 250 ksi (1725 MPa) in the aged condition. Cold working prior to aging can result in even higher strengths. The alloys generally have good ductility and toughness with moderate-to-good corrosion resistance. A better combination of strength and corrosion resistance is obtainable than with the martensitic alloys.

The most well-known precipitation-hardenable stainless steel is Custom 630. It contains chromium and nickel, as do all precipitation-hardenable stainless steels, with copper for age hardening and columbium to stabilize carbon. Age-hardening agents used in other alloys include titanium (Custom 455® stainless), aluminum (PH 13-8 Mo*), and columbium (Custom 450® stainless). Molybdenum may be added to improve mechanical properties or corrosion resistance. Both molybdenum and copper are added for corrosion resistance in Custom 450 stainless. Carbon is normally restricted, except in semi-austenitic alloys such as Pyromet alloy 355 where it is necessary to provide the desired phase transformations.

*Registered trademark of AK Steel Corp.

Free-Machining Alloys

Free-machining alloys contain a free-machining additive such as sulfur to form inclusions which significantly improve overall machining characteristics. In some cases, other compositional changes may be made either within or outside the broad compositional ranges of the corresponding non-free-machining alloy. Such additional compositional changes may serve to improve machining characteristics beyond that obtained by the simple addition of the free-machining agent.

It is important to recognize that the benefit of improved machining characteristics is not obtained without changes in other properties. In particular, the following properties may be degraded by the addition of a free-machining agent:

1. corrosion resistance
2. transverse ductility and toughness
3. hot workability
4. cold formability
5. weldability

Contact a Carpenter representative for alloy availability.

In some cases, variants of the basic free-machining alloy are available to provide an optimum combination of machinability with another property. However, the trade-off among the various properties must still be considered when selecting an alloy; i.e., the ease of machining must be balanced against the possible reduction in other important properties, such as corrosion resistance.

Table 1 shows the relationship between non-free-machining and free-machining alloys within the ferritic, martensitic and austenitic families. Free-machining alloys are currently not available in the duplex or precipitation-hardenable families. Since duplex alloys are noted for excellent corrosion resistance but have somewhat limited hot workability, the addition of a free-machining agent, which would likely degrade both properties, would be undesirable. Likewise, precipitation-hardenable alloys are noted for good toughness at high strength levels, making it undesirable to add large amounts of a free-machining agent, which would degrade toughness.

Table 1

Correspondence of Non-Free-Machining and Free-Machining Stainless Steels		
Non-Free-Machining Alloys	**Related Free-Machining Alloys**	
	Se-bearing Alloys	**S-bearing Alloys**
Ferritic		
Type 430	—	Type 430F
18Cr-2Mo	—	182-FM[a]
Type 434	—	Type 434F
Martensitic		
Type 410	Type 416-Se	Type 416
		No.5F[b]
Type 420	—	Type 420F
Type 440C	Type 440-Se	Type 440F
Austenitic		
—	—	Type 203
Type 304	Type 303Se	Type 303
		Type 303Al Modified®[c]
Type 302 HQ	—	Type 302HQ-FM®[d]
Type 316	—	Type 316F
Type 347	Type 347-Se	Type 347F

(a) Does not contain Ti
(b) Not hardenable
(c) Contains Al
(d) Contains lower Cu

Contact a Carpenter representative for alloy availability.

Table 1 shows that the best-known alloys in the three families represented, Type 430 (ferritic), Type 410 (martensitic) and Type 304 (austenitic), have corresponding free-machining alloys. In addition, the more corrosion-resistant molybdenum-bearing alloys 18Cr-2Mo and Type 316 have free-machining versions in the ferritic and austenitic families, respectively; and the higher-carbon, higher-strength alloys Type 420 and Type 440C have free-machining versions in the martensitic family. Thus, there are a variety of basic free-machining alloys available to satisfy the two most important selection criteria for stainless steels—corrosion resistance and mechanical properties (strength/hardness).

A variety of other distinctions may be made among the other alloys listed in Table 1. Free-machining versions are available for Type 347, a columbium-stabilized austenitic alloy, and for Type 302HQ, a copper-bearing alloy noted for a low work-hardening rate and excellent cold formability for an austenitic alloy. The free-machining version of Type 302HQ, 302HQ-FM® stainless, is intended to offer a good combination of cold formability and machinability. Another alloy which can offer this combination of properties is Type 303Al Modified® stainless. The selenium-bearing free-machining alloys such as Type 303 Se are also noted for better cold formability than the sulfur-bearing alloys, and may be used where machined surface finish is more important than tool life. Type 203, which lacks a corresponding non-free-machining version, is a high-manganese, high-copper alloy with excellent machinability for an austenitic alloy. It can be substituted for Type 303, where specifications permit.

Finally, versions of Type 303, Type 416, and Type 430F are available to provide combinations of properties not obtainable with the standard alloys. The compositions of such versions still fall within the broad ranges of the standard alloy. For instance, Type 303 and Type 416 are available in “forging quality” versions, intended to provide a good combination of hot workability and machinability. Type 416 is also available in a “bright quench” version, Type 416 BQ, intended to provide a higher quenched hardness level after bright hardening. Type 430F is available as “solenoid quality” versions, Type 430F Solenoid Quality and Type 430FR Solenoid Quality, for optimum soft-magnetic properties.

Project 70+® Stainless Enhanced-Machining Alloys

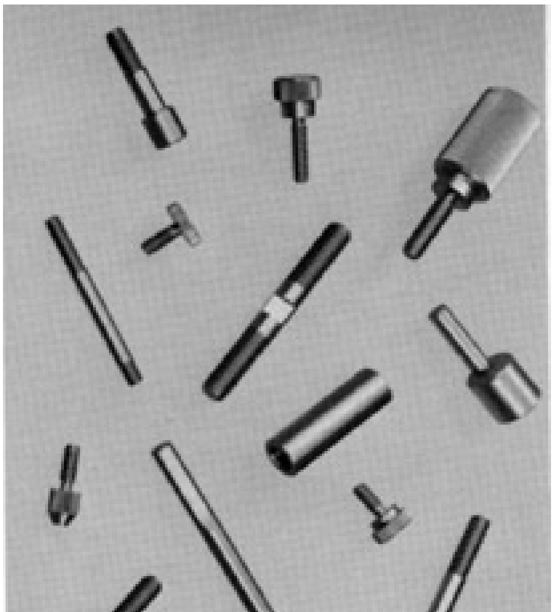
As described earlier, compositions of alloys may be modified within the broad limits to provide an optimum combination of properties. In a similar manner, compositions may be modified to provide optimum machining performance alone. Processing of the alloy may also be modified to further improve machining performance. This approach has been taken with both non-free-machining and free-machining alloys, resulting in enhanced-machining alloys, several of which are designated by Carpenter as Project 70+® stainless alloys, and meet the same specifications as the standard alloys. It should be noted that the enhanced-machining versions of the non-free-machining alloys provide machining performance superior to that of the corresponding standard alloys, but still do not provide the machinability of comparable free-machining alloys. However, other properties, such as corrosion resistance, ductility, toughness, weldability, cold formability, etc., will be superior to those of the corresponding free-machining alloy. Thus, the enhanced-machining versions of the non-free-machining alloys provide a way to obtain improved machining performance without significant degradation of other properties. Table 2 provides a listing of the alloys that are available with enhanced machining performance.

Table 2

Machining Alloy Versions of:	
Enhanced-Machining Alloys	**Free-Machining Alloys**
Project 70+® Type 304/304L Project 70+ Type 316/316L Type 309 A.B.Q® Project 70+ Custom 630 Project 70+ 15Cr-5Ni	Project 70+® Type 416 Project 70+ Type 303 No. 5-F

Certain of the alloys in Table 2 are available in more than one enhanced-machining version. For instance, Type 416 is available in an enhanced-machining version still meeting certain minimum hardness requirements, and, in a version designated No. 5-F, providing even higher machining performance but having limited hardness capability.

Machinability of stainless steels can be affected by changes in processes to provide a variety of levels of machining performance. The level of machinability necessary and the compromises to be made with other properties depend on the needs of the user. Before specifying or purchasing an alloy, consult Carpenter Specialty Alloys Operations to determine the proper alloy, or, more important, the proper version of the alloy, and its availability.



Longer tool life and fewer rejects were experienced with Carpenter's premier machining stainless over generic stainless steels.

Machinability of Stainless Steels

Definitions of Machinability

Defining "machinability" is not a simple matter for two reasons. First, machinability does not mean the same thing to everyone. If the specific aspect of machinability one is interested in is not defined, there will be no basis for a common discussion or understanding. Second, machinability can only be evaluated in a complex, multi-variable system. Again, if all the variables are not defined, misunderstanding can result.

The following list includes some of the specific definitions included in the general concept of machinability:

1. tool life or tool wear
2. machined surface finish
3. chip disposability, or how easily chips are removed from the cutting area
4. maximum cutting rate
5. productivity, or how quickly the largest number of acceptable parts can be produced

These definitions may be interdependent in various ways. For instance, machined surface finish depends on how the tool is wearing. Cutting rate is related to tool life, but is influenced by other factors. Productivity obviously can encompass all the other factors.

Some of the variables which may affect the perception of machinability are as follows:

1. rigidity of the tooling or fixtures
2. type of tools, e.g., high-speed steel versus carbide
3. tool design, e.g., rake angles, relief angles, etc.
4. type and composition of the cutting fluid, e.g., mineral-oil-base cutting fluids versus emulsifiable cutting fluids

In addition, the type of machining operation itself can affect the perception of machinability. For instance, alloys may behave differently in drilling than in turning.

Because of these and other variables involved, machinability rankings among alloys must be viewed with caution. Such rankings may not apply to all aspects of machining performance or to all types of machining operations, and may vary from producer to producer. In addition, the rankings should only be used on a relative basis; absolute, or numerical, comparisons are only for illustrative purposes and cannot be expected to apply in all cases, even for the same type of machining operation.

General Machining Properties

Austenitic Alloys

Austenitic stainless steel, of all the groups, is the most difficult to machine. Compared with ferritic and martensitic alloys, typical austenitic alloys have a higher work-hardening rate, a wider spread between yield and ultimate tensile strengths, and higher toughness and ductility. When machining austenitic stainless steels, particularly the non-free-machining alloys, tools will run hotter with more tendency to a large built-up edge; chips will be stringier with a tendency to tangle, making their removal difficult; there will be a tendency for inadequate or marginal tool rigidity to result in chatter; and cut surfaces will be work-hardened and difficult to machine if cutting is interrupted or feed rate is too low. Because of these factors, the precautions spelled out for machining stainless steels in general must be particularly adhered to for austenitic alloys.

The greatest benefit to the machinability of austenitic stainless steels is brought about by the addition of free-machining agents such as sulfur. For example, Type 303 has a machinability rating between those of the non-free-machining (Type 430F, Type 410) and free-machining (Type 430F, Type 416, etc.) versions of the ferritic and annealed low-carbon martensitic alloys. The following variables also will influence machinability:

1. cold drawing
2. work-hardening rate, as modified by alloy content
3. grain size

A moderate cold draft has generally been regarded as beneficial to the overall machining characteristics of austenitic stainless steels. The cold draft will reduce the ductility of the material, which results in cutting with a cleaner chip and less tendency toward a built-up edge. A better machined surface finish will result. Drilling, however, may be favored by softer material.

The high work-hardening rate of the lower-alloy-content austenitic stainless steels can be decreased by additions of manganese or copper. Such additions will also increase machinability. Austenitic free-machining alloys making use of additions of manganese or copper include Type 203 and 302HQ-FM® stainless. Although higher alloy content generally reduces work-hardening rate, it may not necessarily benefit machinability. Highly alloyed austenitic stainless steels, such as Type 310 and 20Cb-3® stainless, tend to be more difficult to machine.

Grain size will generally increase strength and reduce ductility. Grain size also changes the flow characteristics of the material at the cutting edge. At typical tensile properties, a finer grain size will increase the tendency toward built-up edge and stringy chips. However, combining a fine grain structure with high cold drafts will increase surface finishes and improve chip characteristics.

Ferritic and Martensitic Alloys

Free-machining ferritic alloys (Type 430F, etc.) and annealed, low-carbon free-machining martensitic alloys (Type 416, etc.) are the easiest to machine of the stainless steels. In fact, their machinability ratings approach and in some cases are comparable to those of certain free-machining carbon steels. The non-free-machining lower-chromium ferritic alloys (Type 430) and annealed, low-carbon, straight-chromium martensitic alloys (Type 410) are also generally easier to machine than the majority of other non-free-machining alloys. The higher-chromium ferritic alloys, such as Type 446, are considered by some to be somewhat more difficult to machine than the lower-chromium alloys, due to "gumminess" and stringy chips.

Other than the presence or lack of a free-machining additive like sulfur, the machining characteristics of martensitic stainless steels are influenced by the following variables:

1. hardness level
2. carbon content
3. nickel content

Increasing hardness level for a particular alloy results in a decrease in machinability as measured by tool life, drillability, etc. Surface finish and chip characteristics, however, can be improved by machining harder material. Type 416 is normally supplied in one of three hardness ranges: annealed (condition A), 262HB max.; intermediate temper (condition T), 248-302HB; or hard temper (condition H), 293-352HB. Based on the above information, condition T is expected to provide a good combination of tool life and machined surface finish.

As the carbon content increases from Type 410 to Type 420 to Type 440C, or from Type 416 to Type 420F to Type 440F, machinability decreases. With higher carbon levels, there also tends to be a smaller difference in machinability between the corresponding free-machining and non-free-machining versions. These effects are primarily due to the increasing quantities of abrasive chromium carbides present as carbon level increases in this series of alloys. As a further detriment to machinability, annealed hardness level increases with increasing carbon level.

Nickel content also influences machinability by increasing annealed hardness levels. Consequently, alloys such as Type 414 and Type 431 will be more difficult to machine than Type 410 in the annealed condition.

Duplex Alloys

The machinability of duplex stainless steels is limited by their high annealed strength level. The machinability of the duplex alloy 7-Mo PLUS® stainless lies between that of a high-nitrogen austenitic alloy, 22Cr-13Ni-5Mn, and a conventional austenitic alloy, Type 316. Note that 7-Mo PLUS stainless has a hardness level comparable to that of 22Cr-13Ni-5Mn, but provides better machinability. However, it does not machine as well as Type 316.

Other nitrogen-bearing duplex alloys are expected to machine similarly to 7-Mo PLUS stainless. At this point, there are no enhanced-machining versions of duplex alloys.

Precipitation-Hardenable Alloys

The machinability of precipitation-hardenable stainless steels depends on the type of alloy and its hardness level. Martensitic precipitation-hardenable stainless steels are often machined in the solution-treated condition, so that only a single aging treatment is required afterward to reach the desired strength level. In this condition, the relatively high hardness limits machinability. Most of these alloys machine comparably to or somewhat worse than an austenitic alloy such as Type 304 in its non-enhanced-machining version. Stainless 17Cr-4Ni is available in an enhanced-machining version, Project 70+® Custom 630 stainless, which approaches the machinability of Project 70+ Type 304 stainless.

Martensitic precipitation-hardenable stainless steels may also be machined in an aged condition so that heat treating can be avoided and closer tolerances maintained. The ease of cutting generally varies with the hardness or heat-treated condition, with harder material requiring more horsepower to machine. The use of coated carbide tools or coated high speed steels such as M48 or T15 may enable these alloys to be machined in the hardened condition. Chips are less stringy and surface finishes are better, but the increased hardness can result in faster tool wear. Tool coatings such as TiAlN or TiCN can help decrease tool wear.

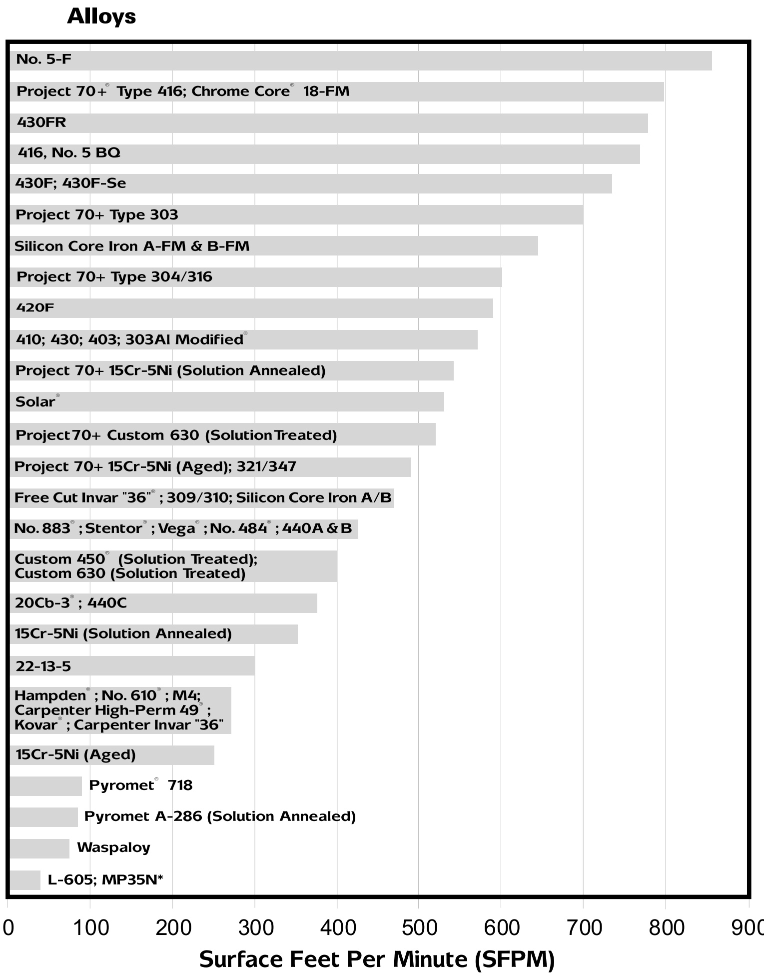
In the annealed, austenitic condition, semi-austenitic alloys can be expected to machine with difficulty, somewhat worse than an alloy like Type 302, which has a high work-hardening rate. Pyromet® Alloy 350 and Pyromet Alloy 355 can be supplied in an equalized and over-tempered condition, which will provide the best machinability from a tool wear position. As with the martensitic precipitation-hardenable alloys, machining is possible in the age hardened condition.

Austenitic precipitation-hardenable alloys, such as Pyromet Alloy A-286, machine quite poorly, requiring slower cutting rates than even the highly-alloyed austenitic stainless steels. Machining in an aged condition will require coated carbide tooling and a rigid setup.

Relative Machinability of Stainless Steels and Other Alloys

Single Point Turning Speed Comparison

Coated Carbide Tools



*MP35N is a trademark of SPS Technologies, Inc.
MP is a registered trademark of SPS Technologies, Inc.

Contact a Carpenter representative for alloy availability.

The Carpenter Selectaloy® Method

The problem facing the manufacturer working with stainless steels becomes the difficult one of choosing the right steel for a particular job.

While many attempts have been made to portray a simple picture of the stainless steel family, Carpenter's Selectaloy® method represents perhaps the first useful selection method for the stainless steel industry.

Criteria for Selecting

Before one can utilize this method, there are certain variables which must be considered in the choice of any stainless steel.

The proper selection technique for the application/evaluation of each of the more than 50 grades of stainless steel is based upon five important criteria.

In order of importance, these requirements are:

1. **Corrosion Resistance -** The primary reason for specifying stainless steel. The level of corrosion resistance required and the corrosive environment expected must be known when selecting a stainless alloy. If corrosion were not a problemthere would be little need for using stainless steel.

2. **Mechanical Properties -** In particular, special emphasis should be placed upon the alloy's strength. Together with the corrosion resistance factor, this second requirement designates the specific alloy type for the application.

3. **Fabrication Operations -** How the material is to be processed. This includes such special considerations as the steel's ability to be machined, welded,cold headed, etc.

4. **Total Cost -** The overall value analysis figure of the stainless steel, including initial alloy price, fabrication costs, and the effective life expectancy of the finished product.

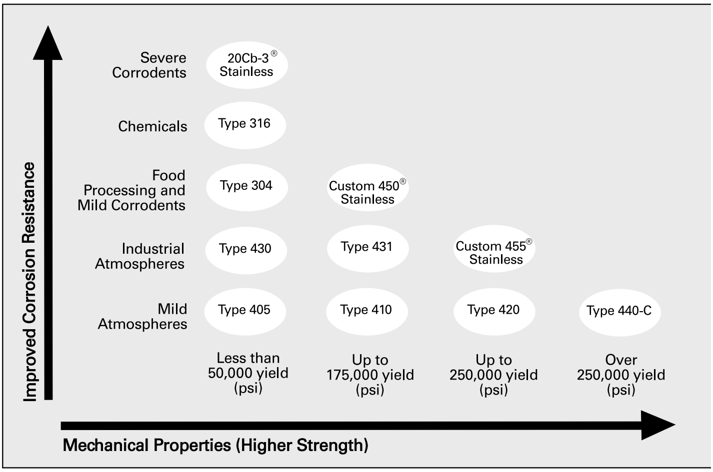
5. **Product Availability -** Availability of the raw material from the mill, service center, warehouse, or supplier is a final consideration in choosing the most economical and practical stainless steel.

Although these factors have long been known throughout the industry, a careful consideration of their relative importance has often been a time consuming and frustrating experience for the veteran stainless metallurgist as well as the apprentice. This problem arises not from a lack of information, but is a result of the publication of volumes of uncoordinated material.

Carpenter Specialty Alloys has developed a simple selection technique for choosing the proper stainless steel for the end use application that you have in mind. It is called the Selectaloy Method for classifying and selecting stainless steel.

Carpenter's Selectaloy® Method is easy to use.

Selectaloy® Method for Stainless Steels



Selectaloy® arrows and ovals diagram registered in the U.S. Patent Office.

Contact a Carpenter representative for alloy availability.

The Selectaloy Projection utilizes 11 basic stainless steels which are representative of certain classifications of types of stainless alloys. The first five steels: 20Cb-3® stainless, Type 316, Type 304, Type 430, and Type 405, are plotted vertically in order of their resistance to corrosion, the most important criterion in choosing stainless steel. Note Type 304 is midway between 20Cb-3 stainless (most resistant) and Type 405 (least resistant) on the corrosion scale. Reading across the chart, the steels increase in strength as you move away from Type 405. Simple additions of carbon plus chromium increase the strength capability of Type 410, Type 420 and Type 440-C while maintaining their corrosion resistance.

All five factors previously mentioned must be considered before making your selection; however, it is wise to start with corrosion resistance.

Selecting for Corrosion Resistance

As you see on the Selectaloy chart, the effectiveness of corrosion resistance begins with an alloy like Type 405, which is useful in less severe environments, and rises in effectiveness along the left side of the chart until it reaches its peak corrosion resistance with 20Cb-3 stainless, an austenitic stainless steel.

When you are looking for the right stainless for a particular application, it is often best to begin your search with Type 304—the most widely used 18-8 stainless. Its middle level of corrosion resistance makes it a candidate for a wide range of corrodents from foodstuffs to organic chemicals.

Should your industrial process require a higher level of resistance, you would move up the Selectaloy scale to Type 316, which adds molybdenum to the composition, helping it to resist process chemicals, acids, bleaches and other highly corrosive materials.

If your application requires less in the way of corrosion resistance than these types offer, perhaps Type 430 or even Type 405 on the lowest level of corrosion resistance may suffice. Conversely, for the most severe corrosive environments you would move to the top level, 20Cb-3 stainless, which provides optimum resistance to hundreds of industrial and process corrodents (including up to 40% sulfuric acid at the boiling point).

Once corrosion levels have been determined, careful consideration of mechanical properties is necessary to select the proper grade for the application.

Selecting for Mechanical Strength

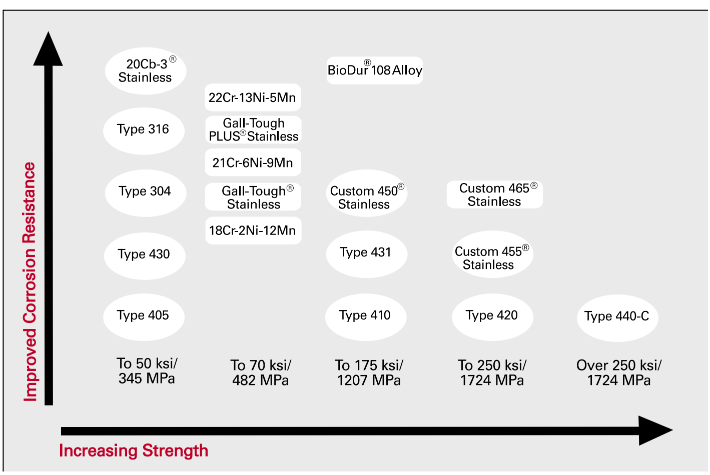
Supposing the corrosion resistance of Type 405 is adequate but higher strength is needed, moving over to Type 410 may provide the combination of properties required.

However, in many cases, the strength offered by Type 410 may not be sufficient. For greater strength and hardness, at the same level of corrosion resistance, Type 420 is specified. And for products requiring the highest hardness values within the same corrosion-resistance level, you would move extreme right to Type 440-C, the stainless steel with the greatest hardness.

Enhanced Selectaloy® Diagram

When seeking greater strength with good corrosion resistance, the specifier should check the family of nitrogen-strengthened and other alloys shown in the Enhanced Selectaloy Diagram.

Enhanced Selectaloy® Diagram



Contact a Carpenter representative for alloy availability.

Nitrogen Strengthened Grades

Many applications require a balanced combination of improved strength and corrosion resistance. When seeking greater strength with good corrosion resistance, the specifier should check the family of nitrogen-strengthened alloys shown in the Enhanced Selectaloy Diagram. The five alloys in the second column have comparable mechanical properties, with yield strength of 50 ksi (345 MPa) to 70 ksi (482 MPa) as annealed, and strength levels in excess of 100 ksi (689 MPa) when cold worked.

A new nitrogen strengthened grade, BioDur® 108 alloy, discussed in the following "Other Grades to Consider" section, has an annealed yield strength in excess of 85 ksi (586 MPa) with a tensile strength in excess of 130 ksi (896 MPa).

These alloys are austenitic stainless grades with nitrogen added for improved strength and corrosion resistance. All of them, except Gall-Tough® stainless, remain nonmagnetic even after severe cold working.

The group starts with 18Cr-2Ni-12Mn stainless, which has corrosion resistance similar to Type 430 stainless. It offers an excellent combination of toughness, ductility, corrosion resistance, strength and good fabricability. Farther up the scale are Gall-Tough stainless, Gall-Tough PLUS® stainless and 21Cr-6Ni-9Mn stainless. These three grades have corrosion resistance ranging between Type 304 stainless and Type 316 stainless with twice the yield strength and excellent high temperature strength.

Gall-Tough stainless and Gall-Tough PLUS stainless, which are resistant to galling, may be considered for applications such as valve and pump components, shafts, bridge pins, fasteners, wire and orthodontic parts. 21Cr-6Ni-9Mn stainless has been used generally for airframe and aircraft engine parts, steam and autoclave components, parts exposed to reciprocating engine exhausts, etc.

The most corrosion resistant stainless in this family is 22Cr-13Ni-5Mn stainless. This alloy has better corrosion resistance than Type 316 stainless, and twice the yield strength. It provides high level resistance to pitting and crevice corrosion and very good resistance in many reducing and oxidizing acids and chlorides.

Other Grades to Consider

Custom 465® stainless is a premium melted, martensitic, age hardenable alloy capable of about 260 ksi (1793 MPa) ultimate tensile strength when peak aged. The alloy was designed to have excellent notch tensile strength and fracture toughness in this condition.

Overaging provides a superior combination of strength, toughness and stress corrosion cracking resistance compared with other high strength precipitation hardenable stainless alloys such as Custom 455 stainless or PH 13-8 Mo* stainless.

This alloy may be considered for medical instruments such as screwdrivers, nut drivers, and instruments for clamping, spreading and impacting; for a variety of aerospace applications including aircraft landing gear, engine mounts, flap tracts, actuators, tail hooks and other structural components; also for shafting subject to heavy stress, bolts, fasteners and other parts requiring an exceptional combination of high strength, toughness and corrosion resistance.

BioDur® 108 alloy is a fully austenitic stainless steel with less than 0.05% nickel that has been designed as a candidate to meet high standards for bio-compatibility in medical applications. Tests for cytotoxicity, irritation, acute systemic toxicity and pyrogenicity have indicated that the alloy is a good candidate for implanted medical devices.

High nitrogen content gives this alloy improved levels of tensile and fatigue strength as compared with nickel-containing alloys such as BioDur 22Cr-13Ni-5Mn alloy and BioDur 734 alloy. The resistance of BioDur 108 alloy to pitting and crevice resistance is superior to Type 316L alloy and equal to that of BioDur 22Cr-13Ni-5Mn alloy and BioDur 734 alloy. The new alloy is produced by the ElectroSlag Remelting (ESR) process to assure its microstructural integrity and cleanness.

BioDur 108 alloy could be considered for use in applications requiring high levels of strength and corrosion resistance. Candidate applications include implantable orthopedic devices such as bone plates, bone screws, spinal fixation components, hip and knee components, jewelry, orthodontic applications and other medical components/instruments fabricated by forging and machining.

**PH 13-8 Mo stainless is a registered trademark of AK Steel Corp..*

Traditional Machining Operations

General Considerations and Guidelines

Note that feeds and speeds in machining tables are suggested starting points. Depending on a number of factors including tool condition and operator experience, you may be able to increase the values.

There is no single set of rules or simple formula that will prove best for all machining situations. The requirements of pertinent specifications together with the equipment and the materials being used must determine the machining parameters that will apply. Stainless steels have a high alloy content which reduces machinability, but free-machining stainless steels are available which compare favorably with some free-machining carbon steels. As discussed previously, the characteristics of stainless steels that have the greatest influence on machinability include: relatively high tensile strength; high work-hardening rate, particularly for the austenitic alloys; and high ductility. These factors explain the material's tendency to form a built-up edge during machining. The chips removed in machining exert high pressures on the nose of the tool, and therefore tend to weld fast. This causes the tool to run hot. In addition, the low thermal conductivity of stainless steels contributes to a rapid heat buildup.

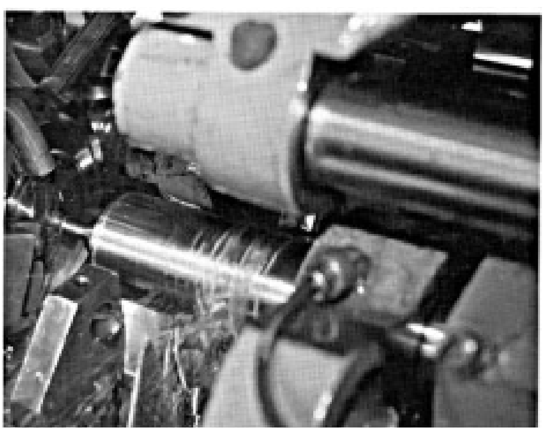
Difficulties in machining stainless steels as a result of the above factors can be minimized by observing the following points:

1. Because more power is generally required to machine stainless steels, equipment should be used only up to about 75% of the rating for carbon steels.

2. To avoid chatter, tooling and fixtures must be as rigid as possible. Overhang or protrusion of either the workpiece or the tool must be minimized. This applies to turning tools, drills, reamers, etc.

3. To avoid glazed, work-hardened surfaces, particularly with austenitic alloys, a positive feed must be maintained. In some cases, increasing the feed and reducing the speed (see following) may be necessary. Dwelling, interrupted cuts or a succession of thin cuts should be avoided.

4. Lower cutting speeds may be necessary, particularly for non-free-machining austenitic alloys, precipitation-hardenable stainless steels or higher-hardness martensitic alloys. Generally, excessive cutting speeds result in tool wear or tool failure and shutdown for tool regrinding or replacement. Slower speeds with longer tool life are often the answer to higher output and lower costs. However, recent advances in tool materials, coatings and design have allowed faster cutting rates.



5. Tools, both high-speed steel and carbide, must be kept sharp, with a fine finish to minimize friction with the chip. A sharp cutting edge produces the best surface finish and provides the longest tool life. In order to produce the best cutting edge on high-speed steel tools, 60 grit roughing should be followed by 120 grit and 150 grit preparation. Honing or stoning produces an even finer finish.

6. Cutting fluids must be selected or modified to provide proper lubrication and heat removal. Fluids must be carefully directed to the cutting area at a sufficient flow rate to prevent overheating.

TURNING

Turning Parameters

Turning operations on automatic screw machines, turret lathes and CNC lathes involve so many variables that it is impossible to make specific recommendations which would apply to all conditions. Suggested tool angles, cutting speeds and feeds are primarily starting points for each specific job. The turning tables on pages 37 and 39 represent reasonable speeds and feeds for single-point turning and the tables on pages 38 and 40 for cut-off and forming operations.

Single-Point Turning Tools

Grinding tools properly is particularly important in machining stainless steels. Figure 1 illustrates suggested starting geometries for high-speed steel single-point turning tools. Tools with a 5 to 20° positive top rake angle for HSS tooling will generate less heat and cut more freely with a cleaner surface. It also is beneficial to select as large a tool as possible to provide a greater heat sink, as well as a more rigid setup. To ensure adequate support for the cutting edge, the front clearance angle should be kept to a minimum, i.e., 7 to 10°, as shown. Austenitic stainless steels, due to their toughness and work-hardening characteristics, require tools ground with top rake angles on the high side of the 5 to 20° range to control the chips and may require increased side clearance angles to prevent rubbing and localized work hardening.

The non-free-machining stainless steels tend to produce long, stringy chips which can be very troublesome. This difficulty can be alleviated by using chip curlers or chip breakers which, in addition to controlling long chips, also reduce friction on the cutting edge of the tool. Chip breakers or curlers for the free-machining stainless steels do not need to be as deep as those for the non-free-machining alloys. Otherwise, the depth of cut and feed rate usually govern the width and depth of the curler or breaker. Heavier chips require deeper curlers or breakers; however, they must be ground without weakening the cutting edge. If a chip curler or breaker cannot be ground into the tool, it is advisable to have a steep top rake angle.

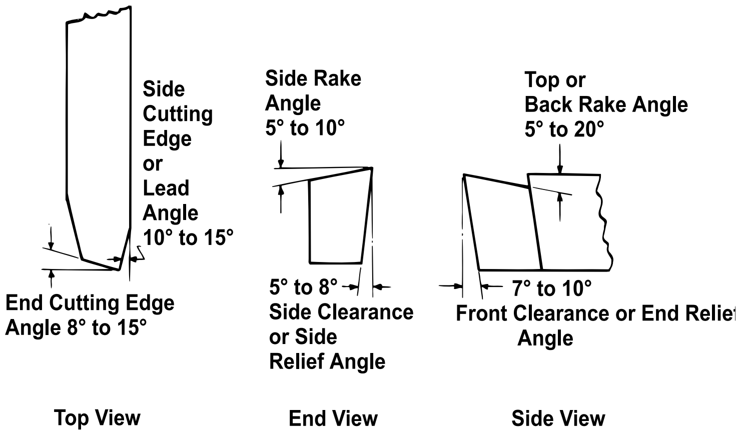


Fig. 1. Suggested geometries for single-point turning tools used on stainless steels.

Carbide tools can be used in single-point turning operations and will allow higher speeds than high-speed steel tools. However, carbide tooling requires even greater attention to rigidity of tooling and the workpiece, and interrupted cuts should be avoided.

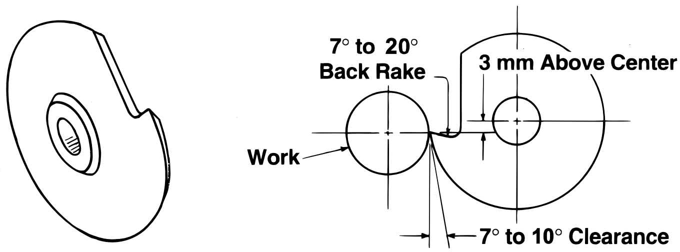


Fig. 2. Suggested geometries for circular cut-off tools used on stainless steels.

Stainless Steels
Turning—Single Point and Box Tools

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Alloy (Annealed Condition)	Depth of Cut (inches)	Micro-Melt® Powder High Speed Tools			Carbide Tools (inserts)			
		Tool Mtl.	Speed (fpm)	Feed (ipr)	Tool Mtl.	Speed (fpm) Un-coated	Speed (fpm) Coated	Feed (ipr)
410	.150	M48, T15	120	.015	C6	435	570	.015
	.025		150	.007	C7	535	670	.007
416	.150	M48, T15	192	.015	C6	615	765	.015
	.025		204	.007	C7	715	815	.007
No. 5 BQ	.150	M48, T15	192	.015	C6	615	765	.015
	.025		204	.007	C7	665	815	.007
Project 70+® 416	.150	M48, T15	210	.015	C6	640	795	.015
	.025		240	.007	C7	715	895	.007
No. 5-F	150	M48, T15	255	.015	C6	680	855	.015
	.025		295	.007	C7	755	955	.007
420	.150	M48, T15	102	.015	C6	375	500	.015
	.025		120	.007	C7	450	600	.007
420F	.150	M48, T15	126	.015	C6	465	590	.015
	.025		156	.007	C7	535	665	.007
431	.150	M48, T15	96	.015	C6	350	475	.015
	.025		114	.007	C7	425	575	.007
440A/440B	.150	M48, T15	90	.015	C6	325	425	.015
	.025		96	.007	C7	400	550	.007
440C	.150	M48, T15	78	.015	C6	290	375	.015
	.025		90	.007	C7	340	475	.007
440F	.150	M48, T15	102	.015	C6	425	525	.015
	.025		120	.007	C7	475	575	.007
430	.150	M48, T15	120	.015	C6	435	570	.015
	.025		150	.007	C7	535	670	.007
430F/430FR	.150	M48, T15	198	.015	C6	600	735	.015
	.025		222	.007	C7	675	835	.007
443	.150	M48, T15	114	.015	C2	400	500	.015
	.025		132	.007	C3	475	600	.007
182-FM	.150	M48, T15	210	.015	C6	625	800	.015
	.025		220	.007	C7	675	900	.007
302/304/316	.150	M48, T15	102	.015	C2	350	450	.015
	.025		120	.007	C3	400	525	.007
Project 70+® 304/316	.150	M48, T15	140	.018	C2	470	600	.018
	.025		171	.0084	C3	530	660	.0084
302HQ-FM®	.150	M48, T15	120	.015	C2	425	525	.015
	.025		144	.007	C2	475	600	.007
303	.150	M48, T15	105	.015	C2	425	600	.015
	.025		130	.007	C2	500	700	.007
Project 70+® 303	.150	M48, T15	171	.018	C2	580	700	.018
	.025		202	.0084	C2	680	800	.0084
303Al Modified®	.150	M48, T15	120	.015	C2	435	570	.015
	.025		144	.007	C2	485	605	.007
203	.150	M48, T15	105	.015	C2	425	600	.015
	.025		130	.015	C2	425	600	.015
321/347	.150	M48, T15	102	.015	C2	385	490	.015
	.025		120	.007	C3	435	565	.007
20Cb-3® Stainless	.150	M48, T15	78	.015	C2	290	375	.015
	.025		90	.007	C3	390	425	.007
18Cr-2Ni-12Mn	.150	M48, T15	72	.015	C6	250	300	.015
	.025		84	.007	C7	300	350	.007
21Cr-6Ni-9Mn	.150	M48, T15	66	.015	C6	250	300	.015
	.025		84	.007	C7	300	350	.007
22Cr-13Ni-5Mn	.150	M48, T15	66	.015	C6	250	300	.015
	.025		84	.007	C7	300	350	.007

Contact a Carpenter representative for alloy availability.

Stainless Steels
Turning—Cut-Off and Form Tools

Alloy (Annealed Condition)	Tool Mtl. Micro-Melt® Powder HS Tools	Tool Mtl. Carbide Tools	Speed (fpm)	Feed (inches per revolution) Cut-Off and Form Tools Width (inches) 1/16	1/8	1/4	1/2	1	1½	2
410	M48, T15		108	.001	.001	.002	.0015	.001	.001	.001
		C6	390	.004	.0055	.007	.005	.004	.0035	.0035
416	M48, T15		120	.0015	.002	.0025	.002	.0015	.001	.001
		C6	408	.004	.005	.007	.005	.004	.0035	.0035
No. 5 BQ	M48, T15		162	.0015	.002	.0025	.002	.0015	.001	.001
		C6	420	.004	.005	.007	.005	.004	.0035	.0035
Project 70+® 416	M48, T15		180	.0015	.002	.0025	.002	.0020	.0015	.001
		C6	432	.004	.005	.007	.005	.004	.0035	.0035
No. 5-F	M48, T15		192	.002	.0025	.003	.0025	.002	.002	.002
		C6	444	.004	.005	.007	.005	.004	.0035	.0035
420	M48, T15		90	.001	.0015	.002	.015	.001	.001	.001
		C6	330	.004	.005	.006	.005	.004	.003	.003
420F	M48, T15		120	.001	.0015	.002	.0015	.0015	.001	.001
		C6	390	.004	.005	.007	.005	.004	.0035	.0035
431	M48, T15		78	.001	.001	.0015	.0015	.001	.001	.0005
		C6	240	.004	.0055	.007	.005	.004	.0035	.003
440A/440B	M48, T15		66	.001	.001	.0015	.001	.001	.001	.0005
		C6	246	.004	.0055	.007	.005	.004	.0035	.0035
440C	M48, T15		60	.001	.001	.0015	.001	.001	.001	.0005
		C6	210	.003	.003	.0045	.003	.002	.002	.002
440F	M48, T15		90	.001	.001	.0015	.0015	.001	.001	.0005
		C6	300	.004	.055	.007	.005	.004	.0035	.0035
430	M48, T15		108	.001	.001	.0015	.0015	.001	.001	.001
		C6	390	.004	.0055	.007	.005	.004	.0035	.0035
430F/430FR	M48, T15		180	.0015	.002	.0025	.0025	.002	.0015	.001
		C6	480	.004	.0055	.007	.005	.004	.0035	.0035
443	M48, T15		96	.001	.0015	.002	.002	.0015	.001	.001
		C6	360	.004	.0055	.007	.005	.004	.0035	.0035
182-FM	M48, T15		180	.0015	.002	.0025	.002	.002	.0015	.001
		C6	350	.004	.0055	.007	.005	.004	.0035	.0035
302/304/316	M48, T15		90	.001	.0015	.002	.0015	.001	.001	.001
		C2	330	.004	.0055	.007	.005	.004	.0035	.0035
Project 70+® 304/316	M48, T15		124	.0018	.0024	.0024	.0024	.0018	.0012	.0012
		C2	468	.0048	.0066	.0084	.0060	.0048	.0042	.0042
302HQ-FM®	M48, T15		108	.0015	.002	.0025	.002	.0015	.0015	.001
		C2	360	.004	.005	.007	.006	.005	.0015	.001
303	M48, T15		100	.015	.002	.0024	.0025	.0018	.0015	.001
		C2	325	.015	.002	.0024	.0025	.0018	.0015	.001
Project 70+® 303	M48, T15		156	.0018	.0024	.0024	.0025	.0018	.0018	.0012
		C2	507	.0048	.0060	.0096	.0072	.0060	.0048	.0036
303Al Modified®	M48, T15		102	.0015	.002	.0025	.002	.0015	.0015	.001
		C2	330	.004	.005	.007	.006	.005	.004	.003
203	M48, T15		100	.015	.002	.0024	.0025	.0018	.0015	.001
		C2	325	.015	.002	.0024	.0025	.0018	.0015	.001
321/347	M48, T15		96	.001	.0015	.002	.0015	.001	.001	.001
		C2	360	.004	.0055	.007	.005	.004	.035	.0035
20Cb-3® Stainless	M48, T15		60	.001	.0015	.002	.001	.001	.001	.001
		C2	210	.004	.0055	.007	.005	.004	.0035	.0035
18Cr-2Ni-12Mn	M48, T15		54	.001	.001	.0015	.0015	.001	.0007	.0007
		C6	192	.004	.0055	.0045	.004	.003	.002	.002
21Cr-6Ni-9Mn	M48, T15		48	.001	.001	.0015	.0015	.001	.0007	.0007
		C6	168	.004	.0055	.0045	.004	.003	.002	.002
22Cr-13Ni-5Mn	M48, T15		48	.001	.001	.0015	.0015	.001	.0007	.0007
		C6	168	.004	.0055	.0045	.004	.003	.002	.002

Contact a Carpenter representative for alloy availability.

Precipitation Hardening Alloys
Turning—Single Point and Box Tools

Alloy	Depth of Cut, (inches)	Micro-Melt® Powder High Speed Tools: Tool Material	Speed (fpm)	Feed (ipr)	Carbide Tools (inserts): Tool Mtl.	Speed (fpm): Un-coated	Speed (fpm): Coated	Feed (ipr)
				Solution Treated				
17Cr-4Ni	.150	M48,	80	.015	C6	300	450	.015
	.025	T15	95	.007	C7	350	525	.007
				Double Aged H 1150-M				
	.150	M48,	80	.015	C6	330	425	.015
	.025	T15	95	.007	C7	350	525	.007
				Aged H 1150 H 1100 H 1075				
	.150	M48,	60	.015	C6	290	390	.015
	.025	T15	75	.007	C7	325	425	.007
				Aged H 1025				
	.150	M48,	60	.015	C6	265	325	.015
	.025	T15	75	.007	C7	300	390	.007
				Aged H 900 H 925				
	.150	M48,	30	.015	C6	180	225	.015
	.025	T15	45	.007	C7	200	275	.007
				Solution Treated				
Project 70+® Custom 630	.150	M48,	90	.015	C6	400	520	.015
	.025	T15	105	.007	C7	450	595	.007
				Double Aged H 1150-M				
	.150	M48,	90	.015	C6	375	475	.015
	.025	T15	105	.007	C7	425	550	.007
				Aged H 1150 H 1100 H 1075				
	.150	M48,	70	.015	C6	325	425	.015
	.025	T15	85	.007	C7	375	475	.007
				Aged H 1025				
	.150	M48,	70	.015	C6	300	375	.010
	.025	T15	85	.007	C7	350	425	.005
				Aged H 900 H 925				
	.150	M48,	40	.010	C6	210	275	.010
	.025	T15	55	.005	C7	250	310	.005
				Solution Treated				
Custom 450®	.150	M48,	84	.015	C6	310	400	.015
	.025	T15	108	.007	C7	350	475	.007
				Aged H 1150-H 1100				
	.105	M48,	78	.015	C6	290	350	.015
	.025	T15	90	.007	C7	310	425	.007
				Aged H 1050-H 1000				
	.150	M48,	66	.015	C6	250	325	.010
	.025	T15	78	.007	C7	300	375	.005
				Aged H 900 H 925				
	.150	M48,	42	.010	C6	170	225	.010
	.025	T15	48	.005	C7	200	260	.005
				Annealed				
Custom 465®	.150	M48,	72	.015	C6	270	350	.010
Custom 455®	.025	T15	84	.007	C7	325	425	.005
PH 13-8 Mo*				**Aged**				
15Cr-5Ni	.150	M48,	48	.010	C6	190	250	.010
	.025	T15	54	.005	C7	225	290	.005
				Solution Treated				
Project 70+®	.150	M48,	132	.015	C6	415	540	.019
15Cr-5Ni .025	.025	T15	150	.010	C7	485	620	.009
				Aged				
	.150	M48,	102	.013	C6	385	490	.013
	.025	T15	126	.008	C7	445	530	.006
				Equalized & Over Tempered				
Pyromet® 350 & 355	.150	M48,	84	.015	C6	280	400	.015
	.025	T15	90	.007	C7	350	475	.007
				Aged Rc 38-40				
	.150	M48,	72	.015	C6	270	350	.010
	.025	T15	84	.007	C7	325	400	.005
				Aged Over Rc 40				
	.150	M48,	48	.010	C6	190	250	.010
	.025	T15	54	.005	C7	225	280	.005

Contact a Carpenter representative for alloy availability.

*Registered trademark of AK Steel Corp.

Precipitation Hardening Alloys
Turning—Cut-Off and Form Tools

Alloy	Tool Material: Micro-Melt® Powder HS Tools	Tool Material: Carbide Tools	Speed (fpm)	Feed (ipr) Cut-Off and Form Tool Width (inches): 1/16	1/8	1/4	1/2	1	1½	2
				Solution Treated						
17Cr-4Ni	M48, T15		60	.0012	.0015	.002	.002	.0016	.0013	.0011
		C6	205	.0012	.0015	.002	.002	.0016	.0013	.0011
				Double Aged H 1150-M						
	M48, T15		70	.0012	.0015	.002	.002	.0016	.0013	.0011
		C6	205	.0012	.0015	.002	.002	.0016	.0013	.0011
				Aged H 1075 - H 1100 - H 1150						
	M48, T15		65	.0012	.0015	.002	.002	.0016	.0013	.0011
		C6	200	.0012	.0015	.002	.002	.0016	.0013	.0011
				Aged H 1025						
	M48, T15		34	.0012	.0015	.002	.002	.0016	.0013	.0011
		C6	110	.0012	.0015	.002	.002	.0016	.0013	.0011
				Aged H 900 - H 925						
	M48, T15		25	.0012	.0015	.002	.002	.0016	.0013	.0011
		C6	95	.0012	.0015	.002	.002	.0016	.0013	.0011
				Solution Treated						
Project 70+® Custom 630	M48, T15		75	.001	.0015	.002	.0015	.001	.001	.0005
		C6	225	.003	.003	.004	.003	.002	.002	.002
				Double Aged H 1150-M						
	M48, T15		100	.0015	.002	.0025	.002	.0015	.001	.001
		C6	250	.003	.003	.0045	.003	.002	.002	.002
				Aged H 1075 - H 1100 - H 1150						
	M48, T15		85	.001	.0015	.002	.0015	.001	.001	.0005
		C6	225	.003	.003	.0045	.003	.002	.002	.002
				Aged H 1025						
	M48, T15		45	.001	.001	.0015	.0015	.001	.001	.0005
		C6	150	.003	.003	.0045	.003	.002	.002	.002
				Aged H 900 - H 925						
	M48, T15		35	.001	.001	.0015	.0015	.001	.001	.0005
		C6	125	.0025	.0025	.004	.0025	.0015	.0015	.0015
				Solution Treated						
Custom 450®	M48, T15		84	.001	.0015	.002	.0015	.001	.001	.0005
		C6	240	.003	.0045	.006	.003	.0025	.0025	.0015
				Annealed						
Custom 465® Custom 455® PH 13-8 Mo* 15Cr-5Ni	M48, T15		72	.001	.0015	.002	.0015	.001	.0007	.0005
		C6	216	.003	.005	.007	.005	.004	.0035	.0035
				Aged						
	M48, T15		36	.001	.001	.0015	.0015	.001	.0005	.0005
		C6	132	.003	.003	.0045	.003	.002	.002	.002
				Solution Treated						
Project 70+® 15Cr-5Ni	M48, T15		96	.0017	.0020	.0025	.0028	.0022	.0019	.0017
		C6	312	.0021	.0024	.0029	.0032	.0024	.0021	.0019
				Aged						
	M48, T15		84	.0014	.0017	.0022	.0025	.0019	.0016	.0014
		C2	288	.0016	.0019	.0024	.0027	.0020	.0017	.0015
				Aged—Rc 38-40						
Pyromet® 350 & 355	M48, T15		54	.001	.001	.0015	.0015	.001	.001	.0005
		C6	210	.0025	.0025	.003	.003	.0025	.0025	.0015
				Equalized & Overtempered						
	M48, T15		48	.001	.001	.0015	.0015	.001	.0005	.0005
		C6	204	.0025	.003	.004	.003	.002	.002	.002
				Aged—Over Rc 40						
	M48, T15		30	.001	.001	.0015	.0015	.001	.0005	.0005
		C6	132	.0025	.0025	.0035	.0025	.0015	.0015	.0015

Contact a Carpenter representative for alloy availability.
*Registered trademark of AK Steel Corp.

Cut-off Tools

Either blade-type or circular cut-off tools are used for stainless steel applications. Blade-type tools usually have sufficient bevel for side clearance, i.e., 3° minimum, but may need greater clearance for deep cuts. In addition, they should be ground to provide for top rake and front clearance. The front clearance angle is 7 to 10°; a similar angle is used for top rake, or a radius or shallow concavity may be ground instead. The end cutting edge angle may range from 5° or less to 15°, with the angle decreasing for larger-diameter material.

Carbide-tipped cut-off tools may be used. However, shock loading from interrupted cuts must be taken into consideration when selecting the carbide.

Form Tools

Form tools are usually dovetail, circular, or insert. The speeds and feeds for form tools are influenced by the width of the tool in relation to the diameter of the bar, the amount of overhang and the contour or shape of the tool. Generally, the width of the form tool should not exceed 1-1/2 times the diameter of the workpiece; otherwise, chatter may be a problem.

Dovetail form tools should be designed with a front clearance angle of 7 to 10°, and be ground with a top rake angle of 5 to 20°. Angles for circular form tools are similar, as shown in Figure 3. Higher rake angles within the 5 to 20° range may be used for roughing operations and lower rake angles for finishing. The design of the tool should incorporate sufficient side clearance or relief angles, typically 1 to 5° depending on depth of cut, to prevent rubbing and localized heat build-up, particularly during rough forming. It may also be necessary to round corners. A finish form or shave tool may be necessary to obtain the final shape, especially for deep or intricate cuts.

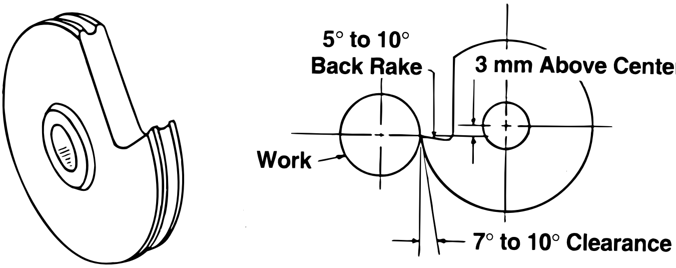
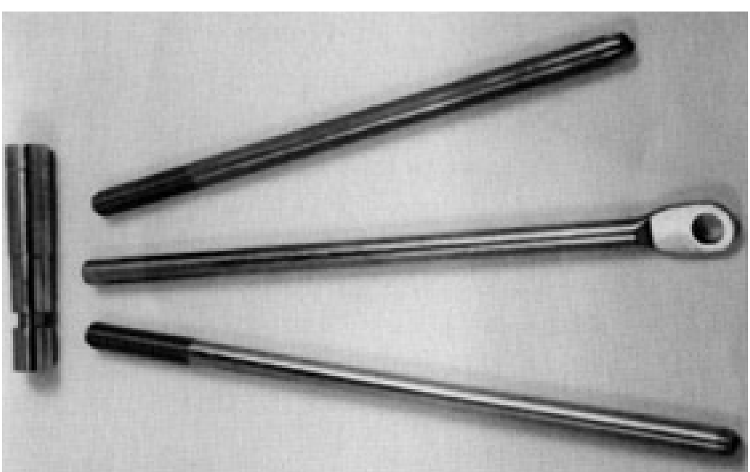


Fig. 3. Suggested geometries for circular form tools used on stainless steels.

Carbide-tipped or carbide-insert tooling may be used for forming operations. However, as with cut-off tools, shock loading from interrupted cuts must be taken into consideration.

Shaving Tools

A shaving tool may be used to obtain optimum machined surface finish or close tolerances on formed parts. Shaving tools remove metal with a tangential rather than a radial cut, with the workpiece supported by integral rollers. Usually a thin layer of metal (approximately .004–.008 in. or .1–.2 mm) is removed at relatively high speeds. The tool must have a very smooth finish on the cutting edge since the finish of the tool will influence the finish of the part. A clearance angle of about 10° is normally needed.



Cable ends and conduit cap that were machined from Carpenter's premium stainless Types 303 and 304.

Trouble-Shooting Check Chart

PROBLEM:	POSSIBLE SOLUTIONS:
Tool heats badly.	● Is tool heavy enough? Does it have enough mass to carry off generated heat? ● Check cutting fluid as it might be too rich in sulphur base oil and should be cut back with a coolant such as paraffin base oil.
Cutting edge breaks off.	● Tool ground with too coarse a grinding wheel. ● Not enough mechanical support due to grinding large concavity in front clearance. Use straight angular grind with minimum clearance, usually between 7° and 10°.
Chips pile on top of tool.	● Top rake angle not steep enough. Should be 5° to 20° angle. ● Also indicates need of "chip curler." If curler is used, it is not deep and wide enough. ● Stoning top rake to a fine smoothness helps chips slide off. ● Tool set too low.
Work cuts with taper.	● Rough turn to .003/.005" over finished size and shave, using light cut at a fast speed. ● Check cutting fluid to be sure mixture has enough paraffin oil to serve as coolant for dissipating heat.
Poor or rough finish.	● Check cutting tool. If ground on coarse grit wheel and not stoned, this is natural result. ● Cut may be too heavy. ● Stock may be too soft, and is "picking up."
Cannot hold close tolerance.	● Close tolerances are not readily obtainable on heavy cuts. Machine to .003/.005" over finished size and tolerance required and then take a shave or finishing cut with fairly fast speed. Have cutting fluid on thin side for cooling purposes.
Tool "rides" work.	● Tool not sharp enough. ● Top rake angle not steep enough, causing "bugging." ● Look for "play or looseness" in machine or tool. ● Feed too low.
Work glazes or hardens.	● Tool either dull or riding too far above center of work. ● The use of a solid type steady-rest will glaze or work-harden job—change to roller type steady-rest.
Tools "hog in."	● Rake angles too small. ● Also check side clearance. ● Stock may be extra dead soft. ● Carriage may be loose. ● Cutting edge of tool below center line. See sketch on page 42.
Circular form tools gall and bind on sides.	● Cut too deep for side clearance allowed. Increase angle of side clearance. If this goes beyond allowable limits of finished piece, a shaving operation will have to be added.

PROBLEM:	POSSIBLE SOLUTIONS:
Cannot take finish cut close enough for threading.	● Stock too soft or cut too heavy. Add shaving operation, taking a light fast finishing cut (.002/.008"). Experienced operators are doing this and eliminating grinding before thread cutting for Class 3 fits.
Tools burn.	● Cutting fluid may be too thin. Add more sulphur base oil. ● Spindle speed too high. Check with tables on pages 37 and 38. ● Material too hard for type of turning tool being used.
Excessive tool wear.	● Generally an indication of too rich a mixture of sulphur base oil. Add paraffin oil until excessive wear is reduced.
Tools won't hold edge.	● See No. 5 on page 33 for information on grinding and stoning of cutting edge. Following these suggestions has generally increased tool life from 10 to 60%. Several cases reported higher than this.
Tool cuts undersize after grinding.	● Look for a "bug" on cutting edge. Sometimes a small one remains after grinding. This starts building up metal right away, resulting in undersized cut. Stoning after grinding will eliminate this. ● Mechanical adjustment of machine may be required.
Chatter marks.	● Tool is not being held tight in fixture, causing vibration. ● Tool is not properly set with center line of work. ● Excessive clearance angles tend to cause chatter. ● Too heavy a cut or too light a machine. ● A roller steady-rest will help to prevent chattering. ● Check for looseness in tool holder. Tool may have too much overhang. ● Tool too wide.
Tool heats excessively and finish is rough.	● Not enough clearance angle. Tool rubbing against work, creating friction heat. This requires more pressure to feed tool and the rubbing causes poor finish. ● Dull tool.
Double chips.	● This occurs when tool has chip groove which is carried through the front of tool or cutter. This can be overcome by proper regrinding.

DRILLING

General Guidelines

In any drilling operation, the following factors are important:

1. Work must be kept clean and chips removed frequently, since dirt and chips act as an abrasive to dull the drill.

2. Drills must be carefully selected and correctly ground.

3. Drills must be properly aligned and the work firmly supported.

4. A stream of cutting fluid must be properly directed at the hole.

5. Drills should be chucked for shortest drilling length to avoid whipping or flexing, which may break drills or cause inaccurate work.

6. Drill coatings, such as TiN, TiAlN, & TiCN, should extend the wear resistance.

When working with stainless steels, particularly the austenitic alloys, it is advisable to use a sharp three-cornered punch rather than prick punch to avoid work hardening the material at the mark. Drilling templates or guides may also be useful.

To relieve chip packing and congestion, drills must occasionally be backed out. The general rule for HSS drills is to drill to a depth of three to four times the diameter of the drill for the first bite, one or two diameters for the second bite and around one diameter for each of the subsequent bites. This is not a good technique for carbide drills. Carbide drills have a tendency to break on a peck operation. A groove ground parallel to the cutting edge in the flute for chip clearance will allow deeper holes to be drilled per bite, particularly with larger-size drills. The groove breaks up the chip for easier removal.

Drills should not be allowed to dwell during cutting, particularly with austenitic stainless steels. Allowing the drill to dwell or ride glazes the bottom of the hole, making restarting difficult. Therefore, when relieving chip congestion, drills must be backed out quickly and reinserted at full speed to avoid glazing.

Drills with a non-cutting land at the point should be avoided. This non-cutting land only pushes material away from the center and will work harden the material. This action can cause hard spots in the center of the material and lead to premature drill failure. Use a split point or a manufacturer's variation of a split point to maintain a cutting action.

Drilling Parameters

Drill feed is an important factor in determining the rate of production. Because proper feed increases drill life and production between grinds, it should be carefully selected for each job. The drilling tables on pages 48 and 49 list feeds and speeds for various size drills.

Grinding of Drills

It is especially important to grind drills correctly. Figure 4 shows suggested geometries for high-speed steel drills to be used with stainless steels. The point angle should be 130° to 140°, although a smaller angle may be used for easier-to-machine alloys. A larger angle produces a more easily removed chip when drilling hard or tough alloys. This wider angle also promotes a straighter hole. The use of a split point drill tip reduces the amount of cold work in the material at the point, thus extending drill life. The lip clearance should be between 9° and 15°, and the two cutting edges must be equal in length and angle. The web thickness at the point should be about 12.5% of the drill diameter, or less. A thinner web reduces feed pressure, heat generation, and glazing or work-hardening of the bottom of the hole. Grinding fixtures should be used when regrinding drills. For best results in grinding high-speed steel drills, medium-grain, soft-grade dry wheels should be used. Blueing or burning is to be avoided, as is quenching. Quenching will often check or crack the drill if it has been overheated.

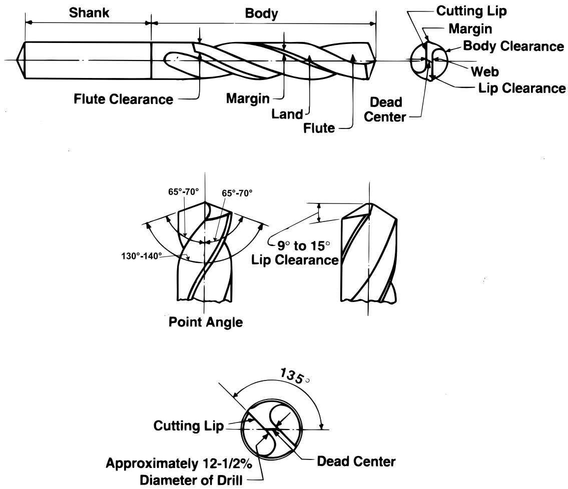


Fig. 4. Suggested geometries for drills used on stainless steels.

Small-Diameter Drills

Procedures used with large or normal-size drills will not always prove successful for small-diameter drills, i.e., 0.070 in. (1.8 mm) and under. These very small drills are subject to deflection, both torsional and longitudinal, due to their length in relation to their diameter. In addition, the web on small drills is proportionally heavier than on large drills. This thicker web adds strength needed for the required work pressure, but decreases chip clearance. Therefore, the depth of each bite may have to be reduced. All small-diameter drilling is actually deep-hole drilling; therefore, careful resharpening, frequent and adequate chip removal and feeds and speeds properly adjusted to the strength and load-carrying capacity of the drill are very important. Good small-hole drilling is dependent on feeds that produce chips instead of "powder."

Stainless Steels
Drilling

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Alloy (Annealed Condition)	High Speed Tools	Speed (fpm)	Feed (inches per revolution)							
			Nominal Hole Diameter (inches)							
			1/16	1/8	1/4	1/2	3/4	1	1½	2
410	M42	60-70	.001	.003	.006	.010	.013	.016	.021	.025
	C2 Coated	205	.0005	.001	.006	.0085	.0111	.0128	.0158	.0158
416	M42	95-110	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	275	.001	.003	.006	.0085	.0119	.0136	.0158	.0158
No. 5 BQ	M42	95-110	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	240	.001	.003	.006	.0085	.0119	.0136	.0158	.0158
Project 70+® 416	M42	120-144	.0014	.0042	.0066	.012	.0155	.019	.024	.028
	C2 Coated	290	.001	.003	.006	.0085	.0119	.0136	.0158	.0158
No. 5-F	M42	110-140	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	295	.001	.003	.006	.0085	.0119	.0136	.0158	.0158
420	M42	55-65	.001	.003	.006	.010	.013	.016	.021	.025
	C2 Coated	205	.0005	.003	.006	.0085	.0111	.0128	.0158	.0158
420F	M42	65-75	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	280	.0005	.003	.006	.0085	.0119	.0136	.0158	.0158
431	M42	50-60	.001	.003	.005	.007	.010	.012	.015	.018
	C2 Coated	150	.001	.003	.005	.006	.0085	.0096	.0113	.0113
440A/440B	M42	45-55	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	140	.0005	.002	.004	.006	.0077	.0088	.0098	.0098
440C	M42	40-50	.001	.003	.005	.007	.009	.011	.014	.018
	C2 Coated	135	.0005	.002	.004	.006	.0077	.0088	.0098	.0098
430	M42	60-70	.001	.002	.004	.007	.010	.012	.015	.018
	C2 Coated	160	.001	.002	.004	.006	.0085	.0096	.0113	.0113
430F/430FR	M42	100-150	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	310	.001	.003	.006	.0085	.0119	.0136	.0158	.0158
443	M42	50-65	.001	.002	.004	.007	.010	.012	.015	.018
	C2 Coated	150	.001	.003	.005	.006	.0085	.0096	.0113	.0113
302/304/316	M42	50-60	.001	.002	.004	.007	.010	.012	.015	.018
	C2 Coated	140	.0005	.002	.004	.006	.0085	.0096	.0113	.0113
Project 70+® 304/316	M42	78-98	.0012	.0024	.0048	.0084	.012	.0204	.0252	.030
Project 70+ 304L/316L	C2 Coated	180	.0005	.002	.004	.006	.0085	.0096	.0113	.0113
302HQ-FM®	M42	70-90	.001	.003	.006	.010	.014	.012	.015	.018
	C2 Coated	200	.0005	.002	.004	.006	.0085	.0096	.0113	.0113
303	M42	120	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	240	.0008	.003	.006	.0085	.0119	.0136	.0158	.0158
Project 70+® 303	M42	91-130	.0012	.0036	.0072	.012	.0168	.0204	.0252	.030
	C2 Coated	240	.001	.003	.006	.0085	.0119	.0136	.0158	.0158
303Al Modified®	M42	65-90	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	200	.001	.003	.006	.0085	.0119	.0136	.0158	.0158
203	M42	120	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	240	.0008	.003	.006	.0085	.0119	.0136	.0158	.0158
321/347	M42	50-60	.001	.002	.004	.007	.010	.012	.015	.018
	C2 Coated	130	.001	.002	.004	.006	.0085	.0096	.0113	.0113
20Cb-3® Stainless	M42	45-55	.001	.003	.006	.010	.014	.017	.021	.025
	C2 Coated	140	.0005	.002	.004	.006	.0077	.0088	.0098	.0098
18Cr-2Ni-12Mn	M42	45-55	.001	.002	.004	.007	.010	.012	.015	.018
	C2 Coated	140	.0005	.002	.004	.006	.0077	.0088	.0098	.0098
21Cr-6Ni-9Mn	M42	50-60	.001	.002	.004	.007	.010	.012	.015	.018
	C2 Coated	155	.0005	.002	.004	.006	.0077	.0088	.0098	.0098
22Cr-13Ni-5Mn	M42	45-50	.001	.002	.004	.007	.010	.012	.015	.018
	C2 Coated	150	.0005	.002	.004	.006	.0077	.0088	.0098	.0098

Contact a Carpenter representative for alloy availability.

Precipitation Hardening Alloys Drilling

Alloy	High Speed Tools		Feed (inches per revolution) Nominal Hole Diameter (inches) 1/8	1/16	1/4	1/2	3/4	1	1½	2
			Solution Treated							
17Cr-4Ni	M42	50	.001	.002	.004	.007	.008	.010	.012	.015
			Double Aged—H 1150M							
	M42	50	.001	.002	.004	.007	.008	.010	.012	.015
			Aged—H 1075 - H 1100 - H 1150							
	M42	45	.001	.002	.004	.007	.008	.010	.012	.015
			Aged—H 1025							
	M42	40	.001	.002	.004	.007	.008	.010	.012	.015
			Aged—H 900 - H 925							
	M42	20	.001	.002	.004	.007	.008	.010	.012	.015
			Solution Treated							
Project 70+® Custom 630	M42	55	.001	.002	.004	.007	.008	.010	.012	.015
			Double Aged—H 1150M							
	M42	65	.001	.002	.004	.007	.009	.011	.013	.016
			Aged—H 1075 - H 1100 - H 1150							
	M42	50	—	.002	.004	.007	.008	.010	.012	.015
			Aged—H 1025							
	M42	40	—	.002	.004	.006	.008	.009	.011	.012
			Aged—H 900 - H 925							
	M42	30	—	.001	.002	.003	.004	.004	.004	.004
			Solution Treated							
Custom 450®	M42	50	.001	.002	.004	.007	.008	.010	.012	.015
			Aged—1100 - 1150							
	M42	45	.001	.002	.004	.007	.008	.010	.012	.015
			Aged—1000 - 1050							
	M42	35	—	.002	.004	.007	.008	.010	.012	.015
			Aged—900 - 950							
	M42	25	—	.001	.002	.003	.004	.004	.004	.004
			Annealed							
Custom 465® Custom 455® PH 13-8 Mo* 15Cr-5Ni	M42	50	.001	.002	.004	.007	.008	.010	.012	.015
			Aged							
	M42	35	—	.001	.002	.003	.004	.004	.004	.004
			Solution Treated							
Project 70+® 15Cr-5Ni	M42	70	.0014	.0024	.0044	.0074	.0084	.0104	.0124	.0154
			Aged							
	M42	60	—	.0022	.0042	.0072	.0082	.0102	.0122	.0152
			Equalized & Overtempered							
Pyromet® 350 & 355	M42	50	.001	.002	.004	.007	.008	.010	.012	.015
			Aged—Rc 38 - 40							
	M42	35	—	.002	.004	.006	.008	.009	.011	.012
			Aged—Over Rc 40							
	M42	20	—	.001	2	3	.004	.004	.004	.004

Contact a Carpenter representative for alloy availability.
*Registered trademark of AK Steel Corp.

Special Drills

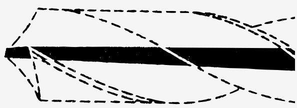
As noted previously, drills should be chucked for shortest drilling length. However, some jobs require exceptionally deep drilled holes, where the depth of the hole is eight to ten times the diameter. Therefore, short chucking is impossible. In such cases, special drills known as crankshaft hole drills may be useful. These drills were originally designed to drill oil holes in forged crankshafts and connecting rods, but have found widespread use in drilling deep holes. They are made with a very heavy web and a higher spiral or helix angle to aid in chip removal. They usually have a notched point-type of web thinning which is done on a sharp-cornered hard grinding wheel.

A cotter pin drill should be used to drill small cross holes in the heads of bolts, screws, pins, etc. Like a crankshaft hole drill, it is a more heavily constructed drill which withstands abnormal strains and has a faster or higher helix angle to aid in chip removal.

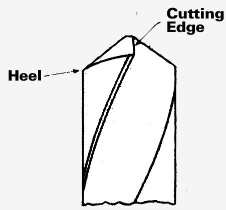
In addition to deep hole gun drilling, these thermometer thermocouple wells were turned, threaded, tapped, reamed and milled for use in the chemical and petroleum industries.

Trouble-Shooting Check Chart

Free-hand and poor grinding cause 90% of all drill troubles. Good grinding fixtures, wheels and careful grinding

PROBLEM:	POSSIBLE SOLUTIONS:
Wear at point.	● Increase point angle.
Broken drills.	● Chuck drills as short as possible to stop flexing or weaving. ● Dull drills break. ● Not enough lip clearance. ● Check speed of drill. Too slow or too fast will break them. See table on pages 48 and 49. ● Check clamp and drill fixture for rigidity, tightness and backlash. ● Be sure chips are not packing.
Splitting up the center.	● Drills without sufficient lip clearance do not have enough cutting edge—so feed pressure builds up and splits drill up the center. If lip clearance is correct, reduce the feed.
Drilling requires abnormal feed pressure.	 ● The center web increases in thickness toward the shank. As drills become shorted from use or repeated regrinding, the web becomes wider and must be thinned. By point-thinning back to 1/8 (or 12½%) of drill diameter, this trouble is eliminated. Point-thinning must be done equally on both sides of the web or web will be off center and drill oversized holes. Don't thin back too far as this weakens the point. ● To avoid the problem of web-thinning, several manufacturers supply drills with a parallel web.
Drills breaking on "through" holes.	● Check drill press and fixtures for rigidity. "Backlash" or "spring" in press or work usually the cause. ● Job may require backing plate.
Drills will not enter work.	● If web is too wide, it will glaze work. Drills are designed to have a web thickness to 12½% (1/8) of their diameter.
Poor cutting results on certain materials.	● For stainless steel, the suggested point is 140° included angle. Therefore, first check point angle. The hardness or softness of material determines angle. As an example, drill manufacturers recommend a 150° point included angle for high manganese steels and a 118° included angle for SAE 1020. Larger point angles produce a thinner chip which is removed more easily.

Trouble-Shooting Check Chart

PROBLEM:	POSSIBLE SOLUTIONS:
Drill wears undersize quickly.	● Check volume of cutting fluid. Is it flooding drill? This condition is either pool lubrication or cutting fluid is too rich in sulphurized base oil and should be cut back with suitable blending oil. ● Undersized drill jig bushing will wear drill.
Poor cutting with a sharp drill.	● Not enough clearance back of the cutting edge.  Drill Ground with Proper Clearance. Note: Heel is Lower Than Cutting Edge
Chipping of "margin."	● Check drill jig bushing for size; usually an oversized drill jig bushing causes chipping.
Breakage of drill tang.	● Generally this trouble comes from worn chuck, or nicks on tang, as well as burrs or dirt. Check these items and be sure shank fits into sleeve or taper snugly. Sleeves may be in poor condition.
Drill "digs in."	● Check bearings and spindles of drill press. Sloppy fits are generators of this trouble. This trouble prevails mostly on small drills, so if press is all right, try grinding a secondary angle of 7° to 9°, which will back up the cutting edge and stop hogging or "digging in."
Rough surface in finished hole.	● Several factors lead to this condition, any one of which can be the cause. Generally it is due to too fast a feed. Try a higher speed and slower feed. ● If this does not correct the trouble, check the drill for proper grinding. ● Check cutting fluid for volume. Be sure enough reaches the drill. ● Poor chip elimination may be the cause. ● Check entire setup, including machine.
Drill breakage on outer corners of cutting edges.	● Assuming that cutting fluid is of correct mixture and in sufficient volume, this is then caused by too high a speed. Reduce speed until trouble disappears. ● Flutes clogged with chips.

PROBLEM: | **POSSIBLE SOLUTIONS:**

Drill chipping or breaking down on cutting edges or lips.

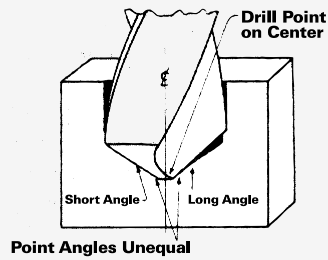
● This can be an indication of too much lip clearance for that particular job. Therefore, check this first. ● The only other cause comes from too much feed, in which case reduce feed until trouble is eliminated.

Change in chip formation while drilling.

● If job has been running satisfactorily, this is an indication the condition of drill has changed. Look for dull or chipped drill.

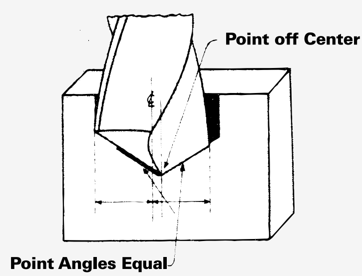
One lip carrrying most of cutting load or drill producing large and small chips.

● Regrind drill to correct the unequal angles of the cutting lips. Both cutting edges must have identically the same angle with center line of drill. The 140° included angle may vary slightly but the variation must be alike on both cut-



Hole drills oversize.

● Check machine spindle for excess wear, and jig bushing for sloppy fit. If these are O.K., the trouble lies in the drill. ● Check lip length of drill. Oversize holes are caused if the lips are not equal in length. This condition throws the point “off center.” Watch the drill and it will operate like a wheel with the hub off center. This also causes press strains and noticeable spindle wobble.



Drill squeak. Drill groaning.

● Friction causes squeaking, usually due to the hole being crooked; drill dull and not cutting; or insufficient lubrication.
● Overloading causes groaning, usually due to overfeeding; poor chip clearance, allowing chips to get under cutting edge. Also land on the flutes toward the cutting edge may be worn and tapered.

TAPPING

Types of Holes and Taps

The initial hole bears an important role in securing a finished tapped hole of the desired quality. The tap is simply a cutting tool and is not intended for correcting a small or poorly drilled hole. Holes having a work-hardened surface due to improper drilling or reaming technique will also cause problems during tapping.

Basically there are two types of holes prepared for tapping: the open or through hole and the blind hole. For open or through holes, taps of either the spiral-fluted or the straight-flute spiral-pointed type can be used, as shown in Figure 5. They are particularly desirable when tapping the softer and non-free-machining alloys because they provide adequate chip relief. The spiral-pointed tap cuts with a shearing motion. It has the least amount of resistance to the thrust, and the entering angle deflects the chips so that they curl out ahead of the tap. This prevents packing in the flutes, a frequent cause of tap breakage. When backing out a spiral-pointed tap, there is less danger of roughing the threads in the tapped part. The spiral-pointed tap should not be used in blind or closed holes unless there is sufficient untapped depth to accommodate the chips. To tap blind holes, special spiral-pointed bottoming taps are available. However, spiral-fluted taps with a spiral of the same hand as the thread are suggested, since they are designed to draw chips out of the hole.

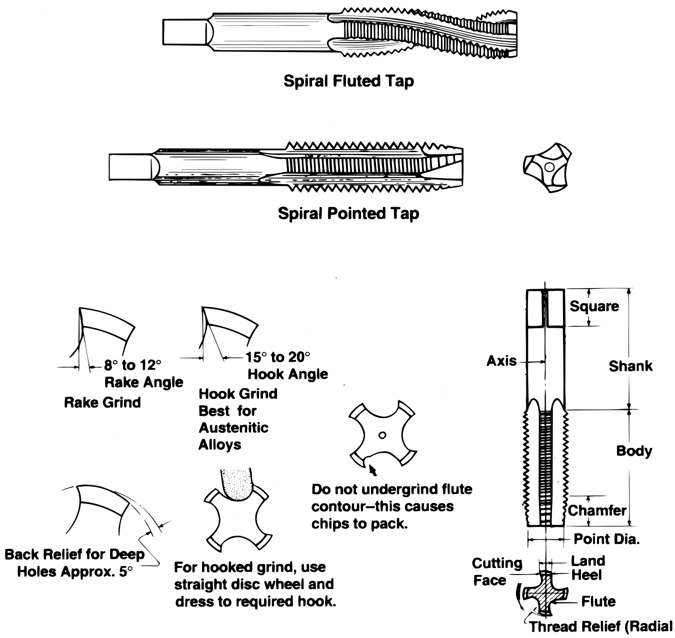


Fig. 5. Typical taps used for stainless steels, with suggested geometries and grinding techniques.

The “class of fit” required for the threads will also be a factor in tap selection. The following three classes are standard:

Class 1 - Loose fit largest tolerance range

Class 2 - General purpose fit moderate tolerance range

Class 3 - High-accuracy fit tight tolerance range

The class of fit determines whether a cut thread tap, ground thread tap or a precision ground thread tap is necessary. A cut thread tap is used for Class 1 fits; ground thread taps are used for Class 2 fits; and precision ground thread taps are used for Class 3 fits.

Chip removal is also important for close tolerance tapping. When the wrong tap is selected, chips crowd into the flutes; therefore, the flutes should not be too shallow or the lands too wide. Often the

Stainless Steels
Tapping

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Alloy (Annealed Condition)	High Speed Tools	Speed (fpm)
410	M7, M10	15-40
416	M7, M10	20-45
No. 5 BQ	M7, M10	20-45
Project 70+® 416	M7, M10	25-50
No. 5-F	M7, M10	25-50
420	M7, M10	15-40
420F	M7, M10	20-45
431	M7, M10	12-25
440A/440B	M7, M10	10-20
440C	M7, M10 Nitrided	8-18
440F	M7, M10	15-40
430	M7, M10	15-40
430F/430FR	M7, M10	20-45
443	M7, M10	15-40
302/304/316	M7, M10	12-25
Project 70+® 304/316 **Project 70+ 304L/316L**	M2, M42	19-50
302HQ-FM®	M7, M10	20-45
303	M7, M10	20-35
Project 70+® 303	M2, M42	25-56
303Al Modified®	M7, M10	20-45
203	M7, M10	20-35
321/347	M7, M10	12-25
20Cb-3® Stainless	M7, M10	12-25
18Cr-2Ni-12Mn	M7, M10	12-25
21Cr-6Ni-9Mn	M7, M10	12-25
22Cr-13Ni-5Mn	M7, M10	12-25

Contact a Carpenter representative for alloy availability.

power required to break packed chips is more than that required to cut the thread and can result in the tap breaking.

Consideration must also be given to the number of flutes on the tap. With small holes, a tap with four flutes is more likely to produce chip congestion than one with fewer flutes. Therefore, general practice is to use a tap with fewer flutes as the size of the hole decreases. Specifically, two-fluted taps may be used for holes up to about 0.125 in. (3 mm) in diameter; three-fluted taps for holes between 0.125 in. (3 mm) and 0.500 in. (13 mm); and four-fluted taps for larger holes.

Precipitation Hardening Alloys
Tapping

Alloy	High Speed Tools	Speed (fpm)
	Solution Treated	
17Cr-4Ni	M7, M10	17-28
	Double Aged—H 1150M	
	M7, M10	18-30
	Aged—H 1075 - H 1150	
	M7, M10	13-23
	Aged—H 1025	
	M7, M10	9-18
	Aged—H 900 - H 925	
	M7, M10 Nitrided	5-13
	Solution Treated	
Project 70+® Custom 630	M7, M10	15-28
	Double Aged—H 1150M	
	M7, M10	17-32
	Aged—H 1075 - H 1150	
	M7, M10	15-28
	Aged—H 1025	
	M7, M10	12-22
	Aged—H 900 - H 925	
	M7, M10 Nitrided	7-17
	Solution Treated	
Custom 450®	M7, M10	12-25
	Aged—H 1100 - H 1150	
	M7, M10	15-20
	Aged—H 1000 - H 1050	
	M7, M10	10-20
	Aged—H 900 - H 950	
	M7, M10 Nitrided	5-15
Custom 465® Custom 455 PH 13-8 Mo* 15Cr-5Ni	**Annealed**	
	M7, M10	12-25
	Aged	
	M7, M10 Nitrided	5-15
	Solution Treated	
Project 70+® 15Cr-5Ni	M7, M10	25
	Aged	
	M7, M10	20
	Equalized & Overtempered	
Pyromet® 350 & 355	M7, M10	12-25
	Aged—Rc 38-40	
	M7, M10 Nitrided	10-20
	Aged—Over Rc 40	
	M7, M10 Nitrided	5-15

Contact a Carpenter representative for alloy availability.
*Registered trademark of AK Steel Corp.

Percent of Thread

The percentage of full thread to be cut must be determined initially, since this will determine the size of the drilled hole. The percent of thread should be governed by the diameter and pitch of tap, depth of hole to be tapped, and toughness or hardness of material. With tougher or harder materials, tap life is increased when a lower percentage of thread is cut. Under such conditions it is economical to tap twice – first, roughing out the hole with an undersized tap, and then finishing to size with a second tap.

Normal commercial practice for percent of thread is between 62% and 75%. A 100% thread is only 5% stronger than a 75% thread, but requires three times as much power to tap. A general rule is to use a 100% thread where the depth of tapped hole is one-half or less than the diameter of tap. A 75% thread is used where depth of tapped hole is up to two times the tap diameter. Where depth of tapped hole exceeds twice the diameter of the tap, it is economical to use only 50% thread.

The following two formulas show tap drill size and the percentage of thread a given drill will produce. It is sometimes an advantage to change from standard decimal drill sizes to millimeter sizes. An example is the common No. 8-32 thread size, where as close to a 75% thread as possible is required. The No. 29 (0.1360 in.) drill provides only a 69% thread, while the No. 30 (0.1285 in.) drill (next size) provides an 87% thread. However, a 3.40 millimeter (0.1339 in.) drill results in a 74% thread. See the tables on pages 151-158 for more information.

No. 1–for obtaining tap drill size:

$$\text{Outside Diameter} - \frac{.0130 \times \%\ \text{Full Thread}}{\text{Number of threads per inch}} = \text{Drill Size}$$

Example — for ¼" x 20 thread:

$$.250 - \frac{.0130'' \times 75}{20} = .2013 \text{ or number 7 drill}$$

No. 2–for obtaining percentage of thread a given drill will produce:

$$\frac{(\text{Outside dia.} - \text{drill size}) \times \text{number threads per}}{.0130} = \%\ \text{of full thread}$$

Example — for ¼" x 20 thread:

$$\frac{(.250 - .201) \times 20}{.0130} = 75.4\%\ \text{thread}$$

Grinding of Taps

The geometries shown in Figure 5 on page 56 for high-speed steel taps are for average applications; for some types of tapping, it may be necessary to alter the cutting face design or angle. Occasionally, due to a combination of variables on certain types of work, the hook grind, which normally is best, will not give satisfactory results. In such cases, an interrupted-thread tap with an uneven number of flutes has solved the problem, since it requires 40% to 50% less power than regular taps (particularly where the tapping machine lacks power). The problem of roughness on the back face of the thread can sometimes be overcome by using a negative grind on the heel of the tap. This prevents tearing of the threads when backing out the tap. Roughness may also be caused by insufficient rake (hook) angle.

In some cases, sharpening may mean only regrinding the chamfered portion or point of the tap. While in many cases this is done by hand, it is not recommended, as an uneven grind often results, causing all the teeth on one or two lands to carry the full load. This places an excessive strain on the tap, requiring greater power for operation and contributing to tap breakage. Another problem with unevenly ground taps is their tendency to cut oversize. The following angles are generally used for grinding the chamfer on taps:

Taper chamfer taps	4° to 5° or 8 to 10 threads
Plug chamfer taps	9° to 10° or 3-1/2 to 4-1/2 threads
Bottoming chamfer taps	30° to 35° or 1-1/2 to 2 threads

Trouble-Shooting Check Chart

PROBLEM:	POSSIBLE SOLUTIONS:
Loose fits won't meet tolerance.	● Two factors cause this trouble. First, oversized drill holes. Was drill selected from an old "Standard Table"? These tables have errors, particulary on fine pitches. Check drill size with formulas on page 59 ● Second, are you using a cut thread tap when a ground thread tap is needed? Remember, a cut thread tap seldom is suitable for anything but Class 1 fit. Commercial ground taps cut Class 2 fits. Precision ground taps cut Class 3 fits. Be sure you are using the right type of tap for the job.
Tapped holes not consistently accurate.	● Usually due to tap holder taking slightly different angle each time. If you are using "floating" holder, check how much it wobbles. Often changing to an accurate, rigid holder overcomes this trouble. ● Check flutes; if shallow, chips will pack causing tap to cut oversize. ● Wrong grid on chamfer can also cause inaccurate holes. ● Was hole drilled accurately to size and roundness?
Tap overloading caused by pick-up.	● Loading or pick-up on tap surfaces causes most tap breakage. As soon as this is observed, it should be corrected. To let it go means the pick-up will finally be so great that tap will weld in hole and power of machine will break it. Check lubrication. Other causes of loading are lands too wide, chips packing in flutes, or dull tap.
Roughness in threads.	● If all other factors and variables have been carefully checked, try a back relief grind on the heel of the tap. This overcomes tap tearing threads when backing out. ● Insufficient hook angle can also cause roughness in threads.
Broken teeth.	● Tap may be too hard (over Rockwell C-63) for type of material being cut. Grind broken teeth entirely away and tap will be serviceable.
Loading on stringy soft metals.	● This can usually be overcome by polishing the tap after grinding. The better the tap is polished, the less tendency for loading. ● Are flutes of tap undercut from regrinding? (See sketch on page 56.)
Flutes require regrinding.	● See sketches on page 56 for correct method and grinding wheel shape.
Poor threads and high tap breakage.	● Chamfer must be ground uniformly on all flutes using the proper angle. (See page 60.)

PROBLEM:	POSSIBLE SOLUTIONS:
High power consumption and quick dulling of tap.	● Chamfer ground even but point diameter too small, throwing all the load of cutting on too small a portion of the chamfer. Chamfer must be ground uniformly on all flutes using the proper angle. (See page 59.) ● Check hardness of tap—may not be hard enough (under Rockwell C-59) for type of material being cut.
Tap slows up. More power required.	● Generally an indication of improperly ground or dull tap. ● Check hole diameter. Drills may have worn enough to be cutting undersized. ● Check to see if axis of hole and tap are parallel. ● Check for chips packing in flute. This can develop if flutes are shallow or lands too wide. Chips can be controlled perfectly, and are, in well designed and correctly ground taps. Power required to break chip packing often more than required to tap. On deep holes this will break taps.
Tap cuts when backing out.	● This is usually caused when tap cuts oversized hole, leaving no support to tap when backing out, thereby permitting it to cut. ● A "floating" tap holder or wobbly spindle contribute to this condition. ● Also check back relief. (See sketch on page 56.)
Tap runs hot; dulls too fast.	● This invariably is due to tapping speed being too high. Check the chart shown on pages 57 and 58.
Tap drags badly.	● Usually a sign of tapping speed being too low. Check charts on pages 57 and 58.
Cutting fluids.	● General information is on page 110. As added precaution for tapping, check to make sure cutting fluid is flooding the tap constantly while it is in the hole. Be sure pressure of cutting fluid is strong enough to wash chips away. ● Generally, tapping speeds are not fast enough to heat the tap. Therefore, coolants are not necessary. It is more important to use a good cutting fluid that will prevent wear and friction on the tap. It also reduces power required to cut.
Threads swell.	● Use the next size larger tap drill.

THREADING

Die Threading

Types of Chasers and Geometries

Thread chasers for self-opening die heads are made of high-speed steel. The standard commercial chasers generally have a satisfactory life when they are kept sharp and correctly ground for the materials cut.

Figure 6 shows suggested geometries for the four main types of thread-cutting tools. The most generally used chaser for close-tolerance threads is the tangent-type. It is particularly adaptable for heavy-duty jobs, such as producing long, coarse threads. The tangent-type chaser maintains thread size better on heavy-duty work and provides good life between grinds. Whenever possible a 20° throat angle should be used. However, where the threads do not run into a shoulder, a 15° throat is desirable.

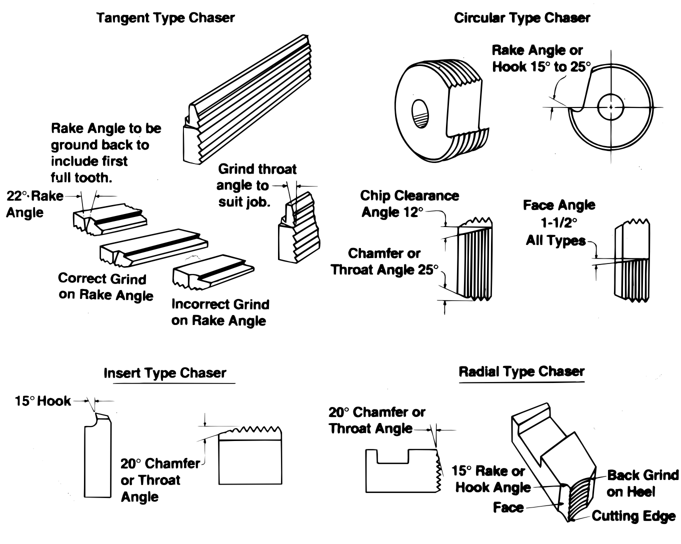


Fig. 6. Typical thread chasers used for stainless steels, with suggested geometries.

The circular-type is considered to be the universal thread chaser, as it is adaptable to all types of threads and will work equally well on tubing. This type of chaser should generally have a 25° throat angle.

The insert type of chaser is widely used. It produces good threads on non-free-machining alloys at a low cost. A 20° throat angle is usually suitable for this type of chaser.

The radial-type of chaser will produce very smooth threads, since it is ground to follow the shape or contour of the threaded piece. On screw machine jobs, where extremely fine threads are required for stainless steel parts, this type of chaser has been used successfully. Radial chasers typically have a 20° throat angle.

The throat angle or chamfer will vary slightly from the typical figure given for each of the chasers described, according to the type of thread being cut and the grade of stainless steel machined. In general, it is advisable to use a 1-1/2 to 3 thread chamfer or lead on the throat. This will usually produce a smooth thread with a fine finish and increase chaser life between grinds. The advantage of using a long throat angle is that each tooth makes a smaller cut and, consequently, produces cleaner threads. As an example, in one particular case a 45° throat angle produced a chip approximately 0.018 in. (0.46 mm) thick, while a 15° throat angle produced a chip only 0.0065 in. (0.17 mm) thick.

When threading close to a shoulder where a long throat angle cannot be used, it may be necessary to grind only a 1/2 or 1 thread chamfer on the chaser. If this short throat angle produces a rough thread, a smooth finish can be obtained by running the chaser over the workpiece a second time, or the thread can be cut in two operations by first taking a rough cut and then finishing with a second cut.

Stainless Steels
Threading, Die

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Alloy (Annealed Condition)	High Speed Tools				
	Tool Material	Speed (fpm)			
		7 or less, tpi	8 to 15, tpi	16 to 24, tpi	25 and up, tpi
410	M7, M10	5-15	10-25	20-35	25-40
416	M7, M10	10-20	15-30	25-40	35-45
No. 5 BQ	M7, M10	10-20	15-30	25-40	35-45
Project 70+® 416	M7, M10	15-25	25-35	35-45	40-50
No. 5-F	M7, M10	15-28	25-38	35-48	40-53
420	M7, M10	5-15	10-25	20-35	25-40
420F	M7, M10	10-20	20-30	30-40	40-50
431	M7, M10	5-15	10-20	20-30	25-35
440A/440B	T15, M42	5-12	8-15	10-20	15-25
440C	T15, M42	5-12	8-15	10-20	15-25
440F	T15, M42	8-15	10-20	15-25	25-30
430	M7, M10	15-20	20-30	35-45	40-50
430F/430FR	M7, M10	15-25	30-40	40-50	50-60
443	M7, M10	5-15	10-20	15-25	20-30
302/304/316	M7, M10	8-15	10-20	15-25	25-30
Project 70+® 304/316 **Project 70+® 304L/316L**	M42	11-13	16-29	26-39	39-46
302HQ-FM®	M7, M10	8-15	13-24	22-32	32-38
303	M7, M10	8-13	14-24	23-30	30-40
Project 70+® 303	M42	13-20	20-33	33-46	46-52
303Al Modified®	M7, M10	8-15	13-24	22-32	32-38
203	M7, M10	8-13	14-24	23-30	30-40
321/347	M7, M10	8-15	10-20	15-25	25-30
20Cb-3® Stainless	T15, M42	4-8	6-10	8-12	10-15
18Cr-2Ni-12Mn	T15, M42	4-8	6-10	8-12	10-15
21Cr-6Ni-9Mn	T15, M42	4-8	6-10	8-12	10-15
22Cr-13Ni-5Mn	T15, M42	4-8	6-10	8-12	10-15

Contact a Carpenter representative for alloy availability.

Die-Threading Parameters and Cutting Fluid

Suggestions for cutting threads are found in the threading tables on this and the following page. Regardless of the type of chaser being used, speeds will vary somewhat with the type of thread being cut. Acme threads are usually cut at somewhat slower speeds. Where extremely fine threads are required, it might be desirable to decrease speeds to 5 to 15 ft/min. (1.5 to 4.5 m/min.).

Precipitation Hardening Alloys
Threading, Die

Alloy	Tool Material	High Speed Tools			
		Speed (fpm)			
		7 or less, tpi	**8 to 15, tpi**	**16 to 24, tpi**	**25 and up, tpi**
Project 70+® Custom 630		**Solution Treated**			
	M2, M7, M10	7-13	10-18	12-25	18-30
		Aged			
	T15, M42	5-10	8-12	10-15	12-18
17Cr-4Ni Custom 450® Custom 465® Custom 455® PH 13-8 Mo* 15Cr-5Ni Pyromet® 350 & 355		**Solution Treated**			
	M2, M7, M10	5-12	8-15	10-22	15-27
		Aged			
	T15, M42	4-8	6-10	8-12	10-15
Project 70+® 15Cr-5Ni		**Solution Treated**			
	M2, M7	5-12	8-15	10-20	25-30
		Aged			
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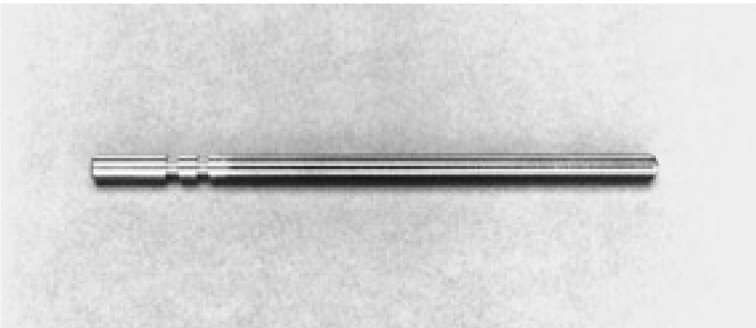
Contact a Carpenter representative for alloy availability.
*Registered trademark of AK Steel Corp.

Percent of Thread

As with tapping, the percent of thread being cut has an effect on production rate and cost. Cutting threads with the maximum major diameter and/or minimum pitch diameter allowed for the class thread involved means more metal must be removed. This decreases tool life and does not necessarily produce a stronger thread. The blank should be turned to leave the minimum allowable stock.

Thread Rolling

Thread rolling can be done on automatic screw machines and turret lathes. However, the equipment must have sufficient power and rigidity for stainless steels. As discussed previously, stainless steels have high strength and work-hardening rates; therefore, substantial pressure is required to form the threads. These characteristics of stainless steels may also limit the amount of thread that can be formed. In addition, care must be taken to avoid work-hardening the surface prior to thread rolling. Despite these cautions, however, thread rolling offers certain advantages. The threads produced are stronger and tougher than cut threads and can be more accurate in size. Generally, the non-free-machining alloys will produce smoother and cleaner threads than the free-machining alloys.



Carpenter's premium machining stainless has improved thread rolling operations through increased dimensional accuracy and reduced hard spots.

One of the many advantages of the austenitic Project 70+® grades, Type 303, Type 304, and Type 316, is the reduced work hardening rate. This has reduced the effort to form threads and has increased thread rolling life.

Trouble-Shooting Check Chart

- Sharp chasers cut better threads. Don't run your chaser too long. It costs less to grind them more often.

- A die head clogged with chips or having weak springs will result in pool threads and possible breakage of chasers.

- You will avoid trouble if the throat angles in the set are ground exactly alike. Chasers with short chamfer or throat angles tend to chip or break. Short chamfers require slower cutting speeds and the chasers will have shorter life between grinds.

- When sharpening chasers you will prevent burning by taking light cuts with a soft wheel. Grinding too slow with heavy cuts, or a hard wheel, will burn the chaser and cause grinding checks.

- A bad start of the die head on the work is most likely the reason for getting a thin first thread, If you want all your threads to be good, check the work and threading spindle for proper alignment and be sure they are O.K. Bad alignment will bring on trouble.

- Where possible, chamfer or bevel the work so all chasers will start cutting at the same time. Die head and work must line up properly to avoid eccentric threads. A good bevel on the work is important in getting concentric threads.

- Rough threads often result when cutting at too high a speed; cutting fluid is not properly blended—or dirty oil loaded with fine chips that act as an abrasive. On circular chasers, rough threads can also result from too much face angle—it is best to hold to an angle of 1½°.

- If there is not enough hook angle on the face of the chaser, the top of the threads will be rough.

- If threads are oversize, it may be caused by excess pressure on the thread rolls or soft stock. In either case the pressure should be reduced. If the blank is too large, this, too will cause oversize threads and can be adjusted by using the correct blank.

- Undersize threads generally require increased pressure due to hard stock or insufficient pressure on the thread rolls. In the case of hard stock, it may be necessary to try a softer stock. Undersize threads can also result from the blank being too small.

- Poor threads can generally be corrected by checking the blank size, adjusting for even pressure on twin thread rolls, or replacing a work thread roll.

MILLING

Types of Milling Cutters

Various high-speed steel cutters are shown in Figure 7. Tooling with carbide inserts may also be used, particularly for alloys which are more difficult to machine. As a general rule, smoothest finishes are obtained with helical or spiral cutters running at high speed, particularly for cuts over 0.75 in. (19 mm) wide. Helical cutters cut with a shearing action and, as a result, cut more freely and with less chatter than straight-tooth cutters. Coarse-tooth or heavy-duty cutters work under less stress and permit higher speeds than fine-tooth or light-duty cutters. They also have more space between the teeth to aid in chip disposal.

For heavy, plain milling work, a heavy-duty cutter with a faster, 45° left-hand spiral is preferred. The higher angle allows more teeth to contact the work at the same time. This puts a steady pressure on the arbor and spindle, thereby reducing chatter. In wide, slab milling, such cutters are particularly necessary to produce smooth finishes and avoid chatter.

Unlike plain milling cutters which have teeth only on the circumference, straddle or side mill cutters have cutting teeth on each side, as well as on the circumference or periphery. Such cutters will mill on both sides of a part or mill shallow slots. For milling shoulders it is common to use half-side cutters that have teeth only on one side and on the circumference.

Milling deep slots in stainless steel sometimes presents the problems of chatter, binding and jamming of wide chips. These difficulties can be eliminated by using a staggered-tooth cutter. Its alternating teeth cut only one-half of the slot, thereby taking a smaller bite and producing a shorter chip.

For end milling of stainless steels, the solid-shank end mill is preferred because of its high strength.

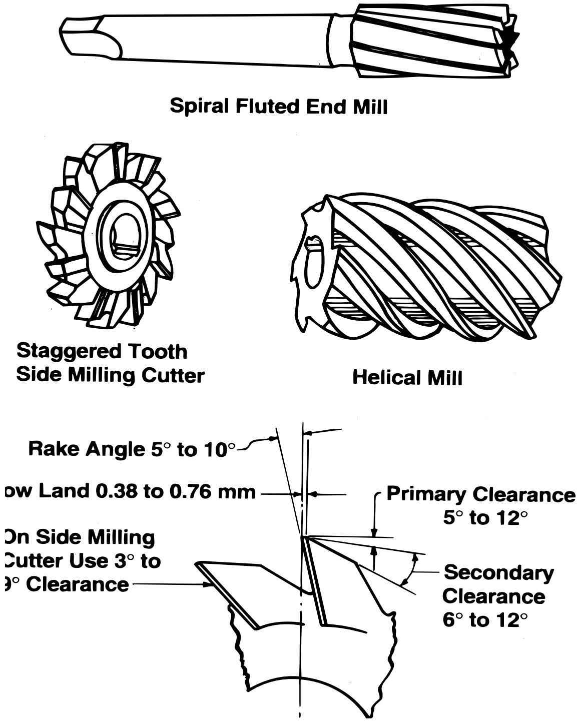


Fig. 7. Typical milling cutters used for stainless steels, with suggested geometries.

Grinding of Milling Cutters

Figure 7 shows rake angle and width of land, as well as primary and secondary clearance for high-speed steel cutters. The geometries shown give sufficient strength and clearance. On cutters up to 4 in. (102 mm) in diameter, the maximum clearance shown in the figure should be used, remembering that small cutters require a greater clearance angle than large cutters. Sufficient clearance behind the cutting edge of every tooth is necessary to avoid a rubbing or burnishing action. Excessive vibration may indicate the cutter has insufficient clearance (rigidity of the tooling and fixtures should also be considered). Hogging-in generally indicates too much rake (or possibly too high a cutting speed).

Stainless Steels
Milling, End—Peripheral

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Alloy (Annealed Condition)	Depth of Cut (inches)	Micro-Melt® Powder HS Tools						Carbide Tools					
		Tool Mtl	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches)				Tool Mtl	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches)			
				1/4	1/2	3/4	1-2			1/4	1/2	3/4	1-2
410	.050	M48,T15	132	.001	.002	.003	.004	C6	345	.001	.002	.004	.006
416	.050	M48, T15	150	.001	.002	.004	.005	C6	350	.001	.002	.005	.007
No. 5 BQ	.050	M48, T15	156	.001	.002	.004	.005	C6	350	.001	.002	.005	.007
Project 70+® 416	.050	M48, T15	168	.001	.002	.004	.005	C6	375	.001	.002	.005	.007
No. 5-F	.050	M48, T15	174	.001	.002	.004	.005	C6	400	.001	.003	.005	.007
420	.050	M48, T15	120	.001	.002	.003	.004	C6	275	.001	.002	.004	.006
420F	.050	M48, T15	162	.001	.002	.004	.005	C6	300	.001	.003	.005	.007
431	.050	M48, T15	96	.001	.002	.003	.004	C6	250	.001	.002	.004	.006
440A/440B	.050	M48, T15	90	.001	.002	.003	.004	C6	240	.001	.002	.004	.006
440C	.050	M48, T15	84	.001	.002	.003	.004	C6	235	.001	.002	.004	.006
440F	.050	M48, T15	150	.001	.002	.003	.004	C6	275	.001	.002	.004	.006
430	.050	M48, T15	132	.001	.002	.003	.004	C6	350	.001	.002	.004	.006
430F/430FR	.050	M48, T15	168	.001	.002	.004	.005	C6	400	.001	.002	.005	.007
443	.050	M48, T15	114	.001	.002	.004	.005	C6	270	.001	.003	.005	.007
302/304/316	.050	M48, T15	90	.001	.002	.003	.004	C2	270	.001	.002	.003	.005
Project 70+® 304/316	.050	M48, T15	140	.0012	.0024	.0036	.0048	C2	358	.0012	.0024	.0036	.006
Project 70+ 304L/316L	.050	M48, T15	140	.0012	.0024	.0036	.0048	C2	358	.0012	.0024	.0036	.006
302HQ-FM®	.050	M48, T15	150	.001	.002	.004	.005	C2	340	.001	.002	.005	.007
303	.050	M48, T15	135	.001	.002	.004	.005	C2	325	.001	.002	.005	.007
Project 70+® 303	.050	M48, T15	202	.0012	.0024	.0048	.006	C2	449	.0012	.0024	.006	.0084
303Al Modified®	.050	M48, T15	150	.001	.002	.004	.005	C2	340	.001	.002	.005	.007
203	.050	M48, T15	135	.001	.002	.004	.005	C2	325	.001	.002	.005	.007
321/347	.050	M48, T15	90	.001	.002	.003	.004	C2	270	.001	.002	.003	.005
20Cb-3® Stainless	.050	M48, T15	84	.001	.002	.003	.004	C2	250	.001	.002	.003	.005
18Cr-2Ni-12Mn	.050	M48, T15	78	.001	.002	.003	.004	C2	245	.001	.002	.003	.005
21Cr-6Ni-9Mn	.050	M48, T15	78	.001	.002	.003	.004	C2	245	.001	.002	.003	.005
22Cr-13Ni-5Mn	.050	M48, T15	78	.001	.002	.003	.004	C2	245	.001	.002	.003	.005

Contact a Carpenter representative for alloy availability.

Notes: 1) Use Cobalt or Tungsten High Speed Grades with Reduced Speeds and Feeds for Heat Treated Conditions
2) Increase Speeds and Reduce Feeds for Lighter Cuts and Better Finish

Precipitation Hardening Alloys
Milling, End—Peripheral

Alloy	Depth of Cut (inch-	Micro-Melt® Powder HS Tools						Carbide Tools					
		Tool Mtl.	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches)				Tool Mtl.	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches)			
				1/4	1/2	3/4	1-2			1/4	1/2	3/4	1-2
Custom 630	**Solution Treated**												
	.050	M48, T15	75	.001	.002	.003	.004	C2	255	.001	.002	.004	.006
	Double Aged H1150-M												
	.050	M48, T15	80	.001	.002	.003	.004	C2	260	.001	.002	.004	.006
	Aged H 1075-H 1150												
	.050	M48, T15	75	.001	.002	.003	.004	C2	255	.001	.002	.004	.006
	Aged H 1025												
	.050	M48, T15	60	.0005	.001	.002	.003	C2	180	.001	.002	.004	.006
	Aged H 900-H 925												
	.050	M48, T15	55	.0005	.001	.002	.003	C2	85	.001	.002	.004	.006
Project 70+® Custom 630 (17Cr-4Ni)	**Solution TreatedS**												
	.050	M48, T15	90	.001	.002	.003	.004	C2	270	.001	.002	.004	.006
	Double Aged H1150-M												
	.050	M48, T15	95	.001	.002	.003	.004	C2	275	.001	.002	.004	.006
	Aged H 1075-H 1150												
	.050	M48, T15	85	.001	.002	.003	.004	C2	265	.001	.002	.004	.006
	Aged H 1025												
	.050	M48, T15	70	.0005	.001	.002	.003	C2	190	.001	.002	.003	.004
	Aged H 900-H 925												
	.050	M48, T15	65	.0005	.001	.002	.003	C2	90	.001	.002	.003	.004
Custom 450®	**Solution Treated**												
	.050	M48, T15	102	.001	.002	.003	.004	C2	275	.001	.002	.004	.006
	Aged H 1075-H 1150												
	.050	M48, T15	96	.001	.002	.003	.004	C2	225	.001	.002	.004	.006
	Aged H 1025												
	.050	M48, T15	84	.0005	.001	.002	.003	C2	195	.001	.002	.003	.004
	Aged H 900-H 925												
	.050	M48, T15	72	.0005	.001	.002	.003	C2	90	.001	.002	.003	.004
Custom 465® Custom 455® PH 13-8 Mo* 15Cr-5Ni	**Annealed**												
	.050	M48, T15	108	.001	.002	.003	.004	C2	275	.001	.002	.004	.006
	Aged												
	.050	M48, T15	72	.0005	.001	.002	.003	C2	90	.001	.002	.003	.004
Project 70+® 15Cr-5Ni	**Solution Treated**												
	.060	M48, T15	132	.0014	.0028	.0042	.0056	C2	380	.0019	.0032	.0059	.0074
	Aged												
	.060	M48, T15	108	.0012	.0026	.0040	.0052	C2	290	.0017	.0028	.0055	.0071
Pyromet® 350 & 355	**Equalized & Overtempered**												
	.050	M48, T15	102	.001	.002	.003	.004	C2	230	.001	.002	.004	.006
	Aged—Rc 38-40												
	.050	M48, T15	78	.0005	.001	.002	.003	C2	190	.001	.002	.003	.004
	Aged—Over Rc 40												
	.050	M48, T15	72	.0005	.001	.002	.003	C2	90	.001	.002	.003	.004

Contact a Carpenter representative for alloy availability.

*Registered trademark of AK Steel Corp.

Notes: 1) M33 and M41 through M47 can be used where T15 is shown
2) Increase Speeds and Reduce Feeds for Lighter Cuts and Better finish

Milling Parameters and Cutting Fluid

The milling tables on pages 71 and 72 show speeds and feeds for milling stainless steels using either high-speed steel or carbide tooling. Feeds may need to be varied from the nominal values. If the feed is too light, the tool will burnish the work; if the feed is too heavy, tool life will be shortened.

Once a milling cut has been started, it should not be stopped unless absolutely necessary, since the tool will undercut when starting again. When it is necessary to back out, the tool should be placed two or three turns behind the work before starting again. This eliminates the danger of backlash and guards against undercutting.

Trouble-Shooting Check Chart

PROBLEM:	POSSIBLE SOLUTIONS:
Cutter "hogs in."	● Check rake angle. Too much rake will cause "hogging in." ● Check speed.
Excessive vibration.	● Check clearance, especially on cutters with more than one cutting surface. If clearance is not enough, rubbing will cause vibration. ● Check cutting fluid. Binding may be result of too heavy an oil, not carrying away heat fast enough.
Cutter wears badly without galling or heating up.	● Add paraffin oil to cutting fluid. Too much sulphur base oil wears away cutting edge, as sulphur is abrasive.
Cutter "bugs" up and burns.	● Check cutting fluid. Mixture may be too thin. Assuming cutting speed is not too fast, add more sulphur base oil.
Cutter burnishing behind cutting edge.	● Check width of land and clearance. This is definite indication the land is too wide.
Plain milling cutter binds in deep slots.	● Change to a staggered tooth side mill with alternating spiral teeth. ● Check alignment to tool and work, axis of cutter may not be parallel with work. ● If using a plain slitting saw, change to one with side chip clearance. These saws have standard concave sides, and on some jobs the depth of this concavity may have to be increased to eliminate galling the sides of the work.
Cuts not straight.	● Check how work is clamped. Work piece can be sprung from over-tightening of clamp or vise.
Work piece slips.	● Some pieces, due to shape are hard to hold. Often, a piece of paper slipped under work will help to prevent slipping.
Chatter on straight tooth cutter.	● If cutter is sharp and clearances sufficient, plus good lubrication, this job requires a helical tooth cutter which has a shearing action that cuts more freely. ● If you are using a helical tooth cutter, look for backlash in machine, a loose arbor or a worn shank on miller. ● Check solid shank cutters for nicks. A nick leaves a high spot and cutter works loose.

PROBLEM:	POSSIBLE SOLUTIONS:
Shell end mill won't cut accu-rately after grinding.	● This is an indication that cutter was removed from arbor for grinding. Once a shell end mill or face mill is on arbor, don't take it off. You can seldom reset it as it was.
Cutter does not run true.	● Generally this is due to "poor housekeeping." Cleanliness is of major importance. Dirt or a fine chip can be caught between the arbor and the spindle or between the cutter and the arbor. This will cause the cutter to run several thousandths out-of-true. ● Also a "sprung" arbor or a "burred" spacer will cause same trouble.
Work cuts out-of-square.	● Again "good housekeeping." This can be from chips between the work and the fixture or chips and dirt in the "T" slots, causing misalignment when clamping fixture. Brush or blow all chips away before a new work piece is mounted.
Work burnishes.	● Cut is too light. Cutter not biting into steel. Increase depth of cut.
Poor or rough finishing cut.	● Your last cut was too heavy. Take a lighter cut and increase speed for better finish. ● Check for dull tool. ● Feed too high. ● Surface speed too low. Increase SFM slowly until proper speed is ascertained.
Indication of high pressure on cutters.	● Change to a coarser tooth cutter. Too many teeth cutting at same time. A coarser tooth cutter will allow more space between teeth and relieve chip packing. ● May be due to chip packing, caused by low oil pressure or misdirected flow so that ships are not washed out of teeth or flutes.
Too much rake.	● This will show up by cutter "hogging in." Use smaller rake angle.
Vibration.	● Not enough clearance on top and sides. Cutter is binding. Grind for more clearance. ● Check size of arbor. It should not

BROACHING

General Guidelines

Broaching is a fast way to remove metal either externally or internally, and produces a finished job to close tolerances. The only limitation is that there must be no interference with the movement or passage of the broach. Broaching machines fall into two general classes, vertical or horizontal. Either can be used for push or pull broaching.

For internal broaching, a properly drilled or reamed hole is satisfactory. For external or surface broaching, preliminary machining operations are seldom required.

It is essential that chips not be allowed to build up during broaching. Otherwise, damage to the broach may result from chip packing. Damage may also occur if the broach is not properly aligned, resulting in excessive localized load on the teeth.

Broach Design and Grinding

Broaches for stainless alloys have been made of Micro-Melt® Powder high speed steel and Micro-Melt Maxamet® alloy. A broach is a simple tool to handle, because the broach manufacturer builds into it the necessary feed and depth of cut by steps from one tooth to another. Basically, a broach can incorporate the roughing cut, the semi-finished cut and the final precision cut, as shown in Figure 8, or any combination of these operations. Some broaches are made with burnishing buttons when a burnished finish is required. Since the form or shape of a broach tooth is unlimited, there is no limitation to the shape or contour of broached surfaces.

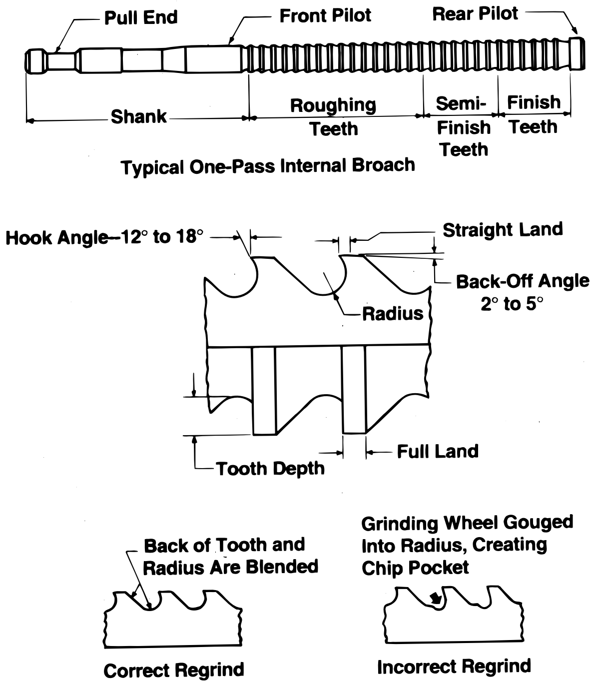


Fig. 8. Typical broaching tool used for stainless steels, with suggested geometries and grinding techniques.

In designing the radius for the broach, the manufacturer provides maximum tooth strength and a pocket for chips. The broach manufacturer may also incorporate into the broach, depending on the job, such items as side relief (flat broaches), undercut and clearance (spline broaches) and chip breakers (to handle wide chips).

When a broach becomes dull, it should be resharpened only on a broach grinder or returned to the manufacturer to be reground. For internal broaches, the back-off angle should be held to a minimum, preferably 2° and not to exceed 5°, as shown in Figure 8. Too much back-off angle will shorten broach life due to size reduction from resharpening.

Any nicks on the cutting edges of the broach will score the surface of the work. Therefore, careful handling is very important.

Stainless Steels
Broaching

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Alloy (Annealed Condition)	Micro-Melt® Powder High Speed Tools		
	Tool Material	**Speed** (fpm)	**Chip Load** (inches per tooth)
410	M48, T15	24	.0040
416	M48, T15	30	.0040
No. 5 BQ	M48, T15	30	.0040
Project 70+® 416	M48, T15	30	.0040
No. 5-F	M48, T15	36	.0040
420	M48, T15	18	.0030
420F	M48, T15	24	.0030
431	M48, T15	18	.0030
440A/440B	M48, T15	18	.0020
440C	M48, T15	12	.0020
440F	M48, T15	18	.0020
430	M48, T15	24	.0030
430F/430FR	M48, T15	36	.0040
443	M48, T15	24	.0030
302/304/316	M48, T15	18	.0040
Project 70+® 304/316	M48, T15	24	.0036
Project 70+® 304L/316L	M48, T15	24	.0036
302HQ-FM®	M48, T15	24	.0040
303	M48, T15	25	.0036
Project 70+® 303	M48, T15	39	.0048
303Al Modified®	M48, T15	24	.0040
203	M48, T15	25	.0036
321/347	M48, T15	18	.0030
20Cb-3® Stainless	M48, T15	12	.0030
18Cr-2Ni-12Mn	M48, T15	12	.0030
21Cr-6Ni-9Mn	M48, T15	12	.0030
22Cr-13Ni-5Mn	M48, T15	12	.0030

Contact a Carpenter representative for alloy availability.

Precipitation Hardening Alloys
Broaching

Alloy	Micro-Melt® Powder High Speed Tools		
	Tool Material	Speed (fpm)	Chip Load (inches per tooth)
		Solution Treated	
17Cr-4Ni	M48, T15	8	.0016
		Double Aged H 1150M	
	M48, T15	8	.0016
		Aged H 1075 - H 1150	
	M48, T15	5	.0016
		Aged H 1025	
	M48, T15	5	.0016
		Aged H 900 - H 925	
	M48, T15	5	.0016
		Solution Treated	
Project 70+® Custom 630	M48, T15	12	.002
		Double Aged H 1150M	
	M48, T15	15	.002
		Aged H 1075 - H 1150	
	M48, T15	10	.002
		Aged H 1025	
	M48, T15	10	.002
		Aged H 900 - H 925	
	M48, T15	10	.002
		Solution Treated	
Custom 450®	M48, T15	18	.002
		Aged H 1100 - H 1150	
	M48, T15	12	.002
		Aged H 1000 - H 1050	
	M48, T15	9.6	.002
		Aged H 900 - H 950	
	M48, T15	9.6	.002
Custom 465® Custom 455® PH 13-8 Mo* 15Cr-5Ni		**Annealed**	
	M48, T15	9.6	.002
		Aged	
	M48, T15	12	.002
		Solution Treated	
Project 70+® 15Cr-5Ni	M48, T15	24	.002
		Aged	
	M48, T15	18	.002
		Equalized & Overtempered	
Pyromet® 350 & 355	M48, T15	12	.002
		Aged Rc 38-40	
	M48, T15	9.6	.002
		Aged Over Rc 40	
	M48, T15	—	—

Contact a Carpenter representative for alloy availability.
*Registered trademark of AK Steel Corp.

Trouble-Shooting Check Chart

Broaching, of all machine operations, is the one where "good housekeeping" is the most essential. Not only should broach teeth be brushed often but broaching machines present many places with relatively small clearances where chips may lodge and jam, causing damage to the machine and broach. Chips are unavoidable and are broaching's greatest menace.

PROBLEM:	POSSIBLE SOLUTIONS:
Broken teeth.	● Packing of chips due to improper grinding (see sketch on page 78) may be one cause for broken teeth. ● Chip packing on stainless can occur where a continuous chip is being made and the proper clearance has not been provided for. ● On surface broaching a large error in alignment can throw too heavy a load on teeth, causing breakage. ● Always check your holder first for straight travel before a part is actually broached. ● When placing broach inserts in holder, be sure everything is clean and free from grit or chips. Foreign matter can force inserts out of line. ● Check steps of inserts with dial indicator. A small difference in their height may tear teeth.
Spoiled work or broken insert on surface broach.	● Check insert assembly in holder to see if screws are too long or too short. If the insert is loose, the screws are too long and a loose insert will not cut accurately. This is also cause of some insert breakage. If screws are too short and are pulled up with force, the screw hole becomes weak and eventually pulls out. Be sure your screws are the right length and then tighten them without excessive force.
Insert breaks in assembly.	● This is usually due to "poor housekeeping." You may have assembled it with a chip or some other foreign matter between insert and holder and the force of tightening screws broke it. All broach inserts are made of fully hardened high speed steel, which contributes further to easy breakage.
Poor finish and variation in size on broached surface.	● Look for loose clamps. ● Check loading fixture and seating of pieces. Improper loading and chip accumulation are causes.

PROBLEM:	POSSIBLE SOLUTIONS:
Breakage of internal broach.	● Check alignment. See that direction of pull is at right angles to face place. ● Check center axis of broach with axis of face plate as these must be in line. This is very important where part is held in a cup in the face place. ● If a "follow rest" is used, this also must be in perfect alignment with pullhead and face plate.
Drifting.	● Check the center of the starting hole. It probably is not centralized with broach center.
Round or spline broaches cut off center.	● This is caused by "drifting." On round holes one side does not clean up. On spline broaches the splines will be eccentric. See above recommendation to eliminate drifting.
Excessive wear and dulling of teeth.	● Again this is usually the result of "drifting." ● Also check cutting fluid. If too rich in sulphur, cut back with paraffin base oil.
Chatter.	● Inserts may have feather edge and require stoning. ● Parts not held tight enough. ● Part vibrates from forcing the cut. ● Chatter can also develop from using too light a machine. ● Check hydraulic system.
Parts will not hold size.	● Look for something loose while broach is cutting. ● Part may be "springing" due to cutting force. ● Check clamps. Are they strong enough? ● Check for deflection in machine.
Tearing and/or heavy burrs.	● Dead soft steel is draggy and can be the cause of this condition.

REAMING

General Guidelines

Reaming is used to finish previously drilled or bored holes to provide accurate dimensions and a smooth finish. It is important that ample material be left from the previous operation to permit the reamer to take a definite cut, particularly with non-free-machining austenitic alloys. This will allow the reamer to get below any work-hardened layer. In addition, it will prevent burnishing or glazing, production of holes which are undersized or have a poor finish, and rapid tool wear.

Types of Reamers

Figure 9 shows several typical high-speed steel reamers. Carbide-tipped reamers may also be used. Spiral-fluted reamers with a helix angle of approximately 7° are suggested. There is less tendency for this type of reamer to chatter, and better chip clearance is secured. This is particularly true for interrupted cuts, such as in a keyway. Left-hand (reverse) spiral reamers with right-hand cutting or rotation are suggested. Right-hand spiraling of the flutes with right-hand rotation helps the tool to cut more freely, but makes it feed into the work too rapidly.

When tapered holes must be reamed, any one of the standard taper reamers, ground for stainless steels, will provide a satisfactory finish. However, the hole must first be carefully drilled or bored.

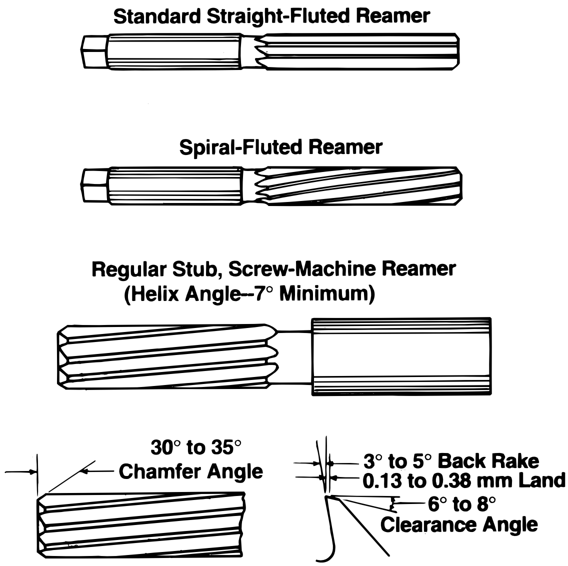


Fig. 9. Typical reamers used for stainless steels, with suggested geometries.

Grinding and Care of Reamers

The clearances and cutting rakes suggested in Figure 9 will minimize binding and apply to either solid or inserted-blade type high-speed steel reamers. Narrow lands are recommended to minimize rubbing and, consequently, chatter or binding. Cutting edges should be stoned to a fine finish, since any coarse grinding marks remaining on the reamer will transfer their pattern to the finished hole. The chamfer must be concentric with all flutes to avoid cutting eccentric holes.

Reamers should be handled and stored carefully, preferably in individual racks or boxes with partitions. If the reamer is dropped on metal or hit by other tools, it may be nicked, as all unprotected areas are ground working edges. When not in use, high-speed steel reamers should be protected from corrosion with a complete coating of oil. A small rust spot on the cutting edge will start a pit or nick. A deep nick can spoil the reamer for any further fine work.

Stainless Steels
Reaming

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Alloy (Annealed Condition)	Micro-Melt® Powder HS Tools		Carbide Tools (inserts)		Feed (inches per revolution) Reamer Diameter (inches)					
	Tool Mtl.	Speed (fpm)	Tool Mtl.	Speed (fpm)	1/8	1/4	1/2	1	1½	2
410	M48, T15	108	C2	110	.003	.006	.010	.014	.018	.022
416	M48, T15	150	C2	145	.003	.008	.013	.018	.022	.025
No. 5 BQ	M48, T15	150	C2	145	.005	.008	.013	.018	.022	.025
Project 70+® 416	M48, T15	156	C2	150	.005	.008	.013	.018	.022	.025
No. 5-F	M48, T15	162	C2	155	.005	.008	.013	.018	.022	.025
420	M48, T15	90	C2	95	.003	.006	.010	.014	.018	.022
420F	M48, T15	104	C2	110	.004	.006	.010	.014	.017	.021
431	M48, T15	78	C2	85	.003	.005	.008	.012	.015	.018
440A/440B	M48, T15	78	C2	85	.003	.006	.010	.015	.018	.021
440C	M48, T15	68	C2	75	.003	.006	.010	.015	.018	.021
440F	M48, T15	80	C2	100	.003	.006	.010	.015	.018	.021
430	M48, T15	102	C2	105	.003	.005	.008	.012	.015	.018
430F/430FR	M48, T15	156	C2	150	.005	.008	.013	.018	.022	.025
443	M48, T15	90	C2	95	.003	.005	.008	.012	.015	.018
302/304/316	M48, T15	84	C2	90	.003	.005	.008	.012	.015	.018
Project 70+® 304/316	M48, T15	124	C2	130	.0036	.006	.0096	.0144	.018	.0216
Project 70+ 304L/316L	M48, T15	124	C2	130	.0036	.006	.0096	.0144	.018	.0216
302HQ-FM®	M48, T15	102	C2	105	.003	.005	.008	.012	.015	.018
303	M48, T15	98	C2	100	.005	.008	.013	.018	.022	.025
Project 70+® 303	M48, T15	140	C2	143	.006	.0096	.0156	.0216	.0264	.0300
303Al Modified®	M48, T15	102	C2	105	.005	.008	.013	.018	.022	.025
203	M48, T15	98	C2	100	.005	.008	.013	.018	.022	.025
321/347	M48, T15	84	C2	90	.003	.005	.008	.012	.015	.018
20Cb-3® Stainless	M48, T15	72	C2	80	.003	.005	.008	.011	.014	.017
18Cr-2Ni-12Mn	M48, T15	72	C2	80	.003	.005	.008	.012	.015	.018
21Cr-6Ni-9Mn	M48, T15	72	C2	80	.003	.005	.008	.012	.015	.018
22Cr-13Ni-5Mn	M48, T15	72	C2	80	.003	.005	.008	.012	.015	.018

Contact a Carpenter representative for alloy availability.

Precipitation Hardening Alloys
Reaming

Alloy	Micro-Melt® Powder HS Tools Tool Mtl.	Micro-Melt® Powder HS Tools Speed (fpm)	Carbide Tools (inserts) Tool Mtl.	Carbide Tools (inserts) Speed (fpm)	Feed (inches per revolution) Reamer Diameter (inches) 1/8	1/4	1/2	1	1½	2
					Solution Treated					
17Cr-4Ni	M48, T15	55	C2	175	.003	.005	.008	.011	.015	.018
					Double Aged H 1150M					
	M48, T15	60	C2	190	.003	.005	.008	.011	.015	.018
					Aged H 1075 - H 1150					
	M48, T15	45	C2	140	.003	.005	.008	.011	.015	.018
					Aged H 1025					
	M48, T15	35	C2	115	.003	.005	.008	.011	.015	.018
					Aged H 900 - H 925					
	M48, T15	28	C2	95	.003	.005	.008	.011	.015	.018
					Solution Treated					
Project 70+® Custom 630	M48, T15	70	C7	200	.003	.005	.008	.011	.015	.018
					Double Aged H 1150M					
	M48, T15	75	C2	210	.003	.005	.008	.011	.015	.018
					Aged H 1075 - H 1150					
	M48, T15	55	C2	160	.003	.005	.008	.011	.015	.018
					Aged H 1025					
	M48, T15	45	C2	135	.003	.004	.006	.010	.013	.016
					Aged H 900 - H 925					
	M48, T15	40	C2	110	.001	.001	.001	.001	.001	.001
					Solution Treated					
Custom 450®	M48, T15	72	C2	190	.003	.005	.008	.011	.015	.018
					Aged H 1100 - H 1150					
	M48, T15	78	C2	190	.003	.005	.008	.011	.015	.018
					Aged H 1000 - H 1050					
	M48, T15	54	C2	150	.003	.005	.008	.011	.015	.018
					Aged H 900 - H 950					
	M48, T15	42	C2	125	.001	.001	.001	.001	.001	.001
					Annealed					
Custom 465® Custom 455® PH 13-8 Mo* 15Cr-5Ni	M48, T15	72	C2	190	.003	.005	.008	.011	.015	.018
					Aged					
	M48, T15	36	C2	100	.001	.001	.001	.001	.001	.001
					Solution Treated					
Project 70+® 15Cr-5Ni	M48, T15	90	—	—	.0033	.0053	.0083	.0106	.0127	.0159
	—	—	C2	95	.0043	.0086	.0128	.0164	.0206	.0247
					Aged					
	M48, T15	66	—	—	.0033	.0056	.0089	.0110	.0136	.0161
	—	—	C2	75	.0043	.0066	.0099	.0156	.0191	.0209
					Equalized and Overtempered					
Pyromet® 350 & 355	M48, T15	72	C2	190	.003	.005	.008	.011	.015	.018
					Aged Rc 38 - 40					
	M48, T15	36	C2	10	.001	.001	.001	.001	.001	.001
					Aged Over Rc 40					
	M48, T15	—	—	—	—	—	—	—	—	—

Contact a Carpenter representative for alloy availability.
*Registered trademark of AK Steel Corp.

Reaming Parameters

Feeds and speeds for both roughing and finishing operations are listed in tables on pages 85 and 86 for both high-speed steel and carbide tooling. When finish of the hole is not critical, the parameters for roughing can be used. Smooth finishes require significantly lower speeds. When both size and finish are important, a two-step operation should be used with both roughing and finishing cuts.

Alignment

A frequent source of trouble in machine reaming is caused when the axis of the spindle is not in proper alignment with the axis of the reamer. Two noticeable types of misalignment occur, (1) parallel and (2) angular. Corrections for either or both must sometimes be made in a single setup. Cause for misalignment, singly or in combination, can be due to wear in the ways, wear or dirt in the sleeve or tool clamp, or poor leveling of the machine. These troubles are generally indicated when a rigidly held reamer produces a poor finish and oversized or eccentric holes, especially at the start of a hole.

To correct misalignment, the machine and tool holders should be examined for chips, dirt, worn sleeves or worn bushings. Turret lathes and multispindle automatic screw machines should be examined for worn ways and improper indexing. A quick way to correct for these conditions and get proper alignment is to use floating holders. It should be noted that some floating holders compensate only for parallel misalignment, while others correct for both parallel and angular misalignment.

Trouble-Shooting Check Chart

PROBLEM:	POSSIBLE SOLUTIONS:
Cutting edges burn.	● Check spindle speed. It may be too fast. ● Check cutting fluid as it must also be good coolant. You may be using too rich a mixture and need paraffin to thin it out, which is helpful in carrying off heat.
Cutting edges wear badly or dull rapidly.	● Check cutting fluid as it may be too rich in sulphur base oil and needs to be thinned out. Sulphur is abrasive and if your mixture is heavy, it will wear away cutting edge rapidly. See page 115 for "rule-of-thumb" governing judgment of mixture. ● Reamer should not be rotated backward to remove from hole. Either pass reamer through hole or withdraw without stopping forward rotation.
Hole cuts ec-centric.	● Check chamfer. It must be concentric with all flutes. A poor start means a poor job. ● Check alignment of work with tool. Misalignment may be due to poor work-holding fixtures. Fine chips and incorrect setting will also cause this trouble. Try using a "floating holder."
Rough finish.	● If you know reamer is sharp and correctly ground and your cutting fluids are satisfactory, reduce spindle speed.
Chatter.	● Check the lands, if using a straight fluted reamer. They may be too wide and are rubbing, which causes chatter. ● Also sometimes caused by dull reamer, or drilled hole too large which does not let reamer get a good bite. ● There is less tendency to chatter with spiral fluted reamers. ● Check rigidity of tool holder; try small chamfer at start of hole.
Work glazes or burnishes.	● This occurs mostly when reaming 18-8 types. Reamer is not biting in deep enough to get good cut. Acts like letting a drill dwell and work-hardens surface of steel. Deeper bite will usually correct this fault.
Tool marks in finished reamed hole.	● Reamer was ground with too coarse a wheel. Use a finer grit, free-cutting grinding wheel; being careful not to burn edges of reamer. See No. 5 on page 33. It is characteristic for tools to leave the pattern of the grinding wheel on the part.
Reamer binds.	● Check clearance and rake angles with sketches on page 84. If reamer is within these limits, it will not bind. ● Wide lands or insufficient back-off angle can also cause binding.
Nicks in flutes.	● This comes from careless handling and storage when not in use. Handle them as carefully as the reamer manufacturer does when he ships them to you. Store in individual boxes or racks with separations. Remember, the cutting edge is always vulnerable. ● Reamers should be well covered with oil when not in use, as a small rust spot on the cutting edge will start a pit or nick.

SAWING

General Guidelines

Stainless steels can be sawed with band saws or power hack saws using high-speed steel blades. Speed and feed depend primarily on the hardness of the material, and the pitch of the blade depends on the size of the material. Thicker materials are cut with coarser teeth to avoid clogging with chips. On the other hand, when sawing thin-gauge material or tubing, a sufficiently fine-tooth saw is required so that at least two or three teeth are cutting at all times. A coarse-tooth saw, besides bridging the work, will gouge out metal and break teeth.

Sawing Parameters

Guidelines for power hack sawing are shown in the table on page 90. Speeds for band saws range from 50 to 100 ft/min. (15 to 30 m/min.), with harder materials requiring a lower speed. Nominal pitches for band saw blades generally range from 8-10 teeth/in. (2.5-3 mm) for material up to 0.25 in. (6 mm) thick, to 3-6 teeth/in. (4-8.5 mm) for material 1.5 in. (38 mm) thick or greater.

Stainless Steels
Sawing—Power Hack Saw

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Alloy (Annealed Condition)	Pitch (teeth per inch) Material Thickness (inches)				Speed	Feed
	Under 1/4	1/4 to 3/4	3/4 to 2	Over 2	Strokes/ Minute	Inches/ Stroke
410	10	10	6	4	120	.006
416	10	10	6	4	125	.006
No. 5 BQ	10	10	6	4	140	.006
Project 70+® 416	10	10	6	4	140	.006
No. 5-F	10	10	6	4	160	.006
420	10	10	6	4	115	.006
420F	10	10	6	4	135	.006
431	10	10	6	4	85	.005
440A/440B	10	10	6	4	60	.005
440C	10	10	6	4	55	.005
440F	10	10	6	4	110	.006
430	10	10	6	4	115	.005
430F/430FR	10	10	6	4	125	.009
443	10	10	6	4	110	.005
302/304/316	10	10	6	4	90	.005
Project 70+® 304/316	10	10	6	4	100	.005
Project 70+	10	10	6	4	100	.005
304L/316L	10	10	6	4	100	.006
302HQ-FM®	10	10	6	4	100	.006
303	10	10	6	4	110	.006
Project 70+® 303	10	10	6	4	100	.006
303Al Modified®	10	10	6	4	100	.006
203	10	10	6	4	90	.005
321/347	10	10	6	4	70	.005
20Cb-3® Stainless	10	10	6	4	70	.005
18Cr-2Ni-12Mn	10	10	6	4	70	.005
21Cr-6Ni-9Mn	10	10	6	4	80	.005

Precipitation Hardening Alloys
Sawing—Power Hack Saw

All Grades	10	6	6	4	80	.006
	Solution Treated					
Aged 275-325 BHN	10	10	6	4	55	.005
Aged 325-375 BHN	10	10	6	4	45	.004

Contact a Carpenter representative for alloy availability.

GRINDING

Wheels

Aluminum oxide wheels are most commonly used for stainless steels. Silicon carbide wheels may also be used, but at a reduced wheel life; therefore, their use is limited to special applications. Medium-density wheels of hardness grades H to L are generally selected for stainless steels, although harder wheels are used for thread grinding. Grit sizes commonly used are 46, 54 or 60; finer grits may be used to produce a finer finish. Vitrified-bond wheels are normally used, although the stronger resinoid-bond wheels are preferred for equipment operated at higher speeds. Grinding wheels used previously to grind another metallic material should not be used to grind a stainless steel, since particles of the other material may be imbedded in the stainless steel, affecting its corrosion resistance.

Grinding Parameters

For many grinding operations, typical wheel speeds are 5000 to 6500 ft/min. (1520 to 1980 m/min.). For surface grinding, table speeds are 50 to 100 ft/min. (15 to 30 m/min.), with a downfeed of up to 0.002 in/pass (0.050 mm/pass) for roughing and 0.0005 in./pass (0.013 mm/pass) for finishing, and a crossfeed of 0.050 to 0.500 in./pass (1.3 to 13 mm/pass). Thread grinding is done at higher speeds with harder wheels, as mentioned previously.

High Temperature Alloys
Turning—Single Point and Box Tools

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Alloy	Depth of Cut (inches)	Micro-Melt® Powder High Speed Tools: Tool Material	Micro-Melt® Powder High Speed Tools: Speed (fpm)	Micro-Melt® Powder High Speed Tools: Feed (ipr)	Carbide Tools (inserts): Tool Mtl.	Carbide Tools (inserts): Speed (fpm) Un-coated	Carbide Tools (inserts): Speed (fpm) Coated	Carbide Tools (inserts): Feed (ipr)
NiMark® 250 NiMark 300 NiMark 350				**Annealed**				
	.150	—	—	—	C3	340	400	.015
	.025		—	—	C3	380	500	.007
				Aged				
	.150	—	—	—	C3	105	140	.010
	.025		—	—	C3	125	160	.005
Stainless Type 410 Greek Ascoloy AMS 5616				**Annealed**				
	.150	—	—	—	C6	275	350	.020
	.025		—	—	C7	350	450	.007
				Rc 35				
	.150	—	—	—	C7	215	280	.015
	.025		—	—	C7	280	350	.007
19-9 DL 19-9 DX Pyromet® N-155 Pyromet A-286 Pyromet V-57				**Solution Treated**				
	.100	—	—	—	C2	135	160	.015
	.025		—	—	C3	160	190	.007
				Aged				
	.100	—	—	—	C2	120	140	.010
	.025		—	—	C3	140	165	.007
Pyromet® 718 Pyromet 625 Pyromet X750 Pyromet 751 Pyromet 80A Waspaloy				**Solution Treated**				
	.100	—	—	—	C2	70	80	.010
	.025		—	—	C3	90	100	.007
				Aged				
	.100	—	—	—	C2	65	75	.010
	.025		—	—	C3	80	95	.007
Pyromet® 90 Pyromet 41				**Solution Treated**				
	.100	—	—	—	C2	60	70	.010
	.025		—	—	C3	70	80	.007
Pyromet® 680				**Solution Treated**				
	.100	—	—	—	C2	90	100	.010
	.025		—	—	C3	100	110	.007

Contact a Carpenter representative for alloy availability.

Electronic Alloys
Turning—Single Point and Box Tools

Alloy	Depth of Cut (inches)	Micro-Melt® Powder High Speed Tools			Carbide Tools (inserts)			
		Tool Material	Speed (fpm)	Feed (ipr)	Tool Mtl.	Speed (fpm) Un-coated	Speed (fpm) Coated	Feed (ipr)
Carpenter High Permeability "49"® Carpenter Invar "36"® Hiperco® 50 A Kovar®	.150 .025	M48, T15	36 48	.010 .005	C2 C3	100 110	120 130	.010 .005
Electrical Iron Silicon Core Iron A & B	.150 .025	M48, T15	96 130	.015 .007	C6 C7	350 400	400 490	.020 .007
Silicon Core Iron `A-FM & B-FM	.150 .025	M48, T15	144 192	.015 .007	C6 C7	400 475	485 625	.020 .007
Silicon Core Iron C	.150 .025	M48, T15	90 126	.015 .007	C6 C7	300 385	375 475	.020 .007
430F & 430 FR Solenoid Quality	.150 .025	M48, T15	192 210	.015 .007	C6 C7	525 575	600 650	.015 .007
Chrome Core® 8	.150 .025	M48, T15	120 150	.015 .007	C6 C7	450 550	600 750	.015 .007
Chrome Core 8-FM	.150 .025	M48, T15	198 222	.015 .007	C6 C7	575 650	750 850	.015 .007
Chrome Core 12	.150 .025	M48, T15	120 150	.015 .007	C6 C7	450 550	600 750	.015 .007
Chrome Core 12-FM	.150 .025	M48, T15	198 222	.015 .007	C6 C7	575 650	750 850	.015 .007
Free-Cut Invar "36"®	.150 .025	M48, T15	96 120	.015 .007	C2 C3	275 320	300 365	.015 .007

Contact a Carpenter representative for alloy availability.

Tool Steels
Turning—Single Point and Box Tools

Alloy	Depth of Cut (inches)	Micro-Melt® Powder High Speed Tools			Carbide Tools (inserts)			
						Speed (fpm)		
		Tool Material	Speed (fpm)	Feed (ipr)	Tool Mtl.	Un-coated	Coated	Feed (ipr)
				Annealed				
No. 11 Special® Green Label	.150 .025	M48, T15	135 180	.015 .007	C6 C7	450 600	600 650	.015 .007
				Annealed				
Solar® No. 481 S7	.150 .025	M48, T15	105 120	.015 .007	C6 C7	310 410	410 500	.015 .007
				Annealed				
Stentor® No. 484® Vega® R.D.S.®	.150 .025	M48, T15	90 100	.015 .007	C6 C7	270 315	315 380	.015 .007
				Annealed				
No. 610® Hampden®	.150 .025	M48, T15	55 72	.010 .005	C6 C7	160 210	210 250	.010 .005
				Annealed				
No. 882 No. 883® No. 345	.150 .025	M48, T15	90 108	.015 .007	C6 C7	300 375	375 425	.015 .007
				Annealed				
T-K® Thermowear® Speed Star® Ten Star® Star Zenith Star-Max®	.150 .025	M48, T15	72 90	.015 .007	C6 C7	225 280	280 370	.015 .007
				Annealed				
Four Star Seven Star® Super Star®	.150 .025	M48, T15	72 78	.015 .007	C6 C7	220 250	250 300	.015 .007
				Solution Treated				
Pyrotool® A Pyrotool V	.100 .025	M48, T15	— —	— —	C2 C3	135 160	160 190	.015 .007
				Aged				
	.100 .025	M48, T15	— —	— —	C2 C3	120 145	145 170	.010 .007
				Solution Treated				
Pyrotool® 7 Pyrotool EX Pyrotool M Pyrotool W	.100 .025	M48, T15	— —	— —	C2 C3	70 80	80 90	.010 .007
				Aged				
	.100 .025	M48, T15	— —	— —	C2 C3	65 75	75 85	.010 .007

Contact a Carpenter representative for alloy availability.

High Temperature Alloys
Turning—Cut-Off and Form Tools

Alloy	Tool Mtl. — Micro-Melt® Powder HS Tools	Tool Mtl. — Carbide Tools	Speed (fpm)	Feed (inches per revolution) — Cut-Off and Form Tool Width (inches) — 1/16	1/8	1/4	1/2	1	1½	2
NiMark® 250 NiMark 300 NiMark 350				**Annealed**						
	M48, T15		—	—	—	—	—	—	—	—
		C6	200	.003	.004	.005	.003	.0025	.0025	.0015
Stainless Type 410 Greek Ascoloy AMS 5616				**Annealed**						
	M48, T15		—	—	—	—	—	—	—	—
		C6	275	.004	.0055	.007	.005	.004	.0035	.0035
				Rc 35						
	M48, T15		—	—	—	—	—	—	—	—
		C6	175	.003	.003	.0045	.003	.002	.002	.002
19-9 DL 19-9 DX Pyromet® N-155 Pyromet A-286 Pyromet V-57				**Solution Treated**						
	M48, T15		—	—	—	—	—	—	—	—
		C2	95	.003	.005	.007	.004	.003	.003	.002
				Aged						
	M48, T15		—	—	—	—	—	—	—	—
		C2	80	.003	.005	.007	.004	.003	.002	.0015
Pyromet® 718 Pyromet 625 Pyromet X750 Pyromet 751 Pyromet 80A Waspaloy				**Solution Treated**						
	M48, T15		—	—	—	—	—	—	—	—
		C2	45	.003	.0045	.006	.004	.003	.0025	.0015
				Aged						
	M48, T15		—	—	—	—	—	—	—	—
		C2	45	.003	.003	.0045	.003	.0025	.002	.001
Pyromet® 90 Pyromet 41				**Solution Treated**						
	M48, T15		—	—	—	—	—	—	—	—
		C2	45	.003	.0045	.006	.004	.003	.0025	.0015
				Solution Treated						
	M48, T15		—	—	—	—	—	—	—	—
		C2	95	.003	.005	.007	.004	.003	.003	.002

Contact a Carpenter representative for alloy availability.

Electronic Alloys
Turning—Cut-Off and Form Tools

Alloy	Tool Mtl.: Micro-Melt® Powder HS Tools	Tool Mtl.: Carbide Tools	Speed (fpm)	Feed (inch per revolution) — Cut-Off and Form Tool Width (inches): 1/16	1/8	1/4	1/2	1	1½	2
Carpenter High Permeability "49"® Carpenter Invar "36"® Hiperco® 50 A Kovar®	M48,T15		30	.001	.001	.0015	.0015	.001	.0007	.0007
		C2	80	.003	.003	.0045	.003	.002	.002	.002
Electrical Iron Silicon Core Iron A & B	M48,T15		89	.001	.0015	.002	.0015	.001	.001	.0007
		C6	250	.003	.0045	.006	.003	.0025	.0025	.0015
Silicon Core Iron `A-FM & B-FM	M48,T15		130	.002	.0025	.003	.0025	.0025	.0015	.0015
		C6	340	.004	.006	.008	.006	.005	.004	.003
Silicon Core Iron C	M48,T15		78	.001	.0015	.002	.0015	.001	.001	.0007
		C6	225	.0035	.0045	.006	.003	.0025	.0025	.0015
430F & 430 FR Solenoid Quality	M48,T15		180	.002	.0025	.003	.0025	.002	.0015	.0001
		C6	350	.004	.0055	.007	.005	.004	.0035	.0035
Chrome Core® 8	M48,T15		117	.001	.001	.0015	.0015	.001	.001	.001
		C6	390	.004	.0055	.007	.005	.004	.0035	.0035
Chrome Core 8-FM	M48,T15		180	.0015	.002	.0025	.0025	.002	.0015	.001
		C6	480	.004	.0055	.007	.005	.004	.0035	.0035
Chrome Core 12	M48,T15		117	.001	.001	.0015	.0015	.001	.001	.001
		C6	390	.004	.0055	.007	.005	.004	.0035	.0035
Chrome Core 12-FM	M48,T15		180	.0015	.002	.0025	.0025	.002	.0015	.001
		C6	480	.004	.0055	.007	.005	.004	.0035	.0035
Free-Cut Invar "36"®	M48,T15		78	.001	.0015	.002	.002	.0015	.001	.0001
		C2	220	.004	.0055	.007	.005	.004	.0035	.0035

Contact a Carpenter representative for alloy availability.

Tool Steels
Turning—Cut-Off and Form Tools

Alloy	Tool Mtl.: Micro-Melt® Powder HS Tools	Tool Mtl.: Carbide Tools	Speed (fpm)	Feed (inch per revolution) Cut-Off and Form Tool Width (inches): 1/16	1/8	1/4	1/2	1	1½	2
No. 11 Special® Green Label	Annealed									
	M48,T15		130	.0015	.002	.0025	.0025	.0015	.0015	.001
		C6	350	.004	.005	.006	.005	.0035	.0035	.0025
Solar® No. 481 S7	Annealed									
	M48,T15		90	.0015	.002	.0025	.0025	.0015	.0015	.001
		C6	250	.004	.005	.006	.005	.0035	.0035	.0025
Stentor® No. 484® Vega® R.D.S.®	Annealed									
	M48,T15		70	.001	.0015	.002	.0015	.001	.001	.0007
		C6	205	.003	.0045	.006	.003	.0025	.0025	.0015
No. 610® Hampden®	Annealed									
	M48,T15		54	.001	.001	.0015	.0015	.001	.0007	.0007
		C6	145	.002	.002	.003	.0025	.0015	.0015	.0015
No. 882 No. 883® No. 345	Annealed									
	M48,T15		78	.001	.0015	.002	.0015	.001	.001	.0007
		C6	195	.003	.0045	.006	.003	.0025	.0025	.0015
T-K® Thermowear® Speed Star® Ten Star® Star Zenith Star-Max®	Annealed									
	M48,T15		70	.001	.001	.0015	.0015	.001	.0007	.0007
		C6	220	.002	.003	.0045	.003	.002	.0015	.0015
Four Star Seven Star® Super Star®	Annealed									
	M48,T15		68	.001	.001	.0015	.0015	.001	.0007	.0007
		C6	190	.002	.003	.0045	.003	.002	.0015	.0015
Pyrotool® A Pyrotool V	Solution Treated									
	—		—	—	—	—	—	—	—	—
		C2	95	.003	.005	.007	.004	.0035	.003	.003
	Aged									
	—		—	—	—	—	—	—	—	—
		C2	80	.003	.005	.007	.004	.003	.002	.0015
Pyrotool® 7 Pyrotool EX Pyrotool M Pyrotool W	Solution Treated									
	—		—	—	—	—	—	—	—	—
		C2	45	.003	.0045	.006	.004	.003	.002	.0015
	Aged									
	—		—	—	—	—	—	—	—	—
		C2	45	.003	.003	.0045	.003	.0025	.002	.001

Contact a Carpenter representative for alloy availability.

High Temperature Alloys
Drilling

Alloy	Tool Mtl.	Condition	Speed (fpm)	Feed (inch per revolution) Nominal Hole Diameter (inches) 1/16	1/8	1/4	1/2	3/4	1	1½	2
NiMark® 250 NiMark 300 NiMark 350	M42	**Annealed**	55	—	.003	.005	.007	.009	.010	.013	.015
		Aged	20	—	.002	.003	.004	.004	.004	.004	.004
Stainless Type 410 Greek Ascoloy AMS 5616	M42	**Annealed**	65	.001	.003	.006	.010	.013	.016	.021	.025
		Rc 35	50	—	.002	.003	.005	.006	.007	.008	.009
19-9 DL 19-9 DX Pyromet® N-155 Pyromet A-286 Pyromet V-57	M42	**Solution Treated**	25	—	.002	.004	.006	.008	.010	—	—
		Aged	20	—	.002	.004	.006	.008	.008	—	—
Pyromet® 718 Pyromet 625 Pyromet X750 Pyromet 751 Pyromet 80A Waspaloy	M42	**Solution Treated**	20	—	.002	.003	.003	.004	—	—	—
		Aged	15	—	.002	.003	.003	.004	—	—	—
Pyromet® 90 Pyromet 41	M42	**Solution Treated**	15	—	.002	.003	.003	.004	—	—	—
Pyromet® 680	M42	**Solution Treated**	15	—	.002	.003	.004	.004	—	—	—

Contact a Carpenter representative for alloy availability.
Note: Hole quality improves using a drill point angle or tip of 150°.

Electronic Alloys
Drilling

Alloy	Tool Mtl.	Speed (fpm)	Feed (inch per revolution) Nominal Hole Diameter (inches)							
			1/16	1/8	1/4	1/2	3/4	1	1½	2
Carpenter High Permeability "49"® Carpenter Invar "36"® Hiperco® 50 A Kovar®	M42	40	.001	.002	.004	.007	.008	.010	.012	.015
Electrical Iron Silicon Core Iron A & B	M42	70	.001	.002	.004	.007	.010	.012	.015	.018
Silicon Core Iron A-FM & B-FM	M42	80-85	.001	.003	.005	.010	.013	.016	.020	.025
Silicon Core Iron C	M42	50	.001	.002	.004	.007	.011	.013	.015	.017
430F & 430FR Solenoid Quality	M42	160	.001	.003	.006	.010	.014	.017	.021	.025
Chrome Core® 8	M1, M10	60-70	.001	.002	.004	.007	.010	.012	.015	.018
Chrome Core 8-FM	M1, M10	100-150	.001	.003	.006	.010	.014	.017	.021	.025
Chrome Core 12	M1, M10	60-70	.001	.002	.004	.007	.010	.012	.015	.018
Chrome Core 12-FM	M1, M10	100-150	.001	.003	.006	.010	.014	.017	.021	.025
Free-Cut Invar "36"®	M1, M10	50	.001	.002	.004	.007	.010	.012	.015	.018

Contact a Carpenter representative for alloy availability.

Note: Hole quality improves using a drill point angle or tip of 130°-140°.

Tool Steels
Drilling

Alloy	Tool Mtl.	Speed (fpm)	Feed (inch per revolution) — Nominal Hole Diameter (inches)							
			1/16	1/8	1/4	1/2	3/4	1	1½	2
			Annealed							
No. 11 Special® Green Label	M42	95	.001	.002	.004	.007	.010	.012	.015	.018
			Annealed							
Solar® No. 481 S7	M42	55	.001	.002	.003	.007	.009	.011	.014	.016
			Annealed							
Stentor® No. 484® Vega® R.D.S.®	M42	45	.001	.001	.003	.005	.007	.008	.010	.012
			Annealed							
No. 610® Hampden®	M42	30	.001	.001	.003	.005	.007	.008	.010	.012
			Annealed							
No. 882 No. 883® No. 345	M42	50	.001	.002	.003	.006	.008	.010	.011	.013
			Annealed							
T-K® Thermowear® Speed Star® Ten Star® Star Zenith Star-Max®	M42	45	.001	.002	.003	.005	.007	.009	.011	.013
			Annealed							
Four Star Seven Star® Super Star®	M42	35	.001	.002	.003	.005	.007	.008	.011	.013
			Solution Treated							
Pyrotool® A Pyrotool V	M42	25	—	.002	.004	.006	.008	.010	—	—
			Aged							
		20	—	.002	.004	.006	.008	.008	—	—
			Solution Treated							
Pyrotool® 7 Pyrotool EX Pyrotool M Pyrotool W	M42	20	—	.002	.003	.003	.004	—	—	—
			Aged							
		15	—	.002	.003	.003	.004	—	—	—

Contact a Carpenter representative for alloy availability.

Note: For Pyrotool alloys hole quality improves using a drill point angle or tip of 150°.

High Temperature Alloys
Tapping

Alloy	Tool Material	Speed (fpm)
NiMark® 250 NiMark 300 NiMark 350	**Annealed**	
	M1, M7, M10	20
	Aged	
	M1, M7, M10, Nitrided	5
Stainless Type 410 Greek Ascoloy AMS 5616	**Annealed**	
	M1, M7, M10	25
	Rc 35	
	M1, M7, M10, Nitrided	15
19-9 DL 19-9 DX Pyromet® N-155 Pyromet A-286 Pyromet V-57	**Solution Treated**	
	M1, M7, M10	15
	Aged	
	M1, M7, M10, Nitrided	10
Pyromet® 718 Pyromet 625 Pyromet X750 Pyromet 751 Pyromet 80A Waspaloy	**Solution Treated**	
	M1, M7, M10	10
	Aged	
	M1, M7, M10, Nitrided	7
Pyromet® 90 Pyromet 41	**Solution Treated**	
	M1, M7, M10, Nitrided	8
	Solution Treated	
	M1, M7, M10, Nitrided	10

Contact a Carpenter representative for alloy availability.

Electronic Alloys
Tapping

Alloy	Tool Material	**Speed** (fpm)
Carpenter High Permeability "49"® Carpenter Invar "36"® Hiperco® 50 A Kovar®	M1, M7, M10	6-15
Electrical Iron Silicon Core Iron A & B	M1, M7, M10	15-20
Silicon Core Iron A-FM & B-FM	M1, M7, M10	25-30
Silicon Core Iron C	M1, M7, M10	10-15
430F & 430FR Solenoid Quality	M1, M7, M10	35-40
Chrome Core® 8	M1, M7, M10	20-45
Chrome Core 8-FM	M1, M7, M10	15-40
Chrome Core 12	M1, M7, M10	20-45
Chrome Core 12-FM	M1, M7, M10	15-40
Free-Cut Invar "36"®	M1, M7, M10	10-15

Threading, Die

Alloy	Tool Material	**Speed** (fpm)			
		7 or less, tpi	8 to 15, tpi	16 to 24, tpi	25 and up, tpi
Tool Steels All Grades	M1, M2, M7, M10	8-12	12-18	18-25	20-30
High Temperature Alloys All Grades		**Annealed**			
	M2, M7, M10	4-6	5-8	6-10	8-12
		Aged			
	M42	3-4	3-5	4-8	5-10
Electronic Alloys Nickel & Cobalt Grades		**Non-FM**			
	M42	5-10	8-13	10-15	15-20
		FM			
	M1, M2, M7, M10, M42	5-12	8-15	10-20	15-25
All other Electronic Grades		**Non-FM**			
	M1, M2, M7, M10	8-20	10-25	15-30	25-40
		FM			
	M1, M2, M7, M10	10-20	15-25	20-35	25-40

Contact a Carpenter representative for alloy availability.

Tool Steels
Tapping

Alloy	Tool Material	Speed (fpm)
	Annealed	
No. 11 Special® **Green Label**	M7, M10	40
	Annealed	
Solar® **No. 481** **S7**	M7, M10	30
	Annealed	
Stentor® **No. 484®** **Vega®** **R.D.S.®**	M7, M10	25
	Annealed	
No. 610® **Hampden®**	M7, M10	15
	Annealed	
No. 882 **No. 883®** **No. 345**	M7, M10	30
	Annealed	
T-K® **Thermowear®** **Speed Star®** **Ten Star®** **Star Zenith** **Star-Max®**	M7, M10	25
	Annealed	
Four Star **Seven Star®** **Super Star®**	M7, M10	20
	Solution Treated	
Pyrotool® A **Pyrotool V**	M7, M10	15
	Aged	
	Nitrided	10
	Solution Treated	
Pyrotool® 7 **Pyrotool EX** **Pyrotool M** **Pyrotool W**	M7, M10	10
	Aged	
	Nitrided	7

Contact a Carpenter representative for alloy availability.

High Temperature Alloys
Milling, End—Peripheral

Alloy	Depth of Cut (Inch-	Micro-Melt® Powder HS Tools						Carbide Tools					
		Tool Mtl.	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches)				Tool Mtl	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches)			
				1/4	1/2	3/4	1-2			1/4	1/2	3/4	1-2
NiMark® 250 NiMark 300 NiMark 350	.050	M2, M7, M42					**Annealed**						
			—	—	—	—	—	C6	275	.001	.002	.004	.005
							Aged						
			—	—	—	—	—	C6	75	—	.002	.003	.004
Stainless Type 410 Greek Ascoloy AMS 5616	.050	M2, M7, M42					**Annealed**						
			—	—	—	—	—	C6	345	.001	.002	.004	.006
							Rc 35						
			—	—	—	—	—	C6	200	.001	.002	.003	.004
19-9 DL 19-9 DX Pyromet® N-155 Pyromet A-286 Pyromet V-57	.050	M42					**Annealed**						
			—	—	—	—	—	C2	120	.001	.002	.003	.004
							Aged						
			—	—	—	—	—	C2	80	.001	.002	.003	.004
Pyromet® 718 Pyromet 625 Pyromet X750 Pyromet 751 Pyromet 80A Waspaloy	.050	M42					**Solution Treated**						
			—	—	—	—	—	C2	60	.001	.002	.003	.004
							Aged						
			—	—	—	—	—	C2	50	.0015	.0015	.002	.003
Pyromet® 90 Pyromet 41	.050	M42					**Solution Treated**						
			—	—	—	—	—	C2	50	.001	.002	.003	.004
	.050	M42					**Solution Treated**						
			—	—	—	—	—	C2	70	.001	.002	.003	.004

Contact a Carpenter representative for alloy availability.

Note: Increase Speeds and Reduce Feeds for Lighter Cuts and Better Finish

Electronic Alloys
Milling, End—Peripheral

Alloy	Depth of Cut (inch-	Micro-Melt® Powder HS Tools						Carbide Tools					
		Tool Mtl.	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches)				Tool Mtl.	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches)			
				1/4	1/2	3/4	1-2			1/4	1/2	3/4	1-2
Carpenter High Permeability "49"® Carpenter Invar "36"® Hiperco® 50 A Kovar®	.050	M48, T15	42	.0005	.001	.002	.006	C6	200	.001	.002	.003	.004
Electrical Iron Silicon Core Iron A & B	.050	M48, T15	72	.002	.003	.005	.006	C6	300	.0025	.004	.006	.008
Silicon Core Iron A-FM & B-FM	.050	M48, T15	96	.002	.003	.005	.007	C6	350	.0025	.005	.007	.009
Silicon Core Iron C	.050	M48, T15	60	.002	.003	.005	.006	C6	300	.003	.004	.006	.007
430F & 430FR Solenoid Quality	.050	M48, T15	168	.001	.002	.004	.005	C6	400	.001	.002	.005	.007
Chrome Core® 8	.050	M48, T15	132	.001	.002	.003	.004	C6	350	.001	.002	.004	.006
Chrome Core 8-FM	.050	M48, T15	168	.002	.002	.004	.005	C6	400	.001	.002	.005	.007
Chrome Core 12	.050	M48, T15	132	.001	.002	.003	.004	C6	350	.001	.002	.004	.006
Chrome Core 12-FM	.050	M48, T15	168	.002	.002	.004	.005	C6	400	.001	.002	.005	.007
Free-Cut Invar "36"®	.050	M48, T15	100	.001	.002	.003	.004	C2	280	.001	.002	.004	.005

Contact a Carpenter representative for alloy availability.

Note: Increase Speeds and Reduce Feeds for Lighter Cuts and Better Finish

Tool Steels
Milling, End—Peripheral

Alloy	Depth of Cut (inch-	Micro-Melt® Powder HS Tools						Carbide Tools					
		Tool Mtl.	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches) 1/4	1/2	3/4	1-2	Tool Mtl.	Speed (fpm)	Feed (inches per tooth) Cutter Diam (inches) 1/4	1/2	3/4	1-2
							Annealed						
No. 11 Special® Green Label	.050	M48, T15	150	.002	.003	.005	.006	C6	400	.0025	.003	.005	.007
							Annealed						
Solar® No. 481 S7	.050	M48, T15	100	.002	.003	.004	.005	C6	365	.002	.003	.005	.007
							Annealed						
Stentor® No. 484® Vega® R.D.S.®	.050	M48, T15	90	.001	.002	.003	.004	C6	300	.0015	.0025	.004	.005
							Annealed						
No. 610® Hampden®	.050	M48, T15	65	.001	.002	.003	.004	C6	200	.0015	.0025	.004	.005
							Annealed						
No. 882 No. 883® No. 345	.050	M48, T15	95	.001	.002	.003	.004	C6	300	.0015	.0025	.004	.005
							Annealed						
T-K® Thermowear® Speed Star® Ten Star® Star Zenith Star-Max®	.050	M48, T15	84	.001	.002	.003	.004	C6	275	.0015	.0025	.004	.005
							Annealed						
Four Star Seven Star® Super Star®	.050	M48, T15	72	.001	.002	.003	.004	C6	225	.0015	.0025	.004	.005
							Solution Treated						
Pyrotool® A Pyrotool V	.050	M48, T15	—	—	—	—	—	C2	120	.001	.002	.003	.004
							Aged						
			—	—	—	—	—	C2	80	.001	.002	.003	.004
							Solution Treated						
Pyrotool® 7 Pyrotool EX Pyrotool M Pyrotool W	.050	M48, T15	—	—	—	—	—	C2	60	.001	.002	.003	.004
							Aged						
			—	—	—	—	—	C2	50	.0015	.0015	.002	.003

Contact a Carpenter representative for alloy availability.

Note: Increase Speeds and Reduce Feeds for Lighter Cuts and Better Finish

High Temperature Alloys
Sawing—Power Hack Saw

Alloy	Pitch (teeth per inch) Matercal Thickness (inches) Under 1/4	1/4 to 3/4	3/4 to 2	Over 2	Speed Strokes/ Minute	Feed Inches/ Stroke
All Grades	10	6	6	4	30-60	.003-.006

Electronic Alloys
Sawing—Power Hack Saw

All Grades	10	6	6	4	40-75	.003-.006

Tool Steels
Sawing—Power Hack Saw

No. 11 Special® Green Label	10	6	6	4	140	.006
Solar® No. 481 S7	10	6	6	4	70	.003
Stentor® No. 484® Vega® R.D.S.®	10	10	6	4	85	.003
No. 610® Hampden®	10	10	6	4	55	.005
No. 882 No. 883® No. 345	10	8	6	4	75	.003
T-K® Thermowear® Speed Star® Ten Star® Star Zenith Star-Max®	10	10	6	4	70	.006
Four Star Seven Star® Super Star®	10	10	6	4	60	.006
K-W	10	6	6	4	100	.006
M-50	10	10	6	4	90	.006
Plastic Mold Steels	10	6	6	4	115	.006
420 Plastic Mold Steel	10	10	6	4	110	.006
Pyrotool® A Pyrotool V	**Solution Treated**					
	10	10	6	4	50	.005
	Aged					
	10	10	6	4	40	.005
Pyrotool® 7 Pyrotool EX Pyrotool M Pyrotool W	**Solution Treated**					
	10	10	6	4	35	.004
	Aged					
	—	—	—	—	—	—

Contact a Carpenter representative for alloy availability.

High Temperature Alloys
Broaching

Alloy	Micro-Melt® Powder High Speed Tools		
	Tool Material	Speed (fpm)	Chip Load (inches per tooth)
NiMark® 250 NiMark 300 NiMark 350		**Annealed**	
	M48, T15	15	.002
Stainless Type 410 Greek Ascoloy AMS 5616		**Annealed**	
	M48, T15	20	.004
		Rc 35	
		10	.002
19-9 DL 19-9 DX Pyromet® N-155 Pyromet A-286 Pyromet V-57		**Solution Treated**	
	M48, T15	12	.002
		Aged	
		10	.002
Pyromet® 718 Pyromet 625 Pyromet X750 Pyromet 751 Pyromet 80A Waspaloy		**Solution Treated**	
	M48, T15	8	.002
		Aged	
		6	.002
Pyromet® 90 Pyromet 41		**Solution Treated**	
	M48, T15	8	.002
		Aged	
		6	.002
		Solution Treated	
	M48, T15	10	.002

Electronic Alloys
Broaching

Alloy	Micro-Melt® Powder High Speed Tools		
	Tool Material	Speed (fpm)	Chip Load (inches per tooth)
		Annealed	
FM Grades	M48, T15	18-30	.002
		Annealed	
All Other Grades	M48, T15	9.6-14.4	.002

Contact a Carpenter representative for alloy availability.

Tool Steels
Broaching

Alloy	Micro-Melt® Powder High Speed Tools		
	Tool Material	**Speed** (fpm)	**Chip Load** (inches per tooth)
No. 11 Special® Green Label	M48, T15	**Annealed** 20	.003
Solar® No. 481 S7	M48, T15	**Annealed** 15	.003
Stentor® No. 484® Vega® R.D.S.®	M48, T15	**Annealed** 15	.003
No. 610® Hampden®	M48, T15	**Annealed** 10	.002
No. 882 No. 883® No. 345	M48, T15	**Annealed** 20	.003
T-K® Thermowear® Speed Star® Ten Star® Star Zenith Star-Max®	M48, T15	**Annealed** 10	.002
Four Star Seven Star® Super Star®	M48, T15	**Annealed** 5	.002
Pyrotool® A Pyrotool V	M48, T15	**Solution Treated** 12 **Aged** 10	.002 .002
Pyrotool® 7 Pyrotool EX Pyrotool M Pyrotool W	M48, T15	**Solution Treated** 8 **Aged** 6	.002 .002

Contact a Carpenter representative for alloy availability.

High Temperature Alloys Reaming

Alloy	Micro-Melt® Powder HS Tools		Carbide Tools (inserts)		Feed (inches per revolution) Reamer Diameter (inches)					
	Tool Mtl.	Speed (fpm)	Tool Mtl.	Speed (fpm)	1/8	1/4	1/2	1	1½	2
NiMark® 250 NiMark 300 NiMark 350					**Annealed**					
	M48, T15	55	C2	160	.003	.005	.008	.012	.015	.018
					Aged					
	M48, T15	10	C2	50	.001	.001	.001	.001	.001	.001
Stainless Type 410 Greek Ascoloy AMS 5616					**Annealed**					
	M48, T15	90	C2	275	.003	.006	.010	.014	.018	.022
					Rc 35					
	M48, T15	30	C2	120	.001	.001	.001	.001	.001	.001
19-9 DL 19-9 DX Pyromet® N-155 Pyromet A-286 Pyromet V-57					**Solution Treated**					
	M48, T15	30	C2	100	.003	.006	.010	.012	.014	.016
					Aged					
	M48, T15	25	C2	80	.003	.006	.010	.012	.014	.016
Pyromet® 718 Pyromet 625 Pyromet X750 Pyromet 751 Pyromet 80A Waspaloy					**Solution Treated**					
	M48, T15	15	C2	60	.002	.006	.008	.010	.012	.014
					Aged					
	M48, T15	12	C2	50	.002	.006	.008	.010	.012	.014
Pyromet® 90 Pyromet 41					**Solution Treated**					
	M48, T15	20	C2	60	.002	.004	.006	.008	.010	.012
					Aged					
	M48, T15	15	C2	40	.002	.004	.006	.008	.010	.012
Pyromet® 680					**Solution Treated**					
	M48, T15	20	C2	70	.002	.006	.008	.010	.012	.014

Electronic Alloys Reaming

Alloy	Micro-Melt® Powder HS Tools		Carbide Tools (inserts)		Feed (inches per revolution) Reamer Diameter (inches)					
	Tool Mtl.	Speed (fpm)	Tool Mtl.	Speed (fpm)	1/8	1/4	1/2	1	1½	2
FM Grades	M48, T15	108-180	C2	275	.002	.006	.008	.010	.012	.014
All Other Grades	M48, T15	36-72	C2	70	.002	.006	.008	.010	.012	.014

Contact a Carpenter representative for alloy availability.

Tool Steels
Reaming

Alloy	Micro-Melt® Powder HS Tools Tool Mtl.	Micro-Melt® Powder HS Tools Speed (fpm)	Carbide Tools (inserts) Tool Mtl.	Carbide Tools (inserts) Speed (fpm)	Feed (inches per revolution) Reamer Diameter (inches) 1/8	1/4	1/2	1	1½	2
No. 11 Special® Green Label	**Annealed**									
	M48, T15	100	C2	300	.003	.005	.007	.011	.014	.017
Solar® No. 481 S7	**Annealed**									
	M48, T15	85	C2	250	.003	.005	.008	.011	.015	.018
Stentor® Nos. 484® Vega® R.D.S.®	**Annealed**									
	M48, T15	45	C2	150	.003	.005	.008	.011	.015	.018
No. 610® Hampden®	**Annealed**									
	M48, T15	25	C2	80	.002	.003	.005	.007	.010	.012
No. 882 No. 883® No. 345	**Annealed**									
	M48, T15	55	C2	175	.003	.005	.008	.012	.015	.018
T-K® Thermowear® Speed Star® Ten Star® Star Zenith Star-Max®	**Annealed**									
	M48, T15	45	C2	150	.003	.005	.008	.012	.015	.018
Four Star Seven Star® Super Star®	**Annealed**									
	M48, T15	30	C2	100	.003	.005	.008	.012	.015	.018
Pyrotool® A Pyrotool V	**Solution Treated**									
	M48, T15	30	C2	100	.003	.006	.010	.012	.014	.016
	Aged									
	M48, T15	25	C2	80	.003	.006	.010	.012	.014	.016
Pyrotool® 7 Pyrotool EX Pyrotool M Pyrotool W	**Solution Treated**									
	M48, T15	20	C2	60	.002	.006	.008	.010	.012	.014
	Aged									
	M48, T15	15	C2	50	.002	.006	.008	.010	.012	.014

Contact a Carpenter representative for alloy availability.

CUTTING FLUIDS

Cutting Fluids

Cutting fluids serve several purposes in machining. During machining operations, both high temperature and pressure are encountered in the tool-workpiece interface. The edge of the cutting tool heats up as it removes metal chips from the workpiece due to friction and deformation of the metal. The heat generated this way transfers to the chips. These chips then may weld to the tool under the high temperature and pressure. The optimal cutting fluid for a specific operation will remove excess heat from the cutting edge and lubricate the tool to reduce friction. These actions will prevent welding of the chips to the tool, scuffing on the surface of the workpiece and provide extended tool life and improved part finish.

Stainless Steel Cutting Oils

Modern technology stainless steel cutting oils are comprised of premium quality, heavily dewaxed parraffinic base stocks with active extreme pressure (E.P.) and natural and synthetic fatty oil additives. Some of the additive packages available in cutting oils today are keyed in for specific operations or for specific stainless steel grades. Due to the complexity of these new additive materials, stainless steel cutting oils tend to be more expensive than cutting oils used for various other metals.

The following suggestions should be kept in mind when using modern technology stainless steel cutting oils for various operations:

1. The most effective E.P. additives for stainless steel machining are chlorinated compounds. Other materials, such as sulfurized fatty oils, phosphorus additives and various esters may also be used for formulating oils for specific operations.

Data provided by Clark Oil and Chemical, Cleveland, Ohio

2. In high speed, light feed automatic screw machines, a lighter viscosity oil with fewer additives is sufficient especially when working with free-machining alloys. In these machines the function of the oil is predominantly to remove heat from the tool-workpiece interface and to provide lubricity to the tool. This in turn will increase tool life.

3. Machines running at normal or average speed or performing operations, which include threading, tapping, drilling and milling, should use heavier viscosity oils with a higher percentage of E.P. additives in their formulations.

4. For bolt threading, nut tapping, pipe threading and broaching, addition of a sulfurized compound to the cutting oil formulation, already containing a chlorinated additive, is recommended. It is not advised however, to use sulfurized oils on high nickel alloys.

5. As a general rule, when machining larger diameter parts, a cutting oil with active sulfochlorinated E.P. additives should be used. When machining smaller diameter parts, the viscosity of the cutting oil should be below 200 SUS at 100°F.

6. When starting a new stainless steel job, it is important to remember that the more difficult the job is, the more highly compounded the cutting oil should be. This does not only mean that for difficult jobs the oil should contain more additives, but also that the oil should contain additives specifically designed for the operation. It is important to work with your oil supplier to maximize the effectiveness of the cutting oil as it relates to feeds and speeds, type of stainless steel being machined, critical tooling and part finish. The oil supplier can accomplish this by fine tuning their product to achieve maximum performance in specific applications.

Emulsifiable Fluids

Water-soluble cutting fluids may also be used on stainless steels, especially in operations where greater cooling capability is necessary, such as cutting with carbide tooling at high speeds. Water-soluble oils for stainless steel machining should contain similar polar E.P. additives that are used in straight stainless steel cutting oils. Water emulsifiable fluids may only be used in machines where mixing of the cutting fluid and the lubricating oil will not happen. Many water-soluble cutting fluids no matter how well formulated may not provide the same benefits as straight oil products would in severe cutting operations.

Using water-soluble stainless steel cutting fluids may in some cases result in better machined surface finish and better heat removal ability from the tool-workpiece interface. The use of water-soluble cutting fluids is also more economical than using a straight oil product.

General Practices

Since the main purpose of cutting fluids, being either straight or soluble oils, is to remove heat from and to lubricate the tool-workpiece interface, delivery of the right amount of fluid in this area is very critical. The size and form of the nozzle through which the fluid is delivered is of paramount importance. For the cutting fluid to be effective, the right volume of it must be delivered to the tool-workpiece interface with the appropriate pressure.

Cutting fluids also play an important role in chip removal. This is another reason to have the fluid nozzle spray in the right direction with the appropriate pressure. If the cutting fluid is not applied to the proper area at the tool-workpiece interface, and not in the correct amount, the fluid will heat up and lose its ability to carry heat away. This in turn will cause degradation of part finish and decrease of tool life. In general, the temperature of the cutting fluid should not exceed 140°F. If the cutting fluid gets too hot, the flow and rate of delivery of it should be adjusted at the nozzle. Some sumps (usually small ones) may use chillers to cool the cutting fluid. Make sure chillers work properly if they are installed on the machine. When using water-soluble cutting fluids, make sure that the machine sumps are always full of the fluid to eliminate the problem of heat build up in the fluid. Water-soluble oils will lose water due to evaporation over time. This water must be replenished to keep the proper concentration of coolant in the machine and to eliminate excessive heat buildup in the sump.

Correct Fluid Flow:
Directed on Work and Tool Edge

Incorrect Fluid Flow:
Bar Diverts Bulk of Flow

Fig. 10. Examples of correct and incorrect flow of cutting fluid.

Another important consideration is the cleanliness of the cutting fluid. Swarf, chips, grit and dust enter the cutting fluid, and if delivered to the tool-workpiece interface, can ruin the finish of the workpiece. Therefore it is highly recommended to filter and periodically change the cutting fluid in the machine sumps. Before introducing new product to the tank, however, the tank and all pipes and pumps must be properly cleaned and flushed. With soluble cutting fluids other precautions should also be taken. With these fluids, the longer the contact time of the emulsion with the swarf and chips, the faster the emulsion degrades. Swarf and chips can act as a filter, to filter out components from the emulsion. Swarf and chips attract dust and allow bacteria to multiply more quickly. This can further degrade the emulsion. Make sure swarf and dust are filtered out quickly and effectively from the soluble cutting fluid systems. Metal chips should be removed from the emulsion continuously to minimize the chips that are present in the machine sump.

Suggested Guidelines for Cutting Fluid Selection

	Austenitic		Ferritic and Martensitic
	Free Machining	Non-free Machining	
Turning Milling Reaming Drilling	D,M,N	F,L	D,M,N
Deep Hole Drilling Gun Drilling Trepanning	A2,L	A2	A2,L
Tapping Threading Thread Chasing	C	L,D	B
Form Tapping Thread Rolling	E,L	B,E	E,L
Vertical Broaching	L	L,A	L
Horizontal Broaching	A	A	A
Sawing	L	L	L
Centerless Grinding	O	O,L	O

Note: The table contains general suggested guidelines or starting points for cutting fluid selection. It is advisable to contact your oil manufacturer or distributor for more information.

Code	Cutting Fluids
A	Heavy duty, active sulfur, fats and chlorinated compounds – Heavy anti-weld properties
A2	Heavy duty, active sulfur, fats and chlorinated compounds – Heavy anti-weld properties in lighter viscosity under 120 SUS @ 100°F
B	Heavy duty, active sulfur, fats and chlorinated compounds – Heavy anti-weld properties with viscosity – 190/220 SUS @ 100°F
C	Heavy duty, active sulfur, fats and chlorinated compounds – 150/170 SUS @ 100°F
D	Chlorine free, non-corrosive, heavily fortified sulfurized fatty acids and extreme pressure additives
E	High extreme pressure, heavily fortified for anti-weld and load carrying additions with active sulfur
F	Heavy duty, inactive sulfur, fats and chlorinated compounds – Heavy anti-weld properties with viscosity – 150/170 SUS @ 100°F
L	Super heavy duty soluble oil with high extreme pressure additives
M	General purpose highly fortified synthetic with no chlorine or sulfur, with biostable, low foam good rust preventative additives
N	General purpose highly fortified semi-synthetic with extreme pressure additives
O	Heavy duty synthetic (made for centerless grinding)

Data provided by Clark Oil and Chemical, Cleveland, Ohio

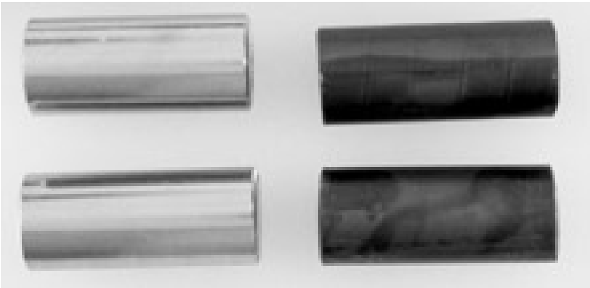
CLEANING AND PASSIVATING

Cleaning Before Heat Treating

Parts made from martensitic stainless steels or precipitation-hardenable alloys may be hardened or solution treated at high temperatures after machining. In such cases, the parts must be thoroughly cleaned with a degreaser or cleanser to remove any traces of cutting fluid before heat treating. Otherwise, cutting fluid remaining on the parts will cause excessive oxidation. This can result in undersized parts with a pitted finish after the scale is removed by acid or abrasive methods. If cutting fluids are allowed to remain on parts that are bright hardened, as in a vacuum furnace or protective atmosphere, surface carburization may result, leading to a loss of corrosion resistance.

Passivating

To ensure that machined parts have optimum corrosion resistance, they should be properly passivated. The primary purpose of passivation is to remove surface contamination, such as iron particles from cutting tools, that can form rust or act as initiation sites for corrosion. In addition, passivation can remove sulfides exposed on the surface of free-machining alloys, which also may act as initiation sites for corrosion.



The parts at left possess clean, shiny, corrosion-resistant surfaces after proper passivating. "Flash attack" on the parts at right resulted from using a contaminated passivating solution.

The first step in passivation is to thoroughly clean the parts with a degreaser or cleanser to remove dirt and cutting fluid. This will prevent contamination of the passivation bath and avoid reactions that may lead to "flash attack," or a heavily etched or darkened surface. After the parts have been cleaned, they should be passivated. Traditional nitric acid passivation practices are described below.

Nitric Acid Passivation of Stainless Steels	
Grades	**Passivation Practice**
— Chromium–Nickel Grades (300 Series) — Grades with 17% Chromium or more (except 440 Series)	20% by vol. nitric acid at 120/140°F (49/60°C) for 30 minutes
— Straight Chromium Grades (12-14% Chromium) — High Carbon–High Chromium Grades (440 Series) — Precipitation Hardening Stainless	20% by vol. nitric acid + 3oz. per gallon (22 g/liter) sodium dichromate at 120/140°F (49/60°C) for 30 minutes OR 50% by vol. nitric acid at 120/140°F (49/60°C) for 30 minutes

Passivation for Free-Machining Stainless Steels Including AISI Types 420F, 430F, 440F, 203, 182-FM and Carpenter Project 70+® Types 303 and 416
1. 5% by wt. sodium hydroxide at 160/180°F (71/82°C) for 30 minutes. 2. Water rinse. 3. 20% by vol. nitric acid + 3 oz. per gal (22 g/liter) sodium dichromate at 120/140°F (49/60°C) for 30 minutes. 4. Water rinse. 5. 5% by wt. sodium hydroxide at 160/180°F (71/82°C) for 30 minutes. 6. Water rinse.

The A-A-A (alkaline-acid-alkaline) method outlined for free-machining alloys illustrated in the second table prevents corrosion that may otherwise occur from residual acid trapped in pits remaining after the free-machining inclusions have been removed by the passivation bath.
The following points should be noted:

1. Passivation is not a scale-removal method. Any particles of oxide or heat tint must be removed before passivating.
2. Water used for passivation baths should have a relatively low chloride content (less than several hundred ppm, preferably less than 50 ppm).

3. Baths should be replaced on a regular schedule to avoid a loss in passivating potential that can result in flash attack.
4. The bath should be maintained at the proper temperature, since lower temperatures may allow localized attack.
5. Carburized or nitrided parts should not be passivated, since their reduced corrosion resistance may result in attack in the bath.
6. High-carbon martensitic alloys should be in a hardened condition before passivating, in order to provide sufficient corrosion resistance.

The left cone is an example of the improved resistance of free-machining stainless steel when passivated using the alkaline-acid-alkaline method. Conventional passivation is shown at right. Both samples were exposed to salt spay.

Citric acid passivation treatments are becoming more popular for fabricators who prefer avoiding the use of mineral acids or solutions containing sodium dichromate. Citric acid passivation treatments found useful for several grades of stainless steel are summarized in the following table:

Citric Acid Passivation of Stainless Steels*	
Grades	**Passivation Practice**
Type 316/316L Project 70+® Type 316/316L Stainless	10 wt. % citric acid, 150°F (66°C), 30 minutes
Type 304/304L Project 70+ Type 304/304L Stainless Custom Flo 302HQ Type 305	same as above
Nitrogen–Strengthened Austenitics	same as above
Type 430	same as above
17Cr-4Ni Project 70+ Custom 630 Stainless	same as above
15Cr-5Ni Project 70+ 15Cr-5Ni Stainless	same as above
Custom 465® Stainless	same as above
Type 409Cb	10 wt. % citric acid, 180/200°F (82/93°C), 30 minutes; after passivation and water rinse, neutralize in 5 wt. % sodium hydroxide, 170°F (77°C), 30 minutes
Type 303 Project 70+Type 303 Stainless	10 wt. % citric acid, 150°F (66°C), 30 minutes; after passivation and water rinse, neutralize in 5 wt. % sodium hydroxide, 170°F (77°C), 30 minutes
Type 410 Type 420 TrimRite® Stainless	10 wt. % citric acid, 120/130°F (49/54°C), 30 minutes; after passivation and water rinse, neutralize in 5 wt. % sodium hydroxide, 170°F (77°C), 30 minutes
Chrome Core® 18-FM Stainless	10 wt. % citric acid, 100°F (38°C), 30 minutes; after passivation and water rinse, neutralize in 5 wt. % sodium hydroxide, 170°F (77°C), 30 minutes
Type 409Cb-FM	10 wt. % citric acid (adjusted to pH 5 with sodium hydroxide), 110°F (43°C), 30 minutes; after passivation and water rinse, neutralize in 5 wt. % sodium hydroxide, 170°F (77°C), 30 minutes
Type 416 Project 70+ Type 416 Stainless	same as above

*Parts should be thoroughly cleaned and degreased prior to citric or nitric acid passivation. Parts must be water rinsed after immersion in acid and sodium hydroxide baths.

It is important to note that a careful balance of time, temperature and concentration is critical to avoid "flash attack" as previously described.

The ultimate choice of a passivation treatment will depend upon the imposed acceptance criteria. For more information, refer to ASTM A967, “Standard Specification of Chemical Passivation Treatments for Stainless Steel Parts.” You can access the specification at www.astm.org.

NONTRADITIONAL MACHINING OPERATIONS

While the majority of stainless steels are machined using conventional techniques, nontraditional techniques are used when justifiable. Such justification involves cost savings when machining alloys at the extremes of toughness or hardness, or when machining intricate shapes. The following sections briefly describe some of the nontraditional machining techniques which have been applied successfully to stainless steels.

Abrasive Jet Machining

In abrasive jet machining, material removal is accomplished using a controlled, high-velocity stream of gas containing abrasive. The stream is directed at the workpiece using a movable nozzle. The process is not meant for bulk material removal; rather, it is used primarily for deburring or cleaning in finishing operations. It may also be used to etch a surface to a matte finish. Although the process is best suited for hard materials, it has been used to deburr alloys such as Type 303.

One advantage of using abrasive jet machining is the fact that it is not a thermal process. Thus, critical dimensions of parts may be adjusted slightly after final heat treatment. However, the resultant matte finish may be undesirable. The following table shows the machined surface finish of a soft, austenitic stainless steel processed with abrasive jet machining. Another disadvantage is the possible loss of edge sharpness when deburring.

Surface Roughness for Annealed Type 316 in Abrasive Jet Machining

Abrasive	Grit size		Surface Roughness Ra	
	µm	µin	µm	µin
Aluminum oxide	10	400	0.20-0.50	8-20
	25	1000	0.25-0.53	10-21
	50	2000	0.38-0.96	15-38
Silicon carbide	20	800	0.30-0.50	12-20
	50	2000	0.43-0.86	17-34
Glass beads	50	2000	0.30-0.96	12-38

Starting surface had been ground to 0.47 µm Ra (18.5 µin)
Source: "Abrasive Jet Machining - AJM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 10-17

For further information, consult the following:
"Abrasive Jet Machining - AJM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 10-15 to 10-20.
T. C. Roberts, "Abrasive Jet Machining - Nontraditional Deburring," Nontraditional Machining, ASM, 1986, p. 105-110.

Abrasive Water Jet Machining

Abrasive water jet machining utilizes a high-velocity stream of water containing an abrasive to cut the workpiece. It provides specific advantages over other types of cutting, which must be considered on an application-by-application basis. It is more versatile than a saw, being able to cut complex shapes with a small kerf. Thicker materials can be cut than with a laser. It is a slower process than plasma arc machining; however, since it is not a thermal process, it does not cause metallurgical changes such as a heat-affected zone, or introduce residual stresses. This may be a particular advantage with fully heat-treated materials. Cutting rates for some alloys are shown in the following table.

Cutting Rates for Stainless Steels in Abrasive Water Jet Machining

Alloy	Thickness		Cutting Rate	
	mm	in.	mm/min.	in/min.
15Cr-5Ni[(a)]*	3	0.13	229-381	9-15
15Cr-5Ni[(a)]*	64	2.50	13-25	0.5-1
Type 316[(a)]	76 (dia.)	3 (dia.)	13-51	0.5-2
Custom 630[(b)]	25	1	51	2

[(a)] 276-345 MPa (40-50 ksi) pressure with 60 mesh garnet.
[(b)] 207 MPa (30 ksi) pressure with 60 mesh garnet. (a)

Sources: B. L. Swartz, "Principles and Applications of Water and Abrasive Jet Cutting," High Productivity Machining: Materials and Processes, ASM, 1985, p.295; A. L. Hitchcock, "Vote of Confidence for Abrasive Waterjet Cutting," Metal Progress, July 1986, p. 34.

For further information, consult the following:

A. Ansorge, "Fluid Jet Principles and Applications," Nontraditional Machining, ASM, 1986, p. 35-41.
B. L. Schwartz, "Principles and Applications of Water and Abrasive Jet Cutting," High Productivity Machining: Materials and Processes, ASM, 1985, p. 291-298.
A. L. Hitchcox, "Vote of Confidence for Abrasive Waterjet Cutting," Metal Progress, July 1986, p. 33-42.
D. Daniels, "AWJ Cutting, A New Tool for Metal Fabricators," Metal Stamping, September 1986, p. 3-6.
R. K. Mosavi, "Comparing Laser and Waterjet Cutting," Lasers and Optronics, Vol. 6 (No. 7), July 1987, p. 65-68.

Electrochemical Machining

In electrochemical machining, metal is removed from an anodic workpiece separated from a cathodic tool by flowing electrolyte in a process that is essentially the reverse of plating. Electrochemical machining is well-suited for hard or tough materials requiring machining into complex shapes, including those with holes. Machined surface finish is excellent and burrs are not formed. In addition, fully heat-treated materials can be machined without metallurgical changes or distortion.

Compared with electrical discharge machining, electrochemical machining proceeds at a much faster rate without a recast layer or heat-affected zone. On the other hand, electrolytes used can be corrosive, all parameters must be closely controlled during the process for optimum results, and electrode (tool) design may require significant manipulation initially to achieve complex shapes with close tolerances. However, once manufactured, the tools do not wear during the machining process.

The following table shows electrolytes used for several alloys.

Electrolytes Used for Srainless Steels in Electrochemical Machining

Alloy	Electrolyte	Concentration		Temp. at inlet	
		g/L	lb./gal.	°C	°F
Type 410	NaCl or	96	0.8	27	80
	$NaCl+NaNO_3$	192-216	1.6-1.8	46	115
Type 302	NaCl+NaF	30-32.4	0.25-0.27	38	100
Type 303	$NaCl+NaNO_3$	120-140	1.0-1.17	21	70
Type 316	NaCl	120	1	38	100
Custom 630	NaCl or	96-120	0.8-1	27	80
	$NaNO_3$	240 (60-480)	2 (0.25-4)	38	100
Pyromet® A-286	$NaNO_3$	240	2.0	38	100

Source: "Electrochemical Machining - ECM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 11-38, 11-39.

The following table shows theoretical removal rates for two alloys.

Material Removal Rates for Electrochemical Machining

Alloy	Theoretical Removal Rate[a] for 155 A/cm² (1000 A/in²)	
	cm^3/min.	$in.^3$/min.
17Cr-4Ni	2.02	0.123
Pyromet® A-286	1.92	0.117

[a]Assuming 100% current efficiency.
Source: "Electrochemical Machining - ECM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 11-34.

The following table shows typical parameters for machining 17Cr-4Ni.

Parameters for Electrochemical Machining of Solution-Treated 17Cr-4Ni

Electrolyte	Concentration		Minimum starting Voltage(ΔE)	Metal removal constant (k)*	
	g/L	lb./gal.		cm^3/A-min. x 10^{-3}	$in.^3$/A-min. x 10^{-5}
$NaNO_3$	270	2.3	3.6	1.41	8.6

**Used for estimating current:*

$$I = \frac{A_W V_f}{k}$$

I = current, amperes
A_W = area machined, cm^2 (in^2)
V_f = feed rate cm/min. (in./min.)
k = metal removal constant

Source: "Electrochemical Machining - ECM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 11-53.

Variations of electrochemical machining include electro-stream machining and shaped tube electrolytic machining. Electro-stream machining is intended for drilling of multiple, very small-diameter holes, while shaped tube electrolytic machining is intended for drilling multiple, small, very deep, round or shaped holes. Alloys such as Types 304, 316, 321 and 414 have been drilled using these techniques. The electrolyte used for drilling is a sulfuric acid solution, since electrolytes containing salts will form a sludge which could cause blockages in fine or deep holes.

For further information, consult the following:

"Electrochemical Machining - ECM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 11-25 to 11-62.
B. Kellock, "Have a Ball with a Cinderella Process!," Machinery and Production Engineering, May 19, 1982, p. 40-46.
"Electro-Stream - ES," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 11-69 to 11-70.
"Shaped Tube Electrolytic Machining - STEM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 11-71 to 11-75.

Electrochemical Grinding

Electrochemical grinding is another variant of electrochemical machining, in which a conductive, abrasive wheel removes any films formed on the workpiece during the process. Because only a small part of the metal removal is by abrasive action, wheel life is significantly prolonged, without the need for frequent redressing. This is a particular advantage in form grinding. Material removal rates are higher than in conventional grinding, particularly for hard alloys, without distortion or metallurgical changes in the parts. Burrs are eliminated and fine surface finishes are obtainable. The following table shows parameters for stainless steels in general and Pyromet® Alloy A-286 in particular.

For further information, consult the following:

"Electrochemical Grinding - ECG," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980 p. 11-9 to 11-22.

R. E. Phillips, "What is Electrochemical Grinding and How Does It Work," Nontraditional Machining, ASM, 1986, p. 65-70.

Parameters for Electrochemical Grinding

Alloy	Wheel	Electrolyte	Concentration		Maximum current density[a]	
			g/L	lb./gal.	A/cm^2	$a/in.^2$
Stainless steel	aluminum oxide	$NaNO_3$	180-200	1.5-1.7	78	500
Pyromet® A-286	aluminum oxide	$NaNO_3$	120-140	1.0-1.2	116	750

[a] May be limited by possibility of overheating the workpiece.
Source: "Electrochemical Grinding - ECG," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 11-13.

Electrical Discharge Machining

In electrical discharge machining, material is removed by sparks generated by a pulsating current flow between the workpiece and a shaped electrode. The workpiece and electrode (tool) are separated by a flowing dielectric fluid, such as oil. Electrical discharge machining is not affected by the hardness or toughness of the material and is well-suited for machining a variety of complex or irregular shapes, including holes. A disadvantage is the presence of a recast layer and heat-affected zone. These may have to be removed for critical applications. Data indicate that fatigue life of an alloy such as Type 410 can be significantly reduced, compared to conventionally machined material.

Electrical discharge sawing is a variant of electrical discharge machining and uses either a moving metal band or disc as the cutting electrode. High cutting rates can be obtained for stainless steels: 263 in^2/min. (1700 cm^2/min.) for a circular arc saw. Cutting rates for electrical discharge band saws are significantly lower.

For further information, consult the following:
"Electrical Discharge Machining - EDM," Machining Data Handbook, Vol.2, Metcut Res. Assoc., 1980, p. 12-15 to 12-46.
M. Field, et.al., "The Surface Effects Produced in Nonconventional Metal Removal - Comparison with Conventional Machining Techniques," Metals Engineering Quarterly, August 1966, p. 32-45.
"Electrical Discharge Sawing - EDS," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 12-47 to 12-48.

Electron Beam Machining

Electron beam machining uses a focused stream of electrons to remove material by melting and vaporization in a vacuum. Electron beam machining may be used for cutting thin materials, drilling fine holes or machining narrow slots with a high degree of precision. As with electrical discharge machining, a thin recast layer and heat- affected zone will be present and may have to be removed for critical applications. Operating parameters for drilling holes are shown in the table at the top of page 129.

Parameters Used to Drill Holes With Electron Beam Machining

Workpiece Thickness mm	Workpiece Thickness in.	Hole Diameter mm	Hole Diameter in.	Drilling Time s	Accel-erating Voltage kV	Average Beam Current µA	Pulse Width µs	Pulse Frequency Hz
			Ferritic/Martensitic Alloys					
0.25	0.010	0.013	0.0005	<1	130	60	4	3000
			Stainless Steels					
1.0	0.040	0.13	0.005	<1	140	100	80	50
2.0	0.080	0.13	0.005	10	140	100	80	50
2.5	0.100	0.13	0.005	10	140	100	80	50
6.4	0.250	0.5-1.0	0.020-0.040	180	145	4000	2100	12.5

Source: "Electron Beam Machining - EBM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 12-7, 12-10.

Operating parameters for cutting slots are shown in the following table.

Parameters Used for Cutting Slots With Electron Beam Machining

Workpiece Thickness mm	Workpiece Thickness in.	Slot Dimensions mm	Slot Dimensions in.	Time or Rate of Cut mm	Time or Rate of Cut in.	Accel-erating Voltage kV	Average Beam Current µA	Pulse Width µs	Pulse Fre-quency Hz
1.57	0.062	0.020 x 6.35	0.008 x 0.250	5 min.		140	120	80	50
0.18	0.007	0.10 wide	0.004 wide	50 mm/min.	2 in/min.	130	50	80	50
0.05	0.002	0.05 wide	0.002 wide	100 mm/min.	4 in/min.	130	20	4	50

Source: "Electron Beam Machining - EBM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p.12-8.

For further information, consult the following:
"Electron Beam Machining - EBM," Machining Data Handbook, Vol.2, Metcut Res. Assoc., 1980, p. 12-3 to 12-10.

Laser Beam Machining

In laser beam machining, a focused beam of high-energy coherent light removes material by melting and vaporization. Unlike electron beam machining, a vacuum is not necessary. Laser beam machining can be used for high-speed drilling of small-diameter holes or cutting of thin material into complex shapes, including contour cuts. Stainless steels may be cut at thicknesses of up to about 0.38 in. (10 mm), depending on the power and type of laser. Texturing, etching or scribing can also be done.

The laser beam cuts a narrow kerf with little or no thermal distortion. As with certain other processes, a recast layer and heat-affected zone will be present and may have to be removed for critical applications. However, they are typically thinner than in other thermal processes using a high heat input, particularly plasma arc cutting.

Gas streams are often used to assist laser cutting. Oxygen or air can be used to enhance the cutting rate. The gas stream also serves to remove molten material, particularly from deep cuts. The table on the following page gives cutting information for various stainless steels.

Parameters Used in CO_2 Laser Cutting of Stainless Steels

Thickness mm	Thickness in.	Assisting gas	Cutting Rate mm/min	Cutting Rate in./min
1250 watt laser[a]				
1.0	0.040[b]	oxygen	8890	350
3.2	0.125[b]	oxygen	3050	120
3.2	0.125[b]	air	1520	60
5.2	0.205[c]	oxygen	1780	70
1000 watt laser				
0.5	0.02	oxygen	19000	750
0.8	0.032	oxygen	16500	650
1.0	0.04[d]	oxygen	14000	550
1.6	0.062	oxygen	11400	450
2.0	0.08	oxygen	8260	325
3.2	0.125	oxygen	5080	200
500 watt laser				
0.1	0.004	oxygen	5000	197
0.3	0.012	oxygen	3710	146
1.0	0.039	oxygen	1650	65
1.6	0.063	oxygen	1900	75
3.2	0.126	oxygen	890	35
6.4	0.252	oxygen	510	20
250 watt laser				
0.6	0.025[d]	oxygen	4570	180
1.6	0.063[e]	oxygen[f]	1520	60
2.3	0.09[d]	oxygen	760	30
3.2	0.0125	oxygen[g]	250	10

[a] TEMoo mode
[b] austenitic alloy
[c] ferritic/martensitic alloy
[d] Type 321
[e] Type 410, Type 321
[f] 414 kPa (60 psi)
[g] 483 kPa (70 psi)

Sources: "Laser Beam Torch - LBT," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p.12-76; R. J. Saunders, "Laser Metalworking," Metal Progress, July 1984, p.51.

The following table shows some information on drilling.

Parameters for Drilling 0.10-0.13 mm (0.004-0.005 in.) Diameter Holes in Type 304 With ND-YAG Laser

Workpiece Thickness mm in.	Assisting gas	Drilling Time Requirement s	Lamp Current A	Avg. Laser Power of 1.06 µm Wave Length W	Maximum Thickness Drilled mm in.
3.0 0.120	oxygen	88	34	31	4.8 0.190
3.0 0.120	air[a]	80	34	31	4.8 0.190
3.0 0.120	argon	221	34	31	48 0.190

[a] *optimum gas for drilling*
Source: "Laser Beam Torch - LBT," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p.12-90.

For further information, consult the following:
"Laser Beam Machining - LBM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 12-55 to 12-70.
"Laser Beam Torch - LBT," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 12-71 to 12-97.
W. F. Tutte, "The Application of Laser Cutting to Stainless Steel," Stainless Steel Industry, Vol. 15 (No. 86), July 1987, p. 9, 11.
M. Pellecchia, "Lasers: The Manufacturer's Outlook," Nontraditional Machining, ASM, 1986, p. 75-78.
R. J. Saunders, "Laser Metalworking," Metal Progress, July 1984, p. 45-51.
D. Elza and S. Burns, "Lasers Take Their Place in Metalworking," Machine and Tool Blue Book, July 1985, p. 34-38.

Plasma Arc Machining

In plasma arc machining, a stream of gas is ionized and heated by a constricted arc between a tungsten electrode and the workpiece. Material is removed by the high velocity, high-temperature gas stream. Plasma arc machining can be used to cut tough materials with straight or profile cuts at high speeds. It has the ability to cut thick materials, up to about 6 inches (152 mm). Disadvantages include the possibility of dross attached to the bottom of the cut and an appreciable recast layer and heat-affected zone.

The gas used for the arc may be nitrogen, hydrogen, argon or various admixtures. Compressed air may also be used and can increase cutting rates. This depends on the thickness of the stainless steel, as shown in the table on the following page. However, cut surfaces will be oxidized.

Comparison of Plasma Arc Cutting Rates Using Argon/Hydrogen or Air as Primary Gases

Thickness		Cutting Rate			
		Argon/Hydrogen		Air	
mm	in.	mm/min	in./min	mm/min	in./min
5	0.2	5000	197	5000	197
10	0.4	2600	102	3400	134
15	0.6	1500	59	1800	71
20	0.8	1100	43	1200	47
25	1.0	800	31	850	33
30	1.2	650	26	600	24
35	1.4	500	20	400	16
40	1.6	400	16	300	12
45	1.8	350	14	250	10
50	2.0	300	14	200	8
60	2.4	300	12	200	8

Source: S. Holden, "The Plasma Cutting of Stainless Steel," Stainless Steel Industry, Vol. 13 (No. 74), July 1985, p. 13.

An external shielding gas around the primary arc may be used to more easily remove molten metal from the cut. For stainless steels, carbon dioxide may be used with nitrogen as the primary gas. Water may be used in place of a shielding gas or may be injected into the plasma stream to produce a cleaner cut with a reduced bevel. Nozzle life can also be improved by the cooling action of the water.

For further information, consult the following:

"Plasma Beam Machining - PBM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 12-97 to 12-104.
S. Holden, "The Plasma Cutting of Stainless Steel," Stainless Steel Industry, Vol. 13 (No. 74), July 1985 p. 12-25.
T. E. Gittens, "Plasma Arc Cutting - Process Fundamentals," AFS Transactions, Vol. 92, 1984, p. 29-35.

The following tables provide guidelines for cutting stainless steels.

Plasma Arc Cutting Parameters For Stainless Steels

Thickness mm	Thickness in.	Cutting Speed mm/min	Cutting Speed in./min	Power Selection A
6	0.25	1780	70	105
		2540	100	140
		3810	150	210
13	0.5	510	20	135
		1020	40	190
		1780	70	250
		2540	100	270
		3810	150	700
		5330	210	1000
25	1	250	10	175
		510	20	210
		760	30	270
		1020	40	350
		2030	80	540
		2790	110	1000
38	1.5	250	10	280
		510	20	420
		1020	40	620
		1780	70	1000
51	2	130	5	320
		250	10	420
		510	20	610
		1020	40	950
64	2.5	130	5	410
		250	10	550
		510	20	820
76	3	130	5	510
		250	10	675
		510	20	1020
89	3.5	130	5	550
		250	10	730
		510	20	1110
102	4	130	5	675
		250	10	900
114	4.5	130	5	900
127	5	76	3	1100
140	5.5	76	3	1100

Source: "Plasma Beam Machining - PBM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 12-99, 12-100.

Plasma Arc Cutting Parameters for Stainless Steels

Machining Conditions	Thickness mm	in.	Cutting Speed Best mm/min	in./min	Max mm/min	in./min
100 A	6	0.25	1270	50	2540	100
Primary gas: nitrogen[(a)]	13	0.50	510	20	760	30
Secondary gas:	19	0.75	300	12	380	15
carbon dioxide[(b)]	25	1.00	230	9	280	11
200 A	6	0.25	1650	65	3430	135
Primary gas: nitrogen[(c)]	13	0.50	1270	50	1780	70
Secondary gas:	19	0.75	890	35	1270	50
carbon dioxide[(b)]	25	1.00	510	20	660	26
	38	1.50	300	12	410	16
400 A	13	0.50	1910	75	3050	120
Primary gas: nitrogen[(d)]	25	1.00	1020	40	1400	55
Secondary gas:	38	1.50	640	25	970	38
carbon dioxide[(b)]	51	2.00	430	17	710	28
	64	2.50	300	12	380	15
	76	3.00	200	8	250	10
300 A	6	0.25	1910	75	3300	130
Primary gas: nitrogen[(e)]	13	0.50	1270	50	1780	70
Water injection[(f)]	19	0.75	1020	40	1400	55
	25	1.00	640	25	890	35
	32	1.25	480	19	580	23
	38	1.50	380	15	460	18

(a) 433 cm3/s (55 ft3./hr), 207 kPa (30 lb/in.2)
(b) 1652 cm3/s (210 ft3./hr), 276 kPa (40 lb/in.2)
(c) 551 cm3/s (70 ft3./hr), 207 kPa (30 lb/in.2)
(d) 393 cm3/s (50 ft3./hr), 138 kPa (20 lb/in.2)
(e) 590 cm3/s (75 ft3./hr), 207 kPa (30 lb/in.2)
(f) 30-57 L/hr (8-15 gal/hr)

Source: "Plasma Beam Machining - PBM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc.,1980, p.12-102, 12-103

Plasma Arc Cutting Parameters for Stainless Steels

Machining Conditions	Thickness mm	in.	Cutting Speed mm/min	in./min
50-100 A	1.5	0.062	7110	280
	3	0.125	4950	195
Primary gas: nitrogen[(a)]	5	0.188	2160	85
Secondary gas: carbon dioxide[(b)]	6	0.250	1780	70
	10	0.375	1400	55
	12	0.500	1020	40

(a) 118 cm3/s (15 ft3./hr), 241-276 kPa (35-40 lb/in.2)
(b) 1180 cm3/s (150 ft3./hr), 310-345 kPa (45-50 lb/in.2)

Source: "Plasma Beam Machining - PBM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc.,1980, p.12-103

Chemical Machining

Chemical machining essentially involves controlled corrosion of the workpiece. A strippable maskant covers areas which are not to be removed. The depth of cut is normally limited to about 0.25 to 0.50 inches (6 to 13 mm); therefore, chemical machining is best suited for machining large, shallow areas. Cut materials will be burr-free, without the introduction of residual stresses or a heat-affected zone. Disadvantages include the danger from the corrosive solutions, low cutting rates, and the fact that the masked areas will be undercut by the corroding solution. In addition, hydrogen embrittlement may be a problem with hardened martensitic alloys and intergranular corrosion may occur, depending on the condition of the workpiece.

Parameters for Chemical Machining

Etchant	Concentration	Temp. °C	Temp. °F	Etching Rate mm/min	Etching Rate in. x 10^{-3}/min	Maskant	Etch Factor[a]	Routine tolerance for depth of cut ±mm	Routine tolerance for depth of cut ±in.	Surface roughness Ra µm	Surface roughness Ra µin.
Austenitic Stainless Steels											
$FeCl_3$[b]	42° Baumé	54	130	0.020-0.130	0.8-5.0	Polyvinyl Chloride	1.5-2.0	0.1	0.004	1.6	63
Martensitic Stainless Steels											
$FeCl_3$[b]	52° Baumé	54	130	0.006	0.25	Polyvinyl Chloride	—	0.1	0.004	3.2	125

[a] The ratio of depth of undercut to depth of cut.
[b] or HCl : HNO_3
Source: "Chemical Machining - CHM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, pp. 13-16.

For further information, consult the following:
"Chemical Machining - CHM," Machining Data Handbook, Vol. 2, Metcut Res. Assoc., 1980, p. 13-3 to 13-16.

AUTOMATIC MACHINING EFFICIENCY INDEX TABLE

Cycle time (Number of seconds)	Parts per hour based on cycle time and efficiency				
	Gross production	90% efficiency	80% efficiency	70% efficiency	60% efficiency
1	3600	3240	2880	2520	2160
1¼	2888	2600	2315	2022	1732
1½	2400	2160	1930	1680	1441
1¾	2056	1849	1643	1440	1233
2	1800	1620	1440	1263	1082
2½	1440	1296	1152	1008	864
3	1200	1080	960	840	720
3½	1029	925	822	719	616
4	900	810	720	630	540
4½	800	720	640	560	480
5	720	648	576	504	432
5½	654	589	523	458	393
6	600	540	480	420	360
6½	554	498	443	388	332
7	514	463	412	360	309
7½	480	432	384	336	288
8	450	405	360	315	270
8½	423	381	339	296	254
9	400	360	320	280	240
9½	379	341	303	265	227
10	360	324	288	252	216
11	327	295	262	229	196
12	300	270	240	210	180
13	277	249	221	194	166
14	257	231	206	180	154
15	240	216	192	168	144
16	225	202	180	157	135
17	212	190	169	148	127
18	200	180	160	140	120
19	189	170	151	132	114
20	180	162	144	126	108

Cycle time (Number of seconds)	Parts per hour based on cycle time and efficiency				
	Gross production	90% efficiency	80% efficiency	70% efficiency	60% efficiency
21	171	154	137	120	103
22	163	147	131	114	98
23	156	141	125	110	94
24	150	135	120	105	90
25	144	129	115	101	86
26	138	124	110	97	83
27	133	120	107	93	80
28	128	115	103	90	77
29	124	111	99	87	74
30	120	108	96	84	72
35	103	92	82	72	62
40	90	81	72	63	54
45	80	72	64	56	48
50	72	65	57	50	43
55	65	59	52	46	39
60	60	54	48	42	36
70	51	46	41	36	31
80	45	40	36	31	27
90	40	36	32	28	24
100	36	32	29	25	22
110	33	29	26	23	19.6
120	30	27	24	21	18
140	26	23	20	18	15.4
160	22	20.2	18	15.7	13.5
180	20	18	16	14	12
200	18	16.2	14.4	12.6	10.1
220	16.4	14.6	13.1	11.5	9.8
240	15	13.5	12	10.5	9
260	13.8	12.5	11.1	9.7	8.3
280	12.8	11.5	10.3	9	7.7
300	12	10.8	9.6	8.4	7.2

MACHINE HOURS PER 1,000 PIECES BASED ON HOURLY PRODUCTION

Net hourly production	Machine hours per 1000 pieces	Net hourly production	Machine hours per 1000 pieces	Net hourly production	Machine hours per 1000 pieces
1	1000.	43	23.3	85	11.8
2	500.	44	22.7	86	11.6
3	333.3	45	22.2	87	11.5
4	250.	46	21.7	88	11.4
5	200.	47	21.3	89	11.3
6	166.6	48	20.9	90	11.1
7	142.8	49	20.4	91	11.
8	125.	50	20.	92	10.9
9	111.1	51	19.6	93	10.8
10	100.	52	19.2	94	10.7
11	90.9	53	18.9	95	10.5
12	83.3	54	18.5	96	10.4
13	77.	55	18.2	97	10.3
14	71.4	56	17.8	98	10.2
15	66.6	57	17.5	99	10.1
16	62.5	58	17.3	100	10.
17	58.8	59	17.	101	9.9
18	55.5	60	16.7	102	9.8
19	52.6	61	16.4	103	9.7
20	50.	62	16.1	104	9.6
21	47.6	63	15.9	105	9.5
22	45.4	64	15.6	106	9.4
23	43.4	65	15.4	107	9.3
24	41.6	66	15.2	108	9.3
25	40.	67	15.	109	9.2
26	38.5	68	14.7	110	9.1
27	37.1	69	14.5	112	9.
28	35.7	70	14.3	114	8.8
29	34.5	71	14.1	116	8.6
30	33.3	72	13.9	118	8.5
31	32.2	73	13.7	120	8.35
32	31.3	74	13.5	122	8.2
33	30.3	75	13.3	124	8.07
34	29.4	76	13.2	126	7.95
35	28.6	77	13.	128	7.81
36	27.8	78	12.8	130	7.7
37	27.	79	12.6	132	7.57
38	26.3	80	12.5	134	7.46
39	25.6	81	12.4	136	7.35
40	25.	82	12.2	138	7.25
41	24.4	83	12.1	140	7.15
42	23.8	84	11.9	142	7.05

Net hourly production	Machine hours per 1000 pieces	Net hourly production	Machine hours per 1000 pieces	Net hourly production	Machine hours per 1000 pieces
144	6.95	350	2.86	960	1.04
146	6.85	360	2.78	980	1.02
148	6.75	370	2.70	1000	1.
150	6.65	380	2.63	1050	.96
155	6.45	390	2.56	1100	.91
160	6.25	400	2.50	1150	.87
165	6.05	410	2.44	1200	.84
170	5.88	420	2.38	1250	.80
175	5.72	430	2.33	1300	.77
180	5.55	440	2.27	1350	.74
185	5.40	450	2.22	1400	.72
190	5.26	460	2.18	1450	.69
195	5.13	470	2.13	1500	.67
200	5.	480	2.08	1600	.63
205	4.88	490	2.04	1700	.59
210	4.76	500	2.	1800	.56
215	4.65	510	1.96	1900	.53
220	4.54	520	1.92	2000	.50
225	4.44	530	1.89	2100	.48
230	4.35	540	1.85	2200	.46
235	4.25	550	1.82	2300	.44
240	4.17	560	1.79	2400	.42
245	4.08	570	1.76	2500	.40
250	4.	580	1.73	2600	.39
255	3.92	590	1.70	2700	.37
260	3.85	600	1.67	2800	.36
265	3.77	620	1.62	2900	.35
270	3.70	640	1.57	3000	.33
275	3.64	660	1.52	3100	.32
280	3.57	680	1.47	3200	.31
285	3.51	700	1.43	3300	.31
290	3.45	720	1.39	3400	.30
295	3.39	740	1.35	3500	.29
300	3.33	760	1.32	3600	.28
305	3.28	780	1.29	3700	.27
310	3.23	800	1.25	3800	.26
315	3.18	820	1.22	3900	.26
320	3.13	840	1.19	4000	.25
325	3.08	860	1.17	4200	.24
330	3.03	880	1.14	4400	.23
335	2.98	900	1.11	4600	.22
340	2.94	920	1.09	4800	.21
345	2.90	940	1.07	5000	.20

APPROXIMATE STOCK REQUIRED TO MAKE 1,000 PIECES

Length of finished piece plus cut-off —inches	Number of feet per 1000 pieces	Length of finished piece plus cut-off —inches	Number of feet per 1000 pieces	Length of finished piece plus cut-off —inches	Number of feet per 1000 pieces	Length of finished piece plus cut-off —inches	Number of feet per 1000 pieces
1/64	1.302	31/64	40.364	61/64	79.427	1 27/64	118.489
1/32	2.604	1/2	41.666	31/32	80.729	1 7/16	119.792
3/64	3.906	33/64	42.969	63/64	82.031	1 29/64	121.094
1/16	5.208	17/32	44.271	1	83.333	1 15/32	122.396
5/64	6.510	35/64	45.573	1 1/64	84.635	1 31/64	123.698
3/32	7.812	9/16	46.875	1 1/32	85.937	1 1/2	125.000
7/64	9.115	37/64	48.177	1 3/64	87.239	1 33/64	126.302
1/8	10.417	19/32	49.479	1 1/16	88.542	1 17/32	127.604
9/64	11.719	39/64	50.781	1 5/64	89.844	1 35/64	118.906
5/32	13.021	5/8	52.083	1 3/32	91.146	1 9/16	130.208
11/64	14.323	41/64	53.385	1 7/64	92.448	1 37/64	131.510
3/16	15.625	21/32	54.687	1 1/8	93.750	1 19/32	132.812
13/64	16.927	43/64	55.989	1 9/64	95.052	1 39/64	134.115
7/32	18.230	11/16	57.292	1 5/32	96.354	1 5/8	135.417
15/64	19.531	45/64	58.594	1 11/64	97.656	1 41/64	136.719
1/4	20.833	23/32	59.896	1 3/16	98.958	1 21/32	138.021
17/64	22.135	47/64	61.198	1 13/64	100.260	1 43/64	139.323
9/32	23.437	3/4	62.500	1 7/32	101.562	1 11/16	140.625
19/64	24.739	49/64	63.802	1 15/64	102.864	1 45/64	141.927
5/16	26.042	25/32	65.104	1 1/4	104.167	1 23/32	143.229
21/64	27.344	51/64	66.406	1 17/64	105.469	1 47/64	144.531
11/32	28.646	13/16	67.708	1 9/32	106.771	1 3/4	145.833
23/64	29.948	53/64	69.010	1 19/64	108.073	1 49/64	147.135
3/8	31.250	27/32	70.312	1 5/16	109.375	1 25/32	148.437
25/64	32.552	55/64	71.614	1 21/64	110.677	1 51/64	149.739
13/32	33.854	7/8	72.917	1 11/32	111.979	1 13/16	151.042
27/64	35.156	57/64	74.219	1 23/64	113.281	1 53/64	152.344
7/16	36.458	29/32	75.521	1 3/8	114.583	1 27/32	153.646
29/64	37.760	59/64	76.823	1 25/64	115.885	1 55/64	154.948
15/32	39.062	15/16	78.125	1 13/32	117.187	1 7/8	156.250

Based on 12′0″ bars, the losses in bar ends are:

1″ bar end—0.7%
2″ " " —1.38%
3″ " " —2.08%
4″ " " —2.80%

Length of finished piece plus cut-off —inches	Number of feet per 1000 pieces	Length of finished piece plus cut-off —inches	Number of feet per 1000 pieces	Length of finished piece plus cut-off —inches	Number of feet per 1000 pieces	Length of finished piece plus cut-off —inches	Number of feet per 1000 pieces
1 57/64	157.552	2 23/64	196.615	2 53/64	235.677	3 19/64	274.739
1 29/32	158.854	2 3/8	197.917	2 27/32	236.979	3 5/16	276.042
1 59/64	160.156	2 25/64	199.219	2 55/64	238.281	3 21/64	277.344
1 15/16	161.458	2 13/32	200.521	2 7/8	239.583	3 11/32	278.646
1 61/64	162.760	2 27/64	201.823	2 57/64	240.885	3 23/64	279.948
1 31/32	164.062	2 7/16	203.125	2 29/32	242.188	3 3/8	281.250
1 63/64	165.365	2 29/64	204.427	2 59/64	243.490	3 25/64	282.552
2	166.667	2 15/32	205.729	2 15/16	244.792	3 13/32	283.854
2 1/64	167.969	2 31/64	207.031	2 61/64	246.094	3 27/64	285.156
2 1/32	169.271	2 1/2	208.333	2 31/32	247.396	3 7/16	286.458
2 3/64	170.573	2 33/64	209.635	2 63/64	248.698	3 29/64	287.760
2 1/16	171.875	2 17/32	210.938	3	250.000	3 15/32	289.062
2 5/64	173.177	2 35/64	212.240	3 1/64	251.302	3 31/64	290.365
2 3/32	174.479	2 9/16	213.542	3 1/32	252.604	3 1/2	291.667
2 7/64	175.781	2 37/64	214.844	3 3/64	253.906	3 33/64	292.969
2 1/8	177.083	2 19/32	216.146	3 1/16	255.208	3 17/32	294.271
2 9/64	178.385	2 39/64	217.448	3 5/64	256.510	3 35/64	295.573
2 5/32	179.688	2 5/8	218.750	3 3/32	257.813	3 9/16	296.875
2 11/64	180.990	2 41/64	220.052	3 7/64	259.115	3 37/64	298.177
2 3/16	182.292	2 21/32	221.354	3 1/8	260.417	3 19/32	299.479
2 13/64	183.594	2 43/64	222.656	3 9/64	261.719	3 39/64	300.781
2 7/32	184.896	2 11/16	223.958	3 5/32	263.021	3 5/8	302.083
2 15/64	186.198	2 45/64	225.260	3 11/64	264.323	3 41/64	303.385
2 1/4	187.500	2 23/32	226.563	3 3/16	265.625	3 21/32	304.688
2 17/64	188.802	2 47/64	227.865	3 13/64	266.927	3 43/64	305.990
2 9/32	190.104	2 3/4	229.167	3 7/32	268.229	3 11/16	307.292
2 19/64	191.406	2 49/64	230.469	3 15/64	269.531	3 45/64	308.594
2 5/16	192.708	2 25/32	231.771	3 1/4	270.833	3 23/32	309.896
2 21/64	194.010	2 51/64	233.073	3 17/64	272.135	3 47/64	311.198
2 11/32	195.312	2 13/16	234.375	3 9/32	273.437	3 3/4	312.500

*WEIGHTS OF STEEL BARS PER LINEAL FOOT

Size in inches	Round	Square	Hexagon	Octagon
1/32	.0026	.0033	.0029	.0028
1/16	.0104	.0133	.0115	.0110
1/8	.0417	.0531	.0460	.0440
3/16	.0938	.1195	.1035	.0990
1/4	.1669	.2123	.1840	.1760
5/16	.2608	.3333	.2875	.2751
3/8	.3756	.4782	.4141	.3961
7/16	.5111	.6508	.5636	.5391
1/2	.6676	.8500	.7361	.7042
9/16	.8449	1.076	.9317	.8912
5/8	1.043	1.328	1.150	1.100
11/16	1.262	1.608	1.392	1.331
3/4	1.502	1.913	1.656	1.584
13/16	1.763	2.245	1.944	1.859
7/8	2.044	2.603	2.254	2.157
15/16	2.347	2.989	2.588	2.476
1	2.670	3.400	2.945	2.817
1 1/16	3.014	3.838	3.324	3.180
1 1/8	3.379	4.303	3.727	3.565
1 3/16	3.766	4.795	4.152	3.972
1 1/4	4.173	5.312	4.601	4.401
1 5/16	4.600	5.857	5.072	4.852
1 3/8	5.019	6.428	5.567	5.325
1 7/16	5.518	7.026	6.085	5.820
1 1/2	6.008	7.650	6.625	6.338
1 9/16	6.520	8.301	7.189	6.877
1 5/8	7.051	8.978	7.775	7.438
1 11/16	7.604	9.682	8.385	8.021
1 3/4	8.178	10.41	9.018	8.626
1 13/16	8.773	11.17	9.673	9.253
1 7/8	9.388	11.95	10.35	9.902
1 15/16	10.02	12.76	11.05	10.57
2	10.68	13.60	11.78	11.27
2 1/16	11.36	14.46	12.53	11.98
2 1/8	12.06	15.35	13.30	12.72
2 3/16	12.78	16.27	14.09	13.48
2 1/4	13.52	17.22	14.91	14.26
2 5/16	14.28	18.19	15.75	15.06
2 3/8	15.07	19.18	16.61	15.89
2 7/16	15.86	20.20	17.49	16.73
2 1/2	16.69	21.25	18.40	17.60
2 9/16	17.53	22.33	19.33	18.50
2 5/8	18.40	23.43	20.29	19.41
2 11/16	19.29	24.56	21.27	20.34
2 3/4	20.20	25.71	22.27	21.30
2 13/16	21.12	26.90	23.29	22.28
2 7/8	22.07	28.10	24.34	23.28
2 15/16	23.04	29.34	25.41	24.30

**Weights are based on 489.6 lbs. per cubic foot of steel.*

See page 164 for decimal and metric equivalents for fractional sizes

Size in inches	Round	Square	Hexagon	Octagon
3	25.03	30.60	26.50	25.35
3 1/16	25.04	31.89	27.62	26.42
3 1/8	26.08	33.20	28.75	27.51
3 3/16	27.13	34.55	29.92	28.62
3 1/4	28.20	35.92	31.10	29.75
3 5/16	29.30	37.31	32.31	30.91
3 3/8	30.42	38.73	33.54	32.08
3 7/16	31.56	40.18	34.79	33.28
3 1/2	32.71	41.65	36.07	34.50
3 9/16	33.90	43.14	37.37	35.75
3 5/8	35.09	44.68	38.69	37.01
3 11/16	36.31	46.24	40.04	38.30
3 3/4	37.56	47.82	41.41	39.61
3 13/16	38.81	49.42	42.80	40.94
3 7/8	40.10	51.05	44.21	42.29
3 15/16	41.40	52.71	45.65	43.67
4	42.73	54.40	47.11	45.07
4 1/16	44.07	56.11	48.65	46.45
4 1/8	45.44	57.85	50.10	47.93
4 3/16	46.83	59.62	51.60	49.38
4 1/4	48.24	61.41	53.16	50.88
4 5/16	49.66	63.23	54.70	52.34
4 3/8	51.11	65.08	56.36	53.91
4 7/16	52.58	66.95	58.05	55.45
4 1/2	54.07	68.85	59.63	57.04
4 9/16	55.59	70.78	61.29	58.62
4 5/8	57.12	72.73	62.98	60.25
4 11/16	58.67	74.70	64.70	61.83
4 3/4	60.25	76.71	66.44	63.55
4 13/16	61.84	78.74	68.25	65.19
4 7/8	63.46	80.81	70.05	66.92
4 15/16	65.10	82.89	71.81	68.64
5	66.76	85.00	73.61	70.42
5 1/16	68.44	87.14	75.53	72.20
5 1/8	70.14	89.30	77.37	73.93
5 3/16	71.86	91.49	79.35	75.79
5 1/4	73.60	93.72	81.16	77.63
5 5/16	75.37	95.96	83.15	79.45
5 3/8	77.15	98.23	85.13	81.40
5 7/16	78.95	100.5	87.14	83.28
5 1/2	80.77	102.8	89.07	85.20
5 9/16	82.62	105.2	91.18	87.15
5 5/8	84.49	107.6	93.24	89.10
5 11/16	86.38	110.0	95.35	91.08
5 3/4	88.29	112.4	97.35	93.13
5 13/16	90.22	114.9	99.58	95.17
5 7/8	92.17	117.4	101.7	96.20
5 15/16	94.14	119.9	103.9	99.26

*WEIGHTS OF STEEL BARS PER LINEAL FOOT (Continued)

Size in inches	Round	Square	Hexagon	Octagon
6	96.14	122.4	106.0	101.4
6 1/16	98.14	125.0	108.2	103.4
6 1/8	100.2	127.6	110.4	105.7
6 3/16	102.2	130.2	112.7	107.7
6 1/4	104.3	132.8	115.1	109.9
6 5/16	106.4	135.5	117.3	112.2
6 3/8	108.5	138.2	119.6	114.3
6 7/16	110.7	140.9	122.0	116.7
6 1/2	112.8	143.6	124.4	118.9
6 9/16	114.9	146.5	126.7	121.2
6 5/8	117.2	149.2	129.3	123.5
6 11/16	119.4	152.1	131.8	125.9
6 3/4	121.7	154.9	134.0	128.4
6 13/16	123.9	157.8	136.7	130.6
6 7/8	126.2	160.8	139.1	133.0
6 15/16	128.5	163.6	141.7	135.4
7	130.9	166.6	144.3	138.0
7 1/16	133.2	169.6	146.8	140.4
7 1/8	135.6	172.6	149.4	142.8
7 3/16	137.9	175.6	152.1	145.4
7 1/4	140.4	178.7	154.8	148.0
7 5/16	142.8	181.8	157.5	150.6
7 3/8	145.3	184.9	160.3	153.2
7 7/16	147.7	188.1	162.8	156.7
7 1/2	150.2	191.3	165.6	158.4
7 9/16	152.7	194.4	168.3	160.8
7 5/8	155.2	197.7	171.2	163.0
7 11/16	157.8	200.9	174.1	166.3
7 3/4	160.3	204.2	176.7	168.9
7 13/16	163.0	207.6	179.7	171.8
7 7/8	165.6	210.8	182.6	174.5
7 15/16	168.2	214.2	185.5	177.3
8	171.0	217.6	188.4	180.3
8 1/16	173.6	221.0	191.4	182.9
8 1/8	176.3	224.5	194.5	185.8
8 3/16	179.0	228.0	197.4	188.7
8 1/4	181.8	231.4	200.6	191.7
8 5/16	184.5	234.9	203.5	194.5
8 3/8	187.3	238.5	206.7	197.4
8 7/16	190.1	242.0	209.7	200.5
8 1/2	193.0	245.6	212.7	203.5
8 9/16	195.7	249.3	215.7	206.3
8 5/8	198.7	252.9	219.6	209.4
8 11/16	201.6	256.6	222.3	212.4
8 3/4	204.4	260.3	225.5	215.5
8 13/16	207.4	264.1	228.7	218.7
8 7/8	210.3	267.9	232.0	221.7
8 15/16	213.3	271.6	235.2	224.8

**Weights are based on 489.6 lbs. per cubic foot of steel.*

Size in inches	Round	Square	Hexagon	Octagon
9	216.3	275.4	238.5	228.1
9 1/16	219.3	279.3	241.9	231.2
9 1/8	222.4	283.2	245.4	234.6
9 3/16	225.4	287.0	248.6	237.5
9 1/4	228.5	290.9	252.2	240.8
9 5/16	231.5	294.9	255.4	244.0
9 3/8	234.7	298.9	259.0	247.5
9 7/16	237.9	302.8	262.4	250.8
9 1/2	241.0	306.8	265.7	254.2
9 9/16	244.2	310.9	269.4	257.4
9 5/8	247.4	315.0	273.8	260.8
9 11/16	250.6	319.1	276.6	264.2
9 3/4	253.9	323.2	280.1	267.6
9 13/16	257.1	327.4	283.6	271.0
9 7/8	260.4	331.6	287.4	274.6
9 15/16	263.7	335.8	290.8	278.0
10	267.0	340.0	294.4	281.7
10 1/16	270.4	344.3	298.4	285.3
10 1/8	273.8	348.5	302.2	288.8
10 3/16	277.1	352.9	305.6	292.1
10 1/4	280.6	357.2	309.6	296.9
10 5/16	284.0	361.6	313.4	299.4
10 3/8	287.4	366.0	317.0	303.0
10 7/16	290.9	370.4	320.8	306.8
10 1/2	294.4	374.9	325.0	310.5
10 9/16	297.9	379.4	328.6	314.1
10 5/8	301.4	383.8	332.5	316.8
10 11/16	305.0	388.3	336.5	321.6
10 3/4	308.6	392.9	340.5	325.4
10 13/16	312.2	397.5	344.3	329.2
10 7/8	315.8	402.1	348.4	333.0
10 15/16	319.5	406.8	353.5	337.0
11	323.1	411.4	356.3	340.8
11 1/16	326.8	416.1	360.7	344.7
11 1/8	330.5	420.9	364.7	348.5
11 3/16	334.3	425.5	368.8	352.4
11 1/4	337.9	430.3	372.6	356.3
11 5/16	341.7	435.1	376.7	360.2
11 3/8	345.5	439.9	381.2	364.3
11 7/16	349.4	444.8	385.6	368.3
11 1/2	353.1	449.6	389.5	372.2
11 9/16	357.0	454.5	392.8	376.5
11 5/8	360.9	459.5	398.2	380.6
11 11/16	364.8	464.4	402.7	384.7
11 3/4	368.6	469.4	406.6	388.6
11 13/16	372.6	474.4	411.1	392.8
11 7/8	376.6	479.5	415.7	397.2
11 15/16	380.6	484.5	419.5	401.4
12	384.4	489.6	424.0	405.6

DECIMAL SIZES OF DRILLS AND LENGTH OF DRILL POINTS
Based on 118° point angle

Drill	Diam. inches	Length of point inches	Drill	Diam. inches	Length of point inches	Drill	Diam. inches	Length of point inches
80	.0135	.004	1.7 mm	.0669	.020	3.5 mm	.1378	.041
79	.0145	.004	51	.0670	.020	28	.1405	.042
1/64	.0156	.005	50	.0700	.021	9/64	.1406	.042
78	.0160	.005	1.8 mm	.0709	.021	3.6 mm	.1417	.042
77	.0180	.005	49	.0730	.022	27	.1440	.043
.5 mm	.0197	.006	1.9 mm	.0748	.023	3.7 mm	.1457	.044
76	.0200	.006	48	.0760	.023	26	.1470	.044
75	.0210	.006	5/64	.0781	.024	25	.1495	.045
74	.0225	.007	47	.0785	.024	3.8 mm	.1496	.045
.6 mm	.0236	.007	2. mm	.0787	.024	24	.1520	.046
73	.0240	.007	46	.0810	.024	3.9 mm	.1535	.046
72	.0250	.008	45	.0820	.025	23	.1540	.046
71	.0260	.008	2.1 mm	.0827	.025	5/32	.1562	.047
.7 mm	.0276	.008	44	.0860	.026	22	.1570	.047
70	.0280	.008	2.2 mm	.0866	.026	4. mm	.1575	.047
69	.0292	.009	43	.0890	.027	21	.1590	.048
68	.0310	.009	2.3 mm	.0905	.027	20	.1610	.048
1/32	.0313	.009	42	.0935	.028	4.1 mm	.1614	.048
.8 mm	.0315	.010	3/32	.0937	.028	4.2 mm	.1654	.050
67	.0320	.010	2.4 mm	.0945	.028	19	.1660	.050
66	.0330	.010	41	.0960	.029	4.3 mm	.1693	.051
65	.0350	.011	40	.0980	.029	18	.1695	.051
.9 mm	.0354	.011	2.5 mm	.0984	.029	11/64	.1719	.052
64	.0360	.011	39	.0995	.029	17	.1730	.052
63	.0370	.011	38	.1015	.030	4.4 mm	.1732	.052
62	.0380	.011	2.6 mm	.1024	.031	16	.1770	.053
61	.0390	.012	37	.1040	.031	4.5 mm	.1771	.053
1. mm	.0394	.012	2.7 mm	.1063	.032	15	.1800	.054
60	.0400	.012	36	.1065	.032	4.6 mm	.1811	.054
59	.0410	.012	7/64	.1093	.033	14	.1820	.055
58	.0420	.013	35	.1100	.033	13	.1850	.056
57	.0430	.013	2.8 mm	.1102	.033	4.7 mm	.1850	.056
1.1 mm	.0433	.013	34	.1110	.033	3/16	.1875	.056
56	.0465	.014	33	.1130	.034	4.8 mm	.1890	.057
3/64	.0469	.014	2.9 mm	.1142	.034	12	.1890	.057
1.2 mm	.0472	.014	32	.1160	.035	11	.1910	.057
1.3 mm	.0512	.015	3. mm	.1181	.035	4.9 mm	.1929	.058
55	.0520	.016	31	.1200	.036	10	.1935	.058
54	.0550	.017	3.1 mm	.1220	.037	9	.1960	.059
1.4 mm	.0551	.017	1/8	.1250	.037	5. mm	.1968	.059
1.5 mm	.0591	.018	3.2 mm	.1260	.038	8	.1990	.060
53	.0595	.018	30	.1285	.039	5.1 mm	.2008	.060
1/16	.0625	.019	3.3 mm	.1299	.039	7	.2010	.060
1.6 mm	.0629	.019	3.4 mm	.1339	.040	13/64	.2031	.061
52	.0635	.019	29	.1360	.041	6	.2040	.061

Drill	Diam. inches	Length of point inches	Drill	Diam. inches	Length of point inches	Drill	Diam. inches	Length of point inches
5.2 mm	.2047	.062	**M**	.2950	.089	**Y**	.4040	.121
5	.2055	.062	7.5 mm	.2953	.089	13/32	.4062	.122
5.3 mm	.2087	.063	19/64	.2968	.089	**Z**	.4130	.124
4	.2090	.063	7.5 mm	.2992	.090	10.5 mm	.4134	.124
5.4 mm	.2126	.064	**N**	.3020	.091	27/64	.4219	.127
3	.2130	.064	7.7 mm	.3031	.091	11. mm	.4330	.130
5.5 mm	.2165	.065	7.8 mm	.3071	.092	7/16	.4375	.131
7/32	.2187	.066	7.9 mm	.3110	.093	11.5 mm	.4528	.136
5.6 mm	.2205	.066	5/16	.3125	.094	29/64	.4531	.136
2	.2210	.066	8. mm	.3150	.095	15/32	.4687	.141
5.7 mm	.2244	.067	**O**	.3160	.095	12. mm	.4724	.142
1	.2280	.068	8.1 mm	.3189	.096	31/64	.4843	.145
5.8 mm	.2283	.069	8.2 mm	.3228	.097	12.5 mm	.4921	.148
5.9 mm	.2323	.070	**P**	.3230	.097	1/2	.5000	.150
A	.2340	.070	8.3 mm	.3268	.098	13. mm	.5118	.154
15/64	.2344	.070	21/64	.3281	.098	33/64	.5156	.155
6. mm	.2362	.071	8.4 mm	.3307	.099	17/32	.5312	.160
B	.2380	.071	**O**	.3320	.099	13.5 mm	.5315	.160
6.1 mm	.2401	.072	8.5 mm	.3346	.101	35/64	.5469	.164
C	.2420	.073	8.6 mm	.3386	.102	14. mm	.5512	.166
6.2 mm	.2441	.073	**R**	.3390	.102	9/16	.5625	.169
D	.2460	.074	8.7 mm	.3425	.103	14.5 mm	.5709	.172
6.3 mm	.2480	.075	11/32	.3437	.103	37/64	.5781	.174
E	.2500	.075	8.8 mm	.3465	.104	15. mm	.5906	.177
1/4	.2500	.075	**S**	.3480	.104	19/32	.5937	.178
6.4 mm	.2520	.076	8.9 mm	.3504	.105	39/64	.6094	.183
6.5 mm	.2559	.077	9. mm	.3543	.105	15.5 mm	.6102	.183
F	.2570	.077	**T**	.3580	.108	5/8	.6250	.188
6.6 mm	.2598	.078	9.1 mm	.3583	.108	16. mm	.6299	.189
G	.2610	.078	23/64	.3594	.108	41/64	.6406	.193
6.7 mm	.2638	.079	9.2 mm	.3622	.109	16.5 mm	.6496	.195
17/64	.2656	.080	9.3 mm	.3661	.110	21/32	.6562	.197
H	.2660	.080	**U**	.3680	.111	17. mm	.6693	.201
6.8 mm	.2677	.080	9.4 mm	.3701	.111	43/64	.6719	.202
6.9 mm	.2716	.082	9.5 mm	.3740	.112	11/16	.6875	.206
I	.2720	.082	3/8	.3750	.113	17.5 mm	.6890	.207
7. mm	.2756	.083	**V**	.3770	.113	45/64	.7031	.211
J	.2770	.083	9.6 mm	.3780	.114	18. mm	.7087	.213
7.1 mm	.2795	.084	9.7 mm	.3819	.115	23/32	.7187	.216
K	.2811	.084	9.8 mm	.3858	.116	18.5 mm	.7283	.219
9/32	.2812	.084	**W**	.3860	.116	47/64	.7344	.221
7.2 mm	.2835	.085	9.9 mm	.3898	.117	19. mm	.7480	.225
7.3 mm	.2874	.086	25/64	.3906	.117	3/4	.7500	.225
L	.2900	.087	10. mm	.3937	.118	49/64	.7656	.230
7.4 mm	.2913	.087	**X**	.3970	.119	19.5 mm	.7677	.231

DECIMAL SIZES OF DRILLS AND LENGTH OF DRILL POINTS
Based on 118° point angle (Continued)

Drill	Diam. inches	Length of point inches	Drill	Diam. inches	Length of point inches	Drill	Diam. inches	Length of point inches
25/32	.7812	.235	1 11/64	1.1719	.352	1 9/16	1.5625	.469
20. mm	.7874	.236	30. mm	1.1811	.355	40. mm	1.5748	.473
51/64	.7969	.239	1 3/16	1.1875	.357	1 37/64	1.5781	.474
20.5 mm	.8071	.242	30.5 mm	1.2008	.361	19/32	1.5937	.479
13/16	.8125	.244	1 13/64	1.2031	.362	40.5 mm	1.5945	.479
21. mm	.8268	.248	1 7/32	1.2187	.366	1 39/64	1.6094	.483
53/64	.8281	.249	31. mm	1.2205	.367	41. mm	1.6142	.485
27/32	.8437	.253	1 15/64	1.2344	.371	1 5/8	1.6250	.488
21.5 mm	.8465	.254	31.5 mm	1.2402	.373	41.5 mm	1.6339	.491
55/64	.8594	.258	1 1/4	1.2500	.376	1 41/64	1.6406	.493
22. mm	.8661	.260	32. mm	1.2599	.378	42. mm	1.6536	.497
7/8	.8750	.263	1 17/64	1.2656	.380	1 21/32	1.6562	.497
22.5 mm	.8858	.266	32.5 mm	1.2795	.384	1 43/64	1.6719	.502
57/64	.8906	.268	1 9/32	1.2812	.385	42.5 mm	1.6732	.503
23. mm	.9055	.272	1 19/64	1.2969	.390	1 11/16	1.6875	.507
29/32	.9062	.272	33. mm	1.2992	.390	43. mm	1.6929	.509
55/64	.9219	.277	1 5/16	1.3125	.394	1 45/64	1.7031	.512
23.5 mm	.9252	.278	33.5 mm	1.3189	.396	43.5 mm	1.7126	.514
15/16	.9375	.282	1 21/64	1.3281	.399	1 23/32	1.7187	.516
24. mm	.9449	.284	34. mm	1.3386	.402	44. mm	1.7323	.520
61/64	.9531	.286	1 11/32	1.3437	.404	1 47/64	1.7344	.521
24.5 mm	.9646	.290	34.5 mm	1.3583	.408	1 3/4	1.7500	.526
31/32	.9687	.291	1 23/64	1.3594	.408	44.5 mm	1.7520	.526
25. mm	.9843	.296	1 3/8	1.3750	.413	1 49/64	1.7656	.530
63/64	.9844	.296	35. mm	1.3780	.414	45. mm	1.7717	.532
1″	1.0000	.300	1 25/64	1.3906	.418	1 25/32	1.7812	.535
25.5 mm	1.0040	.302	35.5 mm	1.3977	.420	45.5 mm	1.7914	.538
1 1/64	1.0156	.305	1 13/32	1.4062	.422	1 51/64	1.7969	.540
26. mm	1.0236	.307	36. mm	1.4173	.426	46. mm	1.8110	.544
1 1/32	1.0312	.310	1 27/64	1.4219	.427	1 13/16	1.8125	.544
26.5 mm	1.0433	.313	36.5 mm	1.4370	.432	1 53/64	1.8281	.549
1 3/64	1.0469	.314	1 7/16	1.4375	.432	46.5 mm	1.8307	.550
1 1/16	1.0625	.319	1 29/64	1.4531	.437	1 27/32	1.8437	.554
27. mm	1.0630	.319	37. mm	1.4567	.438	47. mm	1.8504	.556
1 5/64	1.0781	.324	1 15/32	1.4687	.441	1 55/64	1.8594	.558
27.5 mm	1.0827	.325	37.5 mm	1.4764	.442	47.5 mm	1.8701	.562
1 3/32	1.0937	.329	1 31/64	1.4844	.446	1 7/8	1.8750	.563
28. mm	1.1024	.331	38. mm	1.4961	.449	48. mm	1.8898	.568
1 7/64	1.1094	.333	1 1/2	1.5000	.451	1 57/64	1.8906	.568
28.5 mm	1.1220	.337	1 33/64	1.5156	.455	1 29/32	1.9062	.573
1 1/8	1.1250	.338	38.5 mm	1.5158	.455	48.5 mm	1.9095	.574
1 9/64	1.1406	.343	1 17/32	1.5312	.460	1 59/64	1.9219	.577
29. mm	1.1417	.343	39. mm	1.5354	.461	49. mm	1.9291	.579
1 5/32	1.1562	.347	1 35/64	1.5469	.465	1 15/16	1.9375	.582
29.5 mm	1.1614	.349	39.5 mm	1.5551	.467	49.5 mm	1.9488	.585

Drill	Diam. inches	Length of point inches	Drill	Diam. inches	Length of point inches	Drill	Diam. inches	Length of point inches
1 61/64	1.9531	.587	2 11/32	2.3437	.704	69.5 mm	2.7362	.822
50. mm	1.9685	.591	2 23/64	2.3594	.709	2 3/4	2.7500	.826
1 31/32	1.9687	.591	60. mm	2.3622	.710	70. mm	2.7559	.828
1 63/64	1.9844	.596	2 3/8	2.3750	.713	2 49/64	2.7656	.831
50.5 mm	1.9882	.597	60.5 mm	2.3819	.715	70.5 mm	2.7756	.834
2″	2.0000	.601	2 25/64	2.3906	.718	2 25/32	2.7812	.836
51. mm	2.0079	.603	61. mm	2.4016	.721	71. mm	2.7953	.840
2 1/64	2.0156	.605	2 13/32	2.4062	.723	2 51/64	2.7969	.840
51.5 mm	2.0276	.609	61.5 mm	2.4213	.727	2 13/16	2.8125	.845
2 1/32	2.0312	.610	2 27/64	2.4219	.728	71.5 mm	2.8150	.846
2 3/64	2.0469	.615	2 7/16	2.4375	.732	2 53/64	2.8281	.849
52. mm	2.0473	.615	62. mm	2.4409	.733	72. mm	2.8346	.851
2 1/16	2.0625	.619	2 29/64	2.4531	.737	2 27/32	2.8437	.854
52.5 mm	2.0669	.621	62.5 mm	2.4606	.739	72.5 mm	2.8543	.857
2 5/64	2.0781	.624	2 15/32	2.4687	.741	2 55/64	2.8594	.859
53. mm	2.0867	.627	63. mm	2.4803	.745	73. mm	2.8740	.863
2 3/32	2.0937	.629	2 31/64	2.4844	.746	2 7/8	2.8750	.864
53.5 mm	2.1063	.632	63.5 mm	2.5000	.751	2 57/64	2.8906	.868
2 7/64	2.1094	.633	2 1/2	2.5000	.751	73.5 mm	2.8937	.869
2 1/8	2.1250	.638	2 33/64	2.5156	.756	2 29/32	2.9062	.873
54. mm	2.1260	.639	64. mm	2.5197	.757	74. mm	2.9134	.875
2 9/64	2.1406	.643	2 17/32	2.5312	.760	2 59/64	2.9219	.878
54.5 mm	2.1457	.644	64.5 mm	2.5394	.763	74.5 mm	2.9331	.881
2 5/32	2.1562	.648	2 35/64	2.5469	.765	2 15/16	2.9375	.882
55. mm	2.1654	.650	65. mm	2.5590	.769	75. mm	2.9527	.887
2 11/64	2.1719	.652	2 9/16	2.5625	.770	2 61/64	2.9531	.887
55.5 mm	2.1850	.656	2 37/64	2.5781	.774	2 31/32	2.9687	.892
2 3/16	2.1875	.657	65.5 mm	2.5787	.774	75.5 mm	2.9724	.893
2 13/64	2.2031	.662	2 19/32	2.5937	.779	2 63/64	2.9844	.897
56. mm	2.2047	.662	66. mm	2.5984	.781	76. mm	2.9921	.899
2 7/32	2.2187	.666	2 39/64	2.6093	.784	3″	3.0000	.901
56.5 mm	2.2244	.668	66.5 mm	2.6181	.786	3 1/32	3.0312	.911
2 15/64	2.2344	.671	2 5/8	2.6250	.788	3 1/16	3.0625	.920
57. mm	2.2441	.674	67. mm	2.6378	.792	3 3/32	3.0937	.929
2 1/4	2.2500	.676	2 41/64	2.6406	.793	3 1/8	3.1250	.939
57.5 mm	2.2638	.680	2 21/32	2.6562	.798	3 5/32	3.1562	.948
2 17/64	2.2656	.681	67.5 mm	2.6575	.798	3 3/16	3.1875	.958
2 9/32	2.2812	.685	2 43/64	2.6719	.803	3 7/32	3.2187	.967
58. mm	2.2835	.686	68. mm	2.6772	.804	3 1/4	3.2500	.976
2 19/64	2.2969.	.690	2 11/16	2.6875	.807	3 9/32	3.2812	.986
58.5 mm	2.3031	.692	68.5 mm	2.6968	.810	3 5/16	3.3125	.995
2 5/16	2.3125	.695	2 45/64	2.7031	.812	3 11/32	3.3437	1.004
59. mm	2.3228	.698	68. mm	2.7165	.816	3 3/8	3.3750	1.014
2 21/64	2.3281	.699	2 23/32	2.7187	.817	3 7/16	3.4375	1.033
59.5 mm	2.3425	.704	2 47/64	2.7344	.821	3 1/2	3.5000	1.051

DRILLS FOR TAPPED HOLES*

Thread size and T.P.I.	Drill size			Approximate % thread depth
	Decimal	Fraction and gauge No.	mm	
No. 0—80	0.0453			91
	0.0469	3/64		81
	0.0492		1.25	68
	0.0512		1.3	54
	0.0531			42
No. 1—64	0.0531			98
	0.0550	54		88+
	0.0571			78
	0.0591		1.5	68
	0.0610			59
	0.0625	1/16		51
No. 1—72	0.0550	54		100
	0.0571			88
	0.0591		1.5	77
	0.0610			66
	0.0625	1/16		58
	0.0629			55
	0.0650			45
No. 2—56	0.0629			99
	0.0650			90+
	0.0670	51		82
	0.0700	50		69
	0.0730	49		56
	0.0760	48		43
No. 2—64	0.0670	51		94−
	0.0700	50		79
	0.0730	49		64
	0.0760	48		49
No. 3—48	0.0730	49		96
	0.0760	48		85
	0.0781	5/64		77
	0.0810	46		66+
	0.0827		2.1	60
	0.0860	44		48
No. 3—56	0.0760	48		99
	0.0781	5/64		90
	0.0810	46		77+
	0.0827		2.1	70
	0.0846			62
	0.0860	44		56

**Use of some of the larger drill sizes may result in threads that do not meet UN tolerances. Refer to internal thread standards.*

Thread size and T.P.I.	Drill size			Approximate % thread depth
	Decimal	Fraction and gauge No.	mm	
No. 4—40	0.0810	46		95
	0.0827		2.1	90
	0.0860	44		80
	0.0890	43		71
	0.0906		2.3	66
	0.0937	3/32		56
	0.0960	41		49
No. 4—48	0.0860	44		96
	0.0890	43		85
	0.0906		2.3	79
	0.0937	3/32		67
	0.0960	41		59
	0.0995	39		46
No. 5—40	0.0937	3/32		96
	0.0960	41		89
	0.0995	39		78
	0.1024		2.6	70
	0.1040	37		65
	0.1065	36		57+
No. 5—44	0.0960	41		98
	0.0995	39		86
	0.1024		2.6	76
	0.1040	37		71
	0.1065	36		63
	0.1094	7/64		53
No. 6—32	0.0995	39		95
	0.1024		2.6	87+
	0.1040	37		83+
	0.1065	36		78
	0.1094	7/64		70+
	0.1130	33		62
	0.1160	32		54
No. 6—40	0.1065	36		97+
	0.1094	7/64		88
	0.1130	33		77
	0.1160	32		68
	0.1200	31		65

DRILLS FOR TAPPED HOLES (Continued)

Thread size and T.P.I.	Drill size			Approximate % thread depth
	Decimal	Fraction and gauge No.	mm	
No. 8—32	0.1250	1/8		96
	0.1285	30		87
	0.1299		3.3	84
	0.1339		3.4	74
	0.1360	29		69
	0.1378		3.5	64+
	0.1406	9/64		57+
No. 8—36	0.1285	30		98
	0.1299		3.3	94
	0.1339		3.4	83+
	0.1360	29		77+
	0.1378		3.5	72+
	0.1406	9/64		65
	0.1440	27		55
No. 10—24	0.1360	29		99+
	0.1378		3.5	96
	0.1406	9/64		91
	0.1440	27		85
	0.1470	26		79
	0.1520	24		70
	0.1562	5/32		62
No. 10—32	0.1520	24		93+
	0.1562	5/32		83
	0.1610	20		71
	0.1660	19		59
	0.1695	18		50
No. 10—40	0.1610	20		89
	0.1660	19		74
	0.1695	18		63
	0.1719	11/64		56
No. 12—24	0.1660	19		92
	0.1695	18		86
	0.1719	11/64		81+
	0.1730	17		79
	0.1770	16		72
	0.1800	15		66+
	0.1850	13	4.7	57

Thread size and T.P.I.	Drill size			Approximate % thread depth
	Decimal	Fraction and gauge No.	mm	
No. 12—28	0.1695 0.1719 0.1730 0.1770 0.1800 0.1850 0.1875	18 11/64 17 16 15 13 3/16	 4.7 	100 95 92+ 84 77+ 67 61
No. 12—32	0.1770 0.1800 0.1850 0.1875	16 15 13 3/16	 4.7 	96 88+ 76 70
1/4—20	0.1850 0.1875 0.1910 0.1935 0.1960 0.1990 0.2031 0.2090	13 3/16 11 10 9 8 13/64 4	4.7	100 96 91 87 83 78+ 72 63
1/4—24	0.1960 0.1990 0.2031 0.2090 0.2130	9 8 13/64 4 3		100 94 86+ 76— 68
1/4—28	0.2090 0.2130 0.2187	4 3 7/32		88 80 67
1/4—32	0.2090 0.2130 0.2187 0.2244	4 3 7/32 	 5.7	100 91 77 63
1/4—36	0.2187 0.2244 0.2280	7/32 1	 5.7 	87— 71 61
1/4—40	0.2187 0.2244 0.2280	7/32 1	 5.7 	96 79 68—

DRILLS FOR TAPPED HOLES (Continued)

Thread size and T.P.I.	Drill size			Approximate % thread depth
	Decimal	Fraction and gauge No.	mm	
5/16—18	0.2460	D		92
	0.2500	1/4 (E)		86+
	0.2520		6.4	84
	0.2570	F		77
	0.2610	G		71
	0.2656	17/64		65
5/16—24	0.2610	G		95
	0.2656	17/64		86+
	0.2720	I		75
	0.2770	J		65+
5/16—32	0.2720	I		99+
	0.2770	J		87
	0.2812	9/32		77
3/8—16	0.2969	19/64		96
	0.3020	N		90
	0.3071		7.8	83
	0.3125	5/16		77
	0.3160	O		72+
	0.3230	P		64
3/8—24	0.3281	21/64		86+
	0.3320	Q		79
	0.3390	R		66+
3/8—32	0.3390	R		88+
	0.3437	11/32		77
	0.3480	S		66+
7/16—14	0.3480	S		96
	0.3543		9.0	89+
	0.3594	23/64		84
	0.3680	U		75
	0.3750	3/8		67
7/16—20	0.3750	3/8		96
	0.3860	W		79
	0.3906	25/64		72
	0.3970	X		62+
7/16—24	0.3860	W		95
	0.3906	25/64		86+
	0.3970	X		74+
	0.4062	13/32		58−

Thread size and T.P.I.	Drill size			Approximate % thread depth
	Decimal	Fraction and gauge No.	mm	
7/16—28	0.3970 0.4062	X 13/32		87 67
1/2—12	0.3970 0.4062 0.4219 0.4375	X 13/32 27/64 7/16		95 86+ 72 58—
1/2—13	0.4062 0.4219 0.4375	13/32 27/64 7/16		94 78 62+
1/2—16	0.4219 0.4375 0.4531	27/64 7/16 29/64		96 77 58—
1/2—20	0.4375 0.4531 0.4687	7/16 29/64 15/32		96 72 48
1/2—24	0.4531 0.4687	29/64 15/32		86 57+
1/2—28	0.4531 0.4687	29/64 15/32		100+ 67
9/16—12	0.4531 0.4687 0.4844 0.5000	29/64 15/32 31/64 1/2		100+ 86+ 72 58
9/16—16	0.4844 0.5000 0.5118 0.5156	31/64 1/2 33/64	 13.0 	97 77 62 57+
9/16—18	0.5000 0.5118 0.5156	1/2 33/64	 13.0 	86+ 70 65
9/16—24	0.5118 0.5126 0.5312	 17/32	13.0 	93+ 86+ 58—
9/16—27	0.5312 0.5216	17/32		65 85

DRILLS FOR TAPPED HOLES (Continued)

Thread size and T.P.I.	Drill size			Approximate % thread depth
	Decimal	Fraction and gauge No.	mm	
5/8—11	0.5468 0.5312	 17/32		66 79
5/8—12	0.5468 0.5312	 17/32		72 87
5/8—18	0.5709 0.5625	 9/16	14.5	75 87
5/8—27	0.5906 0.5807		15.0	71 92
11/16—11	0.6093 0.5937	 19/32		66 79
11/16—16	0.6250	5/8		77
3/4—10	0.6562 0.6406	21/32 41/64		72 84
3/4—12	0.6718 0.6562	43/64 21/32		72 86
3/4—16	0.6875	11/16		77
3/4—27	0.7087		18.0	86
7/8—9	0.7812 0.7656 0.7500	25/32 49/64 3/4		65 76 86
7/8—12	0.7968 0.7812	51/64 25/32		72 87
7/8—14	0.8125 0.8071 0.7968	13/16 51/64	 20.5 	67 73 84
7/8—27	0.8437	27/32		65
1—8	0.8750 0.8593	7/8 55/64		77 87
1—12	0.9218 0.9062	59/64 29/32		72 86
1—14	0.9375 0.9218	15/16 59/64		67 84
1—27	0.9687 0.9646	31/32 	 24.5	65 74

Thread size and T.P.I.	Drill size			Approximate % thread depth
	Decimal	Fraction and gauge No.	mm	
1-1/8—7	0.9844	63/64		76
1-1/8—12	1.0469	1-3/64		72
1-1/4—7	1.1094	1-7/64		75
1-1/4—12	1.1719	1-11/64		72
1-3/8—6	1.2187	1-7/32		72
1-3/8—12	1.2969	1-19/64		72
1-1/2—6	1.3281	1-21/64		79
1-1/2—12	1.4219	1-27/64		72
1-5/8—5-1/2	1.4531	1-29/64		73
1-3/4—5	1.5469	1-35/64		78
1-3/4—10	1.6562	1-21/32		72
1-7/8—5	1.6875	1-11/16		72
2—4-1/2	1.7812	1-25/32		76
2—10	1.9062	1-29/32		72
2-1/8—4-1/2	1.9062	1-29/32		76
2-1/4—4-1/2	2.0312	2-1/32		76
2-1/4—8	2.1250	2-1/8		77
2-3/8—4	2.1250	2-1/8		77
2-1/2—4	2.2500	2-1/4		77
2-1/2—8	2.3750	2-3/8		77
2-3/4—4	2.5000	2-1/2		77
2-3/4—8	2.6250	2-5/8		77
3—3-1/2	2.7187	2-23/32		76
3—4	2.7500	2-3/4		77
3—8	2.8750	2-7/8		77
3-1/4—4	3.0000	3		77
3-1/2—4	3.2500	3-1/4		77
3-3/4—4	3.5000	3-1/2		77
4—4	3.7500	3-3/4		77

TABLE OF CUTTING SPEEDS

Feet per min.	15*	20	25	30	35	40	45	50	55	60
Dia.	Revolutions per minute									
1/16	917	1223	1528	1834	2140	2445	2751	3057	3363	3668
1/8	459	611	764	917	1070	1222	1375	1528	1681	1834
3/16	306	408	509	611	713	815	917	1019	1121	1222
1/4	229	306	382	458	535	611	688	764	851	917
5/16	183	245	306	367	428	489	550	611	672	733
3/8	153	204	255	306	357	408	458	509	560	611
7/16	131	175	218	262	306	349	393	437	481	524
1/2	115	153	191	229	268	306	344	382	420	459
9/16	102	136	170	204	238	272	306	340	373	407
5/8	92	123	153	184	214	245	276	306	337	367
11/16	83	111	138	167	194	222	249	273	300	333
3/4	76	102	127	153	178	203	229	254	279	306
13/16	71	95	119	142	166	190	213	237	261	284
7/8	66	87	109	131	153	175	196	219	241	262
15/16	61	81	101	122	142	163	183	204	224	244
1	57	76	96	115	134	153	172	191	210	229
1-1/16	54	72	90	108	126	144	162	180	197	215
1-1/8	51	68	85	102	119	136	153	170	187	204
1-3/16	48	64	81	97	113	129	145	161	177	193
1-1/4	46	61	76	92	107	123	137	153	168	183
1-5/16	44	58	73	87	102	116	131	146	160	175
1-3/8	42	56	70	83	97	111	125	139	153	167
1-7/16	40	53	66	80	93	106	119	133	146	159
1-1/2	38	51	64	76	90	102	115	127	140	153
1-9/16	37	49	61	73	85	98	110	122	134	146
1-5/8	35	47	59	71	82	94	106	117	129	141
1-11/16	34	45	57	68	79	90	102	113	124	136
1-3/4	33	44	55	66	76	87	98	109	120	131
1-13/16	32	42	53	63	74	84	95	106	116	127
1-7/8	31	41	51	61	71	82	92	102	112	122
1-15/16	30	39	49	59	69	79	89	99	108	118
2	29	38	48	57	67	76	86	96	105	115
2-1/8	27	36	45	54	63	72	81	90	99	108
2-1/4	25	34	42	51	59	68	76	86	94	102
2-3/8	24	32	40	48	56	64	73	81	89	97
2-1/2	23	31	38	46	54	61	69	76	84	92
2-5/8	22	29	36	44	51	58	65	73	80	87
2-3/4	21	28	35	42	49	56	63	70	77	83
2-7/8	20	26	33	40	46	53	59	66	73	79
3	19	26	32	38	45	51	57	64	70	76
3-1/8	18	24	31	37	43	49	55	61	67	73
3-1/4	18	23	29	35	41	47	53	59	64	70
3-3/8	17	23	28	34	40	45	51	57	62	68
3-1/2	16	22	27	33	38	44	49	55	60	66
3-5/8	16	21	26	32	37	42	47	52	58	63
3-3/4	15	20	26	31	36	41	46	51	56	61
3-7/8	15	20	25	30	35	39	44	49	54	59
4	14	19	24	29	33	38	43	48	53	57
4-1/4	14	18	23	27	31	36	40	45	49	54
4-1/2	13	17	21	25	30	34	38	42	47	51
4-3/4	12	16	20	24	28	32	36	40	44	48
5	12	15	19	23	27	31	34	38	42	46

*See page 167 for formula for speeds less than 15 sfm.

Feet per min.	65	70	75	80	85	90	95	100	110	120
Dia.	Revolutions per minute									
1/16	3974	4280	4586	4891	5197	5502	5800	6114	6725	7337
1/8	1986	2139	2292	2445	2598	2750	2903	3056	3362	3667
3/16	1325	1426	1529	1630	1732	1834	1936	2038	2242	2446
1/4	994	1070	1147	1222	1300	1376	1453	1528	1681	1734
5/16	794	856	917	978	1039	1100	1161	1222	1344	1466
3/8	662	713	764	815	865	916	967	1018	1121	1222
7/16	568	611	656	699	743	786	830	874	961	1049
1/2	497	535	573	611	649	688	726	764	840	917
9/16	441	475	509	543	577	611	645	679	747	813
5/8	398	428	459	489	520	552	581	612	673	736
11/16	360	389	416	444	472	500	527	555	611	666
3/4	330	357	381	409	432	458	483	508	559	610
13/16	308	332	356	379	403	427	450	474	521	569
7/8	285	306	329	349	372	392	416	438	482	526
15/16	265	285	305	326	346	366	387	407	448	488
1	258	267	287	306	325	344	363	382	420	458
1-1/16	233	251	269	287	305	323	341	359	395	431
1-1/8	221	238	255	272	289	306	324	340	374	408
1-3/16	209	225	242	258	274	290	306	322	354	386
1-1/4	199	214	230	245	260	274	291	306	337	367
1-5/16	189	204	218	233	247	262	276	291	320	349
1-3/8	180	195	208	222	236	250	264	278	306	334
1-7/16	172	186	199	212	225	239	252	265	292	318
1-1/2	165	178	191	204	216	230	241	254	279	305
1-9/16	159	171	183	195	207	220	232	244	268	293
1-5/8	152	165	176	188	199	212	222	234	257	281
1-11/16	147	158	170	181	192	203	215	226	249	271
1-3/4	142	153	164	175	185	196	207	218	240	262
1-13/16	137	148	158	169	179	190	200	211	232	253
1-7/8	133	143	153	163	173	184	194	204	224	244
1-15/16	128	138	148	158	167	177	187	197	217	236
2	124	134	143	153	162	172	181	191	210	229
2-1/8	117	126	135	144	153	162	171	180	198	216
2-1/4	111	119	128	136	145	153	162	170	187	204
2-3/8	105	113	121	129	137	145	153	161	177	193
2-1/2	100	107	114	122	130	138	145	153	168	184
2-5/8	94	102	109	116	123	131	138	145	160	174
2-3/4	90	97	104	111	118	125	132	139	153	167
2-7/8	86	92	99	106	112	119	125	132	145	158
3	83	89	95	102	108	114	121	127	140	152
3-1/8	79	85	92	98	104	110	116	122	134	146
3-1/4	76	82	88	94	100	105	111	117	129	140
3-3/8	74	79	85	90	96	102	108	113	124	136
3-1/2	71	76	82	87	93	98	104	109	120	131
3-5/8	68	74	79	84	89	95	100	105	116	126
3-3/4	66	71	77	82	87	92	97	102	112	122
3-7/8	64	69	74	79	84	89	94	99	108	118
4	62	67	72	76	81	86	91	96	105	115
4-1/4	58	63	67	72	76	81	85	90	99	108
4-1/2	55	59	64	68	72	76	81	85	93	102
4-3/4	52	56	60	64	68	72	76	80	88	97
5	50	54	57	61	65	69	73	76	84	92

TABLE OF CUTTING SPEEDS (Continued)

Feet per min.	125	130	140	150	160	170	175	180	190	200
Dia.	Revolutions per minute									
1/16	7643	7948	8560	9171	9782	—	—	—	—	—
1/8	3820	3973	4278	4584	4890	5195	5348	5501	5806	6112
3/16	2548	2649	2853	3055	3261	3465	3567	3668	3872	4076
1/4	1910	1986	2139	2292	2445	2598	2674	2750	2903	3056
5/16	1527	1589	1711	1833	1955	2077	2139	2200	2322	2444
3/8	1273	1323	1425	1527	1629	1731	1782	1832	1934	2036
7/16	1093	1136	1224	1311	1398	1486	1530	1573	1661	1748
1/2	955	993	1070	1146	1222	1299	1337	1375	1452	1528
9/16	869	883	951	1019	1086	1154	1188	1222	1290	1358
5/8	765	796	857	918	979	1040	1071	1102	1163	1224
11/16	692	722	770	833	888	944	971	999	1054	1110
3/4	635	661	711	762	813	864	889	914	965	1016
13/16	593	616	664	711	758	806	830	853	901	948
7/8	548	569	613	657	701	745	767	788	832	876
15/16	509	529	570	611	651	692	712	733	773	814
1	478	497	535	573	611	649	669	688	726	764
1-1/16	449	467	503	539	579	610	628	646	682	718
1-1/8	425	442	476	510	544	578	595	612	646	680
1-3/16	403	419	451	483	515	547	564	580	612	644
1-1/4	383	398	428	459	490	520	536	551	581	612
1-5/16	351	378	407	437	466	495	509	524	553	582
1-3/8	348	361	389	417	445	472	487	500	528	556
1-7/16	331	345	371	398	424	451	464	477	504	530
1-1/2	318	330	356	381	406	432	445	457	483	509
1-9/16	305	317	342	366	390	415	427	439	464	488
1-5/8	293	304	328	351	374	398	410	421	445	468
1-11/16	283	294	316	339	362	384	396	407	429	452
1-3/4	273	283	305	327	349	371	382	392	414	436
1-13/16	264	274	295	317	338	359	369	380	401	422
1-7/8	255	265	286	306	326	347	357	367	388	408
1-15/16	246	256	276	296	315	335	345	355	374	394
2	239	248	267	287	306	325	334	344	363	382
2-1/8	225	234	252	270	288	306	315	324	342	360
2-1/4	213	221	238	255	272	289	298	306	313	340
2-3/8	201	209	225	242	258	274	282	290	306	322
2-1/2	191	199	213	230	245	260	268	275	291	306
2-5/8	181	189	203	218	232	247	254	261	276	290
2-3/4	174	181	195	209	222	236	242	250	264	278
2-7/8	165	172	185	198	211	224	231	238	251	264
3	159	165	178	191	203	216	222	228	241	254
3-1/8	153	159	171	183	195	207	214	219	232	244
3-1/4	146	152	164	176	188	199	205	211	222	234
3-3/8	141	147	158	170	181	192	198	203	215	226
3-1/2	136	142	153	164	174	186	191	196	207	218
3-5/8	131	137	147	158	168	179	184	189	200	210
3-3/4	128	133	143	153	163	175	179	184	194	205
3-7/8	123	128	138	148	158	167	172	177	186	197
4	120	124	134	143	153	163	167	172	182	191
4-1/4	112	117	126	135	144	153	157	162	171	180
4-1/2	106	110	119	127	136	144	148	153	161	170
4-3/4	101	105	113	121	129	137	141	145	153	161
5	96	99	107	115	122	130	134	138	145	153

Feet per min.	210	220	230	240	250	260	270	280	290	300
Dia.	Revolutions per minute									
1/16	—	—	—	—	—	—	—	—	—	—
1/8	6417	6723	7028	7334	7639	7945	8251	8556	8862	9171
3/16	4278	4482	4686	4890	5093	5297	5501	5705	5908	6114
1/4	3209	3361	3514	3667	3820	3972	4125	4278	4431	4584
5/16	2567	2689	2811	2934	3056	3178	3300	3423	3545	3666
3/8	2139	2241	2343	2445	2546	2648	2750	2852	2954	3057
7/16	1833	1921	2008	2095	2183	2270	2357	2445	2532	2620
1/2	1604	1681	1757	1833	1910	1986	2063	2139	2215	2292
9/16	1426	1494	1562	1630	1698	1766	1833	1901	1969	2037
5/8	1283	1345	1406	1467	1528	1589	1650	1711	1772	1834
11/16	1167	1222	1278	1333	1389	1445	1500	1556	1611	1667
3/4	1070	1120	1171	1222	1273	1324	1375	1426	1477	1528
13/16	987	1034	1081	1128	1175	1222	1269	1316	1363	1410
7/8	917	960	1004	1048	1091	1135	1179	1222	1266	1310
15/16	857	896	937	978	1019	1059	1100	1141	1182	1222
1	802	840	879	917	955	993	1031	1070	1108	1146
1-1/16	755	791	827	863	899	935	971	1007	1043	1078
1-1/8	714	747	781	815	849	883	917	951	985	1018
1-3/16	675	708	740	772	804	836	868	901	933	965
1-1/4	641	672	703	733	764	794	825	856	886	917
1-5/16	611	640	669	698	728	757	786	815	844	873
1-3/8	584	611	639	667	694	722	750	778	806	833
1-7/16	558	584	611	638	664	691	717	744	771	797
1-1/2	535	560	586	611	637	662	688	713	738	764
1-9/16	514	538	562	587	611	636	660	684	709	733
1-5/8	493	517	541	564	588	611	635	658	682	705
1-11/16	475	498	521	543	566	589	611	634	656	679
1-3/4	459	481	502	524	546	567	589	611	633	654
1-13/16	443	464	485	506	527	548	569	590	611	632
1-7/8	428	449	469	489	509	530	550	570	591	611
1-15/16	414	434	453	473	493	513	532	552	572	591
2	402	421	439	458	477	497	516	535	554	573
2-1/8	378	395	413	431	449	467	485	503	521	539
2-1/4	357	374	390	407	424	441	458	475	492	509
2-3/8	338	353	370	386	402	418	434	450	466	482
2-1/2	321	336	344	367	382	397	413	428	443	458
2-5/8	306	320	335	349	364	378	393	407	422	436
2-3/4	292	306	319	333	347	361	375	389	403	416
2-7/8	279	292	306	319	332	345	359	372	385	398
3	267	279	293	306	318	331	344	357	369	381
3-1/8	257	268	281	293	306	318	330	342	354	366
3-1/4	247	259	270	282	294	306	317	329	341	352
3-3/8	238	249	260	272	283	294	306	317	328	339
3-1/2	229	240	251	262	273	284	295	306	316	327
3-5/8	221	232	242	253	263	274	285	295	306	316
3-3/4	214	224	234	244	255	265	275	285	295	305
3-7/8	207	217	227	237	246	256	266	276	285	295
4	201	210	220	229	239	248	258	267	277	286
4-1/4	189	198	207	216	225	234	243	252	261	269
4-1/2	178	187	195	204	212	221	229	238	246	254
4-3/4	167	177	185	193	201	209	217	225	233	241
5	160	168	176	183	191	199	206	214	222	229

TABLE OF CUTTING SPEEDS (Continued)

Feet per min.	325	350	375	400	425	450	475	500	525	550
Dia.	Revolutions per minute									
1/16	—	—	—	—	—	—	—	—	—	—
1/8	9935	10699	11463	—	—	—	—	—	—	—
3/16	6623	7133	7642	8152	8661	9171	9680	10190	10699	11209
1/4	4966	5348	5730	6112	6494	6876	7258	7640	8022	8404
5/16	3971	4277	4582	4888	5193	5499	5804	6110	6415	6721
3/8	3311	3566	3821	4076	4330	4585	4840	5095	5349	5604
7/16	2838	3057	3275	3494	3712	3930	4149	4367	4585	4084
1/2	2483	2675	2866	3057	3248	3439	3630	3821	4012	4203
9/16	2207	2377	2547	2717	2887	3056	3226	3396	3566	3736
5/8	1987	2139	2292	2445	2598	2751	2904	3057	3209	3362
11/16	1806	1941	2084	2223	2362	2501	2640	2779	2917	3056
3/4	1655	1783	1910	2038	2165	2292	2420	2547	2674	2802
13/16	1528	1646	1763	1881	1998	2116	2233	2351	2469	2586
7/8	1419	1528	1637	1746	1855	1965	2074	2183	2292	2401
15/16	1324	1426	1528	1630	1732	1834	1936	2038	2139	2241
1	1241	1337	1432	1528	1623	1719	1814	1910	2006	2101
1-1/16	1168	1258	1348	1438	1528	1618	1708	1798	1887	1977
1-1/8	1103	1188	1273	1358	1443	1528	1613	1698	1782	1867
1-3/16	1045	1126	1206	1287	1367	1448	1528	1609	1689	1769
1-1/4	993	1069	1146	1222	1299	1375	1452	1528	1604	1681
1-5/16	946	1018	1091	1164	1237	1309	1382	1455	1528	1601
1-3/8	903	972	1042	1111	1181	1250	1320	1389	1458	1528
1-7/16	863	930	996	1063	1129	1196	1262	1329	1395	1461
1-1/2	827	891	955	1018	1082	1146	1209	1273	1337	1400
1-9/16	794	855	916	978	1039	1100	1161	1222	1283	1344
1-5/8	764	822	881	940	999	1057	1116	1175	1234	1293
1-11/16	735	792	849	905	962	1018	1075	1132	1188	1245
1-3/4	709	764	818	873	927	982	1036	1091	1146	1200
1-13/16	685	737	790	843	895	948	1001	1054	1106	1159
1-7/8	662	713	764	815	866	917	968	1019	1069	1120
1-15/16	640	690	739	788	838	887	936	986	1035	1084
2	620	668	716	764	811	859	907	955	1002	1050
2-1/8	584	629	674	719	764	809	854	899	943	988
2-1/4	551	594	636	679	721	764	806	849	891	933
2-3/8	522	563	603	643	683	724	764	804	844	884
2-1/2	496	534	573	611	649	687	725	764	802	840
2-5/8	472	509	545	582	618	654	691	727	763	800
2-3/4	451	486	520	555	590	625	659	694	729	763
2-7/8	431	465	498	531	564	598	631	664	697	730
3	413	445	477	509	541	572	604	636	668	700
3-1/8	397	427	458	488	519	549	580	611	641	672
3-1/4	381	411	440	470	499	528	558	587	616	646
3-3/8	367	396	424	452	481	509	537	566	594	622
3-1/2	354	381	409	436	463	490	518	545	572	600
3-5/8	342	368	395	421	447	474	500	527	553	579
3-3/4	331	356	382	407	433	458	484	509	534	560
3-7/8	320	345	369	394	419	443	468	493	517	542
4	310	334	358	382	405	429	453	477	501	525
4-1/4	292	314	337	359	382	404	427	449	471	494
4-1/2	275	297	318	339	360	382	403	424	445	466
4-3/4	261	281	301	321	341	361	381	402	422	442
5	248	267	286	305	324	343	362	382	401	420

FRACTIONS OF ONE INCH AND DECIMAL AND METRIC EQUIVALENTS

Fractions of an Inch	Decimals of an Inch	Milli-meters	Fractions of an Inch	Decimals of an Inch	Milli-meters
1/64	.0156	0.397	33/64	.5156	13.097
1/32	.0313	0.794	17/32	.5313	13.494
3/64	.0469	1.191	35/64	.5469	13.891
1/16	.0625	1.588	9/16	.5625	14.287
5/64	.0781	1.985	37/64	.5781	14.684
3/32	.0938	2.381	19/32	.5938	15.081
7/64	.1094	2.778	39/64	.6094	15.478
1/8	.1250	3.175	5/8	.6250	15.875
9/64	.1406	3.572	41/64	.6406	16.272
5/32	.1563	3.969	21/32	.6563	16.688
11/64	.1719	4.366	43/64	.6719	17.085
3/16	.1875	4.762	11/16	.6875	17.462
13/64	.2031	5.159	45/64	.7031	17.859
7/32	.2188	5.556	23/32	.7188	18.256
15/64	.2344	5.953	47/64	.7344	18.653
1/4	.2500	6.350	3/4	.7500	19.050
17/64	.2656	6.747	49/64	.7656	19.447
9/32	.2813	7.144	25/32	.7813	19.843
19/64	.2969	7.541	51/64	.7969	20.240
5/16	.3125	7.937	13/16	.8125	20.637
21/64	.3281	8.334	53/64	.8281	21.034
11/32	.3438	8.731	27/32	.8438	21.430
23/64	.3594	9.128	55/64	.8594	21.827
3/8	.3750	9.525	7/8	.8750	22.224
25/64	.3906	9.922	57/64	.8906	22.621
13/32	.4063	10.319	29/32	.9063	23.018
27/64	.4219	10.716	59/64	.9219	23.415
7/16	.4375	11.112	15/16	.9375	23.812
29/64	.4531	11.509	61/64	.9531	24.209
15/32	.4688	11.906	31/32	.9688	24.606
31/64	.4844	12.303	63/64	.9844	25.003
1/2	.5000	12.700	1	1.0000	25.400

HARDNESS CONVERSION TABLE
NOTE: Hardness readings taken from curved surfaces will require correction.

Brinell indentation diameter, mm	Brinell hardness number		Rockwell hardness number		Rockwell superficial hardness number superficial diamond penetrator.			Tensile strength (approximate) 1000 psi
	Standard ball	Tungsten-carbide ball	B scale	C scale	15 N scale	30 N scale	45 N scale	
2.45	...	627	....	58.7	89.6	76.3	65.1	347
2.50	...	601	....	57.3	89.0	75.1	63.5	328
2.55	...	578	....	56.0	88.4	73.9	62.1	313
2.60	...	555	....	54.7	87.8	72.7	60.6	298
2.65	...	534	....	53.5	87.2	71.6	59.2	288
2.70	...	514	....	52.1	86.5	70.3	57.6	274
2.75	...	495	....	51.0	85.9	69.4	56.1	264
2.80	...	477	....	49.6	85 3	68.2	54.5	252
2.85	...	461	....	48.5	84.7	67.2	53.2	242
2.90	...	444	....	47.1	84.0	65.8	51.5	230
2.95	429	429	....	45.7	83.4	64.6	49.9	219
3.00	415	415	....	44.5	82.8	63.5	48.4	212
3.05	401	401	....	43.1	82.0	62.3	46.9	202
3.10	388	388	....	41.8	81.4	61.1	4.53	193
3.15	375	375	....	40.4	80.6	59.9	43.6	184
3.20	363	363	....	39.1	80.0	58.7	42.0	177
3.25	352	352	....	37.9	79.3	57.6	40.5	170
3.30	341	341	....	36.6	78.6	56.4	39.1	163
3.35	331	331	....	35.5	78.0	55.4	37.8	158
3.40	321	321	....	34.3	77.3	54.3	36.4	152
3.45	311	311	....	33.1	76.7	53.3	34.4	147
3.50	302	302	....	32.1	76.1	52.2	33.8	143
3.55	293	293	....	30.9	75.5	51.2	32.4	139
3.60	285	285	....	29.9	75.0	50.3	31.2	136
3.65	277	277	....	28.8	74.4	49.3	29.9	131
3.70	269	269	...	27.6	73.7	48.3	28.5	128
3.75	262	262	....	26.6	73.1	47.3	27.3	125
3.80	255	255	...	25.4	72.5	46.2	26.0	121
3.85	248	248	....	24.2	71.7	45.1	24.5	118
3.90	241	241	100.0	22.8	70.9	43.9	22.8	114
3.95	235	235	99.0	21.7	70.3	42.9	21.5	111
4.00	229	229	98.2	20.5	69.7	41.9	20.1	109
4.05	223	223	97.3	....	....	....	....	104
4.10	217	217	96.4	....	....	....	....	103
4.15	212	212	95.5	...	....	....	....	100
4.20	207	207	94.6	....	....	....	....	99
4.25	201	201	93.8	....	....	....	....	97
4.30	197	197	92.8	....	....	....	....	94
4.35	192	192	91.9	....	....	....	....	92
4.40	187	187	90.7	....	....	....	....	90
4.45	183	183	90.0	....	....	....	....	89
4.50	179	179	89.0	....	....	...	....	88
4.55	174	174	87.8	....	....	....	....	86
4.60	170	170	86.8	....	....	....	....	84
4.65	167	167	86.0	....	....	....	....	83
4.70	163	163	85.0	....	....	....	....	82
4.80	156	156	82.9	....	....	....	....	80
4.90	149	149	80.8	....	....	....	....	73
5.00	143	143	78.7	....	....	....	...	71
5.10	137	137	76.4	....	....	....	....	67
5.20	131	131	74.0	....	....	....	....	65
5.30	126	126	72.0	....	....	....	....	63
5.40	121	121	69.0	....	....	...	....	60
5.50	116	116	67.6	....	....	....	....	58
5.60	111	111	65.7	....	....	....	....	56

WIRE GAUGES

Number of wire gauge	American or Brown & Sharpe, inches	Washburn & Moen Mfg. Co., A.S. & W. Roebling, inches	Imperial Wire Gauge, inches	Stubs' Steel Wire, inches	Birmingham or Stubs' Iron Wire, inches
0000000	.....	.4900	.5000	...	...
000000	.5800	.4615	.4640	...	...
00000	.5165	.4305	.4320	...	.500
0000	.460	.3938	.4000	...	.454
000	.40964	.3625	.3720	...	.425
00	.3648	.3310	.3480	...	.380
0	.32486	.3065	.3240	...	.340
1	.2893	.2830	.3000	.227	.300
2	.25763	.2625	.2760	.219	.284
3	.22942	.2437	.2520	.212	.259
4	.20431	.2253	.2320	.207	.238
5	.18194	.2070	.2120	.204	.220
6	.16202	.1920	.1920	.201	.203
7	.14428	.1770	.1760	.199	.180
8	.12849	.1620	.1600	.197	.165
9	.11443	.1483	.1440	.194	.148
10	.10189	.1350	.1280	.191	.134
11	.090742	.1205	.1160	.188	.120
12	.080808	.1055	.1040	.185	.109
13	.071961	.0915	.0920	.182	.095
14	.064084	.0800	.0800	.180	.083
15	.057068	.0720	.0720	.178	.072
16	.05082	.0625	.0640	.175	.065
17	.045257	.0540	.0560	.172	.058
18	.040303	.0475	.0480	.168	.049
19	.03589	.0410	.0400	.164	.042
20	.031961	.0348	.0360	.161	.035
21	.028462	.0317	.0320	.157	.032
22	.025347	.0286	.0280	.155	.028
23	.022571	.0258	.0240	.153	.025
24	.0201	.0230	.0220	.151	.022
25	.0179	.0204	.0200	.148	.020
26	.01594	.0181	.0180	.146	.018
27	.014195	.0173	.0164	.143	.016
28	.012641	.0162	.0148	.139	.014
29	.011257	.0150	.0136	.134	.013
30	.010025	.0140	.0124	.127	.012
31	.008928	.0132	.0116	.120	.010
32	.00795	.0128	.0108	.115	.009
33	.00708	.0118	.0100	.112	.008
34	.006304	.0104	.0092	.110	.007
35	.005614	.0095	.0084	.108	.005
36	.005	.0090	.0076	.106	.004
37	.004453	.0085	.0068	.103	...
38	.003965	.0080	.0060	.101	...
39	.003531	.0075	.0052	.099	...
40	.003144	.0070	.0048	.097	...

FORMULAS
Percent of Full Thread—see page 59.

Surface speed — feet/minute	
Round bars	$\frac{\text{Diameter} \times 3.1416 \times \text{RPM}}{12}$
Hexagon bars (distance across corners)	$\frac{\text{Size} \times 3.1416 \times \text{RPM} \times 1.155}{12}$
	$\frac{\text{Distance} \times 3.1416 \times \text{RPM}}{12}$
Square bars (distance across corners)	$\frac{\text{Size} \times 3.1416 \times \text{RPM} \times 1.414}{12}$
	$\frac{\text{Distance} \times 3.1416 \times \text{RPM}}{12}$
Revolutions — number/minute	
Round bars	$\frac{\text{SFM} \times 12}{\text{Diameter} \times 3.1416}$
Hexagon bars	$\frac{\text{SFM} \times 12}{\text{Size} \times 3.1416 \times 1.155}$
	$\frac{\text{SFM} \times 12}{\text{Distance} \times 3.1416}$
Square bars	$\frac{\text{SFM} \times 12}{\text{Size} \times 3.1416 \times 1.414}$
	$\frac{\text{SFM} \times 12}{\text{Distance} \times 3.1416}$
Feed — inches/revolution ...	$\frac{\text{Feed inches per minute}}{\text{RPM}}$
	$\frac{\text{Diameter} \times 3.1416 \times \text{Feed}}{\text{SFM} \times 12}$
inches/tooth	$\frac{\text{Feed}}{\text{No. of teeth}}$
Time for actual machining — seconds	$\frac{\text{Revolutions required} \times 60 \text{ sec.}}{\text{RPM}}$
Machine time	Time for machining + idle time.
Tapping or threading time — seconds	$\frac{\text{No. of threads} \times 60 \text{ (sec.)}}{\text{Actual threading speed in RPM}}$

NOTE: All sizes are in inches.

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