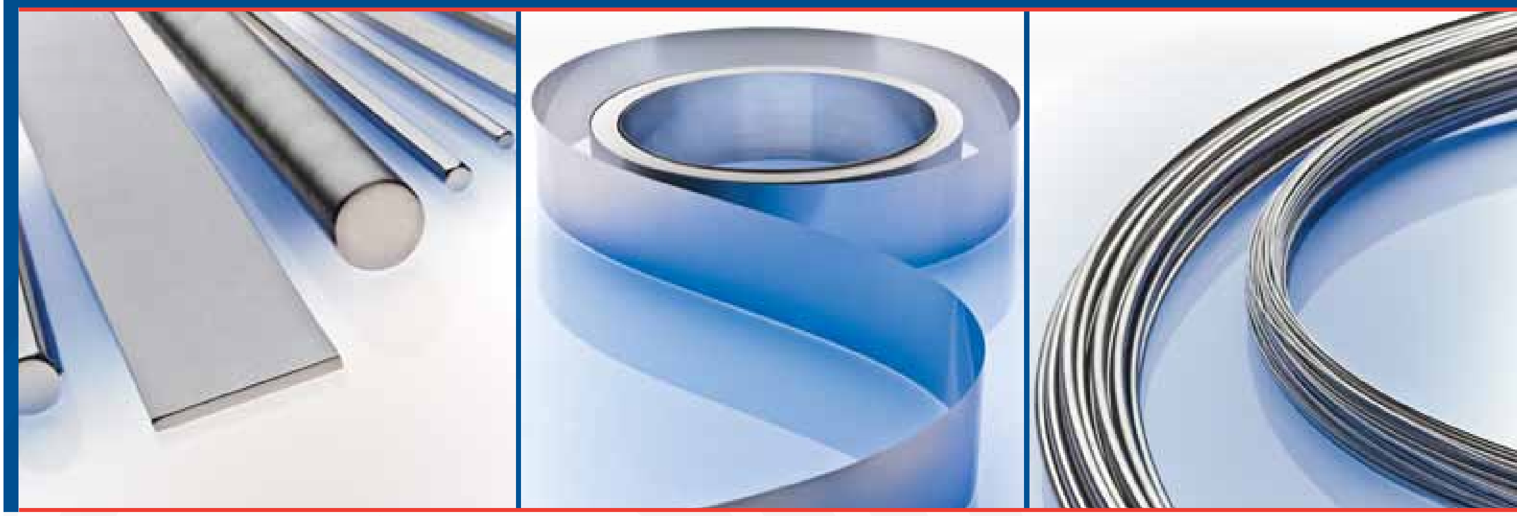
2012

Carpenter's Stainless Steel Blue Book

Selection | Alloy Data | Fabrication



CARPENTER

CARPENTER STAINLESS STEELS

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For comprehensive alloy data, including a typical properties slider search and technical articles, visit www.cartech.com/alloytechzone.html.

About Carpenter Technology Corporation

Carpenter: Leadership in Specialty Alloy Manufacturing and Distribution

For more than a century, Carpenter Technology Corporation has been a leader in the development, manufacture and distribution of conventional and powder metal stainless steels and specialty alloys including high temperature, stainless, superior corrosion resistant, controlled expansion alloys, ultra high-strength and implantable alloys, tool and die steels, and other specialty metals as well as titanium alloys. These alloys have been used in the high performance aerospace and defense; transportation; energy; medical; and the industrial and consumer products markets.

Along with Carpenter's superior product offering, we also offer an expert worldwide staff of metallurgists, research and development scientists, engineers and service professionals to customers around the world. Carpenter expertise is available at all times through our website, Alloy TechZone, MetalMass, and this Stainless Steel Blue Book.

Carpenter requests your feedback, technical questions, and comments about this Blue Book or our superior metals through the following channels: carpenter@cartech.com, Facebook and Twitter.

Contact customer service.

Selectaloy® Method

A simplified method known as the Carpenter Selectaloy® method (Fig. 1) can help engineers select the most suitable stainless steel based on corrosion and strength requirements. The Selectaloy method uses 14 basic grades that are representative of certain types of stainless steels and heat resisting alloys. Corrosion resistance increases vertically in the Selectaloy diagram, and mechanical properties, or strength, increase from left to right.

Many times a good starting point is Type 304 stainless because it is the most widely used stainless grade. For increased corrosion resistance, move up to Type 316 stainless, and for still more resistance, go higher to 20Cb-3®. For less corrosion resistance, drop down to Type 430 stainless, or to Type 409Cb stainless for even less resistance. Reading left to right across the lowest level of corrosion resistance, strength increases progressively from Type 409Cb stainless to Types 410, 420 and 440C stainless steels.

Custom 450® stainless, Type 431 stainless and Custom 455® stainless are positioned in the middle of the diagram to show their relative corrosion resistance and strength compared with the alloys along the vertical axis and horizontal axis.

After the initial stainless alloy has been chosen based on corrosion and strength criteria, consider how it is to be fabricated. Will the part be machined, headed, welded or heat-treated? These processes may affect the properties essential to the application and influence the alloy selected.

Types 304 and 410 stainless steels are available in alloy modifications offering improved machining or cold heading characteristics, while retaining corrosion resistance and mechanical properties comparable to those of the basic grade. If machining Type 304 stainless is a problem, four alloy variations will offer improved machinability – Project 70+® Type 304 stainless, Type 303 Se stainless, Type 303 stainless and Project 70+ Type 303 stainless, in that order.

If Type 304 stainless is desired with better cold headability, similar choices are available. Type 305 stainless is easier to head, Type 302HQ-FM® stainless is even better, and Carpenter No. 10 stainless is the easiest in the group to cold head.

The same concept applies to Type 410 stainless. Several modifications will offer progressively better machinability, i.e. Type 416 stainless, Project 70+ Type 416 stainless and No. 5-F stainless, in that order.

Evaluate these five key factors before choosing a stainless alloy for a specific application.

1. **Corrosion Resistance**—The primary driver for specifying a stainless steel. Basically, candidate materials must resist corrosion in the service environment.

2. **Mechanical Properties**—Along with alloy strength, consider hardness, fatigue, impact and stress-rupture properties.

Together with corrosion resistance, the mechanical properties often indicate the specific alloy type for the application.

3. **Fabrication Operation**—Material processing and machining methods often influence alloy selection. Some alloys are better suited than others for machining, heading, welding or heat treating.

4. **Value/Cost**—The overall value/cost analysis of the material involves material cost, processing cost, added product value and effective life of the finished product, among others. All these considerations play important roles in evaluating cost/value and should be considered for cost-effective design.

5. **Product Availability**—Availability of the material and minimum purchase requirements are also a consideration in choosing material for your application.

More detailed information on corrosion is available on Alloy TechZone.

Although these factors are commonly recognized throughout the metalworking industry, we know that the careful consideration of their importance can be a time-consuming and frustrating experience. That's why Carpenter developed its exclusive Selectaloy® method to help you with the selection process.

The Selectaloy chart can help you identify a stainless steel for a variety of applications. The diagram organizes alloys by the combination of corrosion resistance and strength. For example, suppose you are using Type 304 stainless, but you require more corrosion resistance at that same strength level. Simply move up to Type 316 stainless.

A move over from Type 304 to Custom 450® stainless increases strength while maintaining comparable corrosion resistance. If you are looking for an alloy to control severe corrosives, the Alloy Selection Guide at right can help put your material selection process into perspective. It was developed as a guideline to the relative potential of each alloy to resist corrosion in specific environments. Use the information in this booklet as a starting point to help determine the alloy that may suit your specific application.

Carpenter's online technical information database, Alloy TechZone is another useful tool in researching alloys. Registration is easy, fast and free at www.cartech.com/register.aspx.

If you would like to receive a quote, need technical assistance or have a question about selecting a Carpenter alloy, contact us toll-free in the U.S. at **1-800-654-6543** or visit us at **www.cartech.com.**

For questions and comments on this section, please visit our Facebook or Twitter account!

Learn More! **Download the Alloys for Corrosive Environments booklet.**

FIGURE 1

Selectaloy® Method

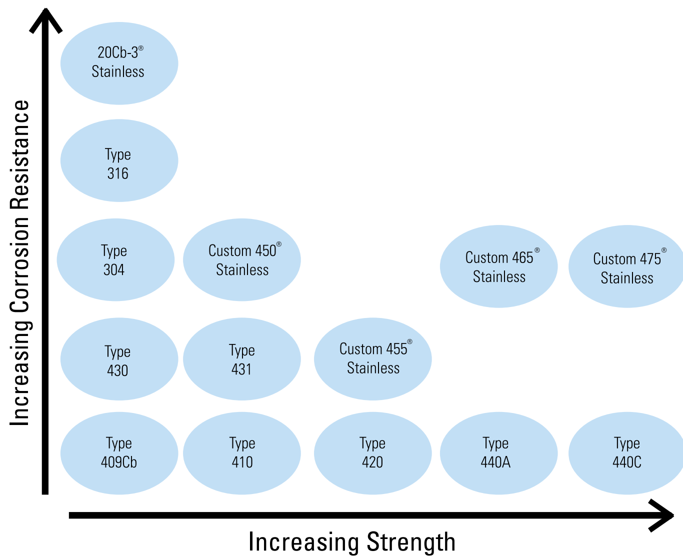


FIGURE 2

Levels of Corrosion Resistance

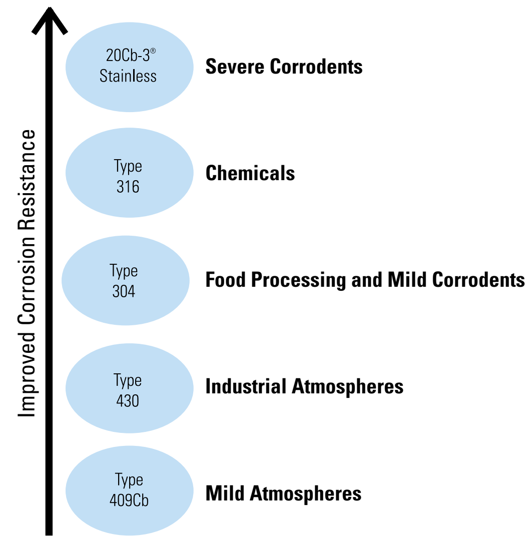
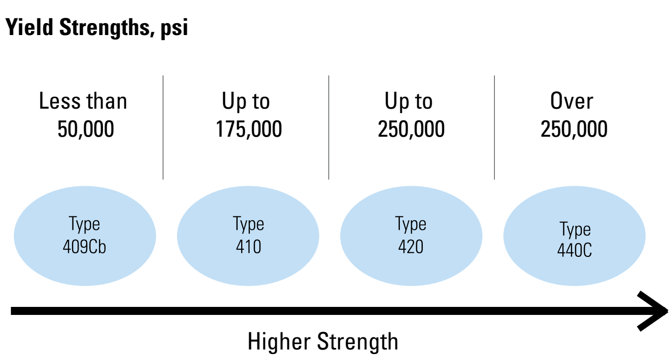


FIGURE 3

Levels of Strength

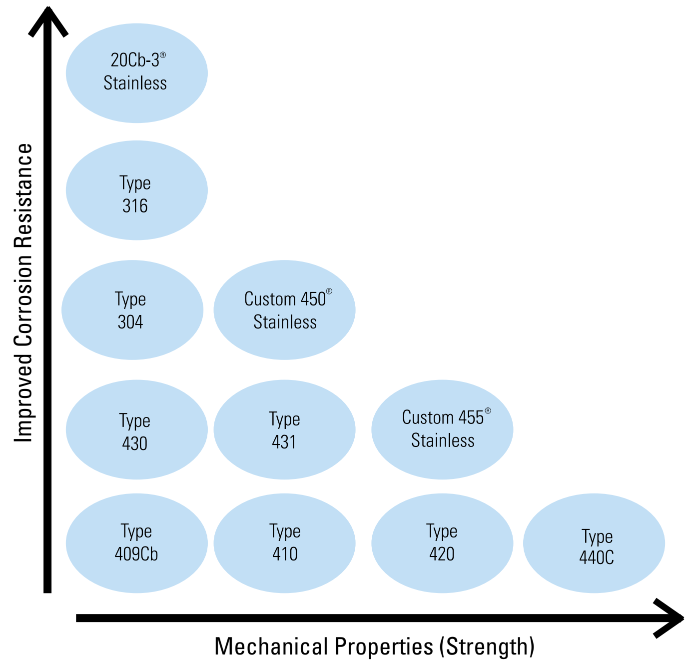


Contact Carpenter for further assistance in selecting an alloy for your application.

For more information about selecting stainless steels, read "Selecting New Stainless Steels for Unique Applications."

Fabrication

After making your selection according to resistance to corrosion and mechanical properties, fabrication–the third most important selection variable–should be considered. Most of the 11 basic steels shown on the diagram are representative of a group or family of closely allied steels having similar corrosion resistance and strength levels.



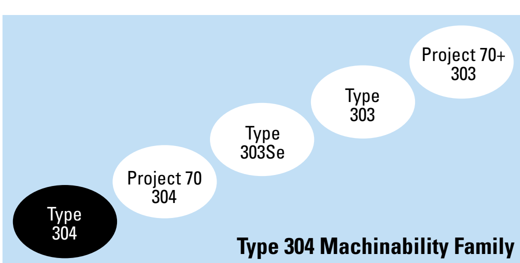
These many variations and modifications of the 11 basic stainless steels offer improved fabrication properties. In turn, each modification is given a different name or TYPE number dependent upon its chemical analysis. We can see, then, that the entire stainless steel family continues to grow because of variations to improve important fabrication qualities within the basic 11 alloy groups.

This is the reason why there are so many different grades of stainless steel. In most cases, the 11 listed alloys are the most common and versatile stainless of the groups they represent. Perhaps this may best be demonstrated through examples.

Let us again take our basic and most popular stainless grade–304. Suppose, that in this case, 304 was our choice for the best combination of corrosion resistance and strength. Now, the question remains, "How are we going to fabricate our product?"

Will it be machined, forged, welded, cold headed, etc.? Our final choice of the correct grade within the Selectaloy 304 fabrication family depends upon the production process used.

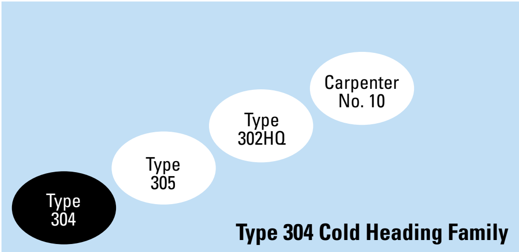
Let us also suppose that you have a difficult machining problem. As you can see by the illustrated 304 machinability family, there are superior machining alloys related to 304 with about the same corrosion-resistant characteristics and approximately the same mechanical properties.



Although 304 can be machined, when machining is the most important consideration there are other members of the group which possess better machinability. Project 70+® Type 304 is easier to machine than 304. 303Se and 303 are further improvements and Project 70+ Type 303 is the ultimate in ease of machining for an alloy with that particular strength and corrosion resistance.

On the other hand, if our primary concern were to cold head the material, we would refer to 304's headability family.

Moving in the direction of better cold headability, we find 305 is an improvement over the basic 304, and 302 HQ is even easier to cold head. No. 10 (Type 384) is the easiest stainless steel to head with that particular resistance to corrosion and mechanical strength.

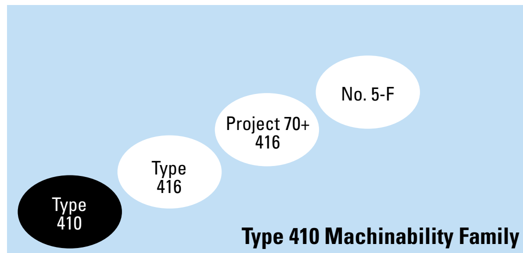


It can easily be seen, therefore, that choosing a stainless steel according to the necessary fabrication qualities is a matter of selecting a modification or refinement of one of the basic eleven alloys. In effect, you are moving about within the basic fabrication families searching for a suitable alloy modification. One should also note that as you move away from the basic alloy (304) towards the ultimate in a particular fabrication family, you tend to lose certain other fabrication qualities. For instance, in moving towards better machinability, the alloy loses somewhat its ability to be cold worked.

One final example might help serve to illustrate this remarkable versatility when using the Selectaloy method.

After determining by careful investigation of corrosion resistance and strength characteristics that 410 is the most suitable choice of the basic type alloys for a particular application, we refer to the 410 machinability family.

416 is easier to machine that 410, with Project 70+ Type 416 a further improvement. The easiest of all the alloys to machine within the 410 machinability family is 5-F. Hardenability decreases somewhat as machinability increases.



The CARPENTER Selectaloy method is a simple three-step selection system.

Step I–Select the level of corrosion resistance required.

Step II–Then select level of strength. These two determine the alloy.

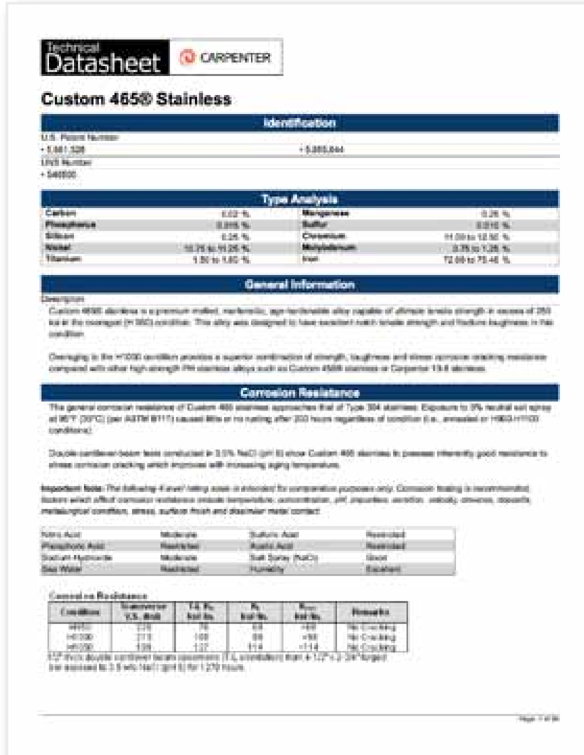
Step III–When there are special fabrication problems, select one of the basic alloy modifications which provides the most desirable fabrication characteristics.

Alloy Data

Alloy TechZone

Carpenter Technology's Alloy TechZone™ offers extensive, free technical information resources. Begin using the Alloy TechZone now.

- View a list of stainless steel datasheets
- Interact with the Stainless Selectaloy® Diagram
- Read Technical Articles about alloys, applications and manufacturing processes
- Typical Properties Search featuring min-max sliders and real-time results
- Email-a-Datasheet to yourself or a colleague
- Experiment with other alloy selectors as well as My Materials to save your searches. Register for My Materials and advanced searches.


Technical Datasheet CARPENTER

Custom 465® Stainless

Identification

Type Analysis

General Information

Corrosion Resistance

Other Alloy Information

- Access the online catalog of Carpenter specialty alloys
- Download the Project 70+® Stainless Machining Bar brochure
- Download the all products line card
- Download the Guide to Machining Specialty Alloys booklet
- Download the Stainless Rebar Information Kit
- Download the Heading Hints: A Guide to Cold Forming Specialty Alloys booklet
- Download the Alloys for Corrosive Environments booklet

Corrosion Control

The following industry associations and technical societies are good resources for additional information:
National Association of Corrosion Engineers | *www.nace.org*

All metals and alloys are susceptible to corrosion in some environments and, therefore, no single metal or alloy is suitable for all applications. For example, gold, which historically is known for its excellent resistance to the atmosphere, will corrode if exposed to mercury at ambient temperature. On the other hand, iron is relatively inert to mercury but corrodes readily in the atmosphere.

Fortunately, there are generally one or more materials which will perform satisfactorily in a given environment. The stainless steels are versatile in that they are resistant to corrosion in a wide range of environments.

The Problem of Corrosion

Selecting a material with inadequate corrosion resistance for a particular application can be a very expensive mistake. Direct and indirect economic losses which can result from corrosion include expenses due to:

1. Replacement of corroded equipment.
2. Overdesign to allow for corrosion.
3. Shutdown of equipment because of a corrosion failure.
4. Loss of a product, such as a container that corroded through.
5. Contamination of a product.
6. Loss of efficiency. For example, corrosion product lowers heat transfer rate in heat exchangers.

Some of these indirect losses, such as loss due to shutdown of equipment, can cost many times more than the difference between buying a material that would have performed satisfactorily and one that did not. Be sure to consider potential indirect losses due to corrosion when making a material selection.

Corrosion can also constitute a significant safety hazard, for example, in containers for toxic products (poisonous gases, etc.) and critical parts in transportation media.

The Special Case of Stainless Steel

The fundamental resistance of stainless steel to corrosion occurs because of its ability to form a protective coating on its surface. This coating is a passive film which is resistant to further oxidation or other forms of chemical attack. This passive film may be monomolecular in thickness, usually invisible, but generally protective in oxidizing environments such as air and nitric acid. The passive film will, however, tend to lose its protectiveness in reducing environments such as hydrochloric acid. Whether an environment is oxidizing or reducing is not always a function of its oxygen content. For example, different aqueous solutions can oxidize the surface of a metal to different degrees independent of their oxygen content. Also, the oxidizing power of the given solution may change with concentration, temperature and impurity content.

Chromium is the most important element in maintaining the passive film. With free chromium (not present as carbides or other compounds) in excess of about 11%, steels do not typically form red rust, and so they are called "stainless." Increasing the chromium content of the stainless steel invariably broadens the range of environments which are sufficiently oxidizing to maintain a passive film. Alloying additions of nickel and molybdenum also expand the range of passivity.

Fundamental to most types of corrosion to which stainless steels are subject is that halogen salts, primarily chlorides, easily penetrate the passive film and allow corrosive attack to occur. Chlorides are abundant in nature and are used extensively for de-icing, cooking, etc. Chlorides are soluble, active ions and the basis for good electrolytes—good conditions for chemical attack or corrosion.

Types of Corrosion

Corrosion can be divided into two basic types:

1. **General Corrosion** in which the metal corrodes at a uniform rate over the entire surface; and
2. **Localized Corrosion** in which only a small area of the metal surface is affected but the rate of corrosion in this small area is relatively high.

All metals and alloys are subject to these two types of corrosion, but we will focus on stainless steels.

General Corrosion

As its name implies, general corrosion is uniform dissolution of the metal over all the metal surface exposed to a corrodent. The general corrosion that occurs on the exposed surface may be expressed as a corrosion "rate," that is, a regular rate of metal loss over the entire surface. General corrosion is shown in Figure 1 showing two samples of stainless steel, one that has not been corroded and one that has experienced severe general corrosion. The second one obviously is lighter in weight than the first. By measuring this weight loss over a given time, and knowing the density and dimensions of the test sample, one can calculate depth of penetration in terms such as mils penetration per year (mpy). Conversion factors for other corrosion rate units appear in Table 1.

Figure 1 *Example of uncorroded test sample and general corrosion*

TABLE 1

Conversion of Corrosion Rate Units

Given Units	Multiplier to Convert to MPY
ipy	1000
ipm	12000
mm/y	39.4
µm/y	0.039
pm/s	1.24
$g/m^2/h$	345/p
mdd	1.44/p
$\mu g/m^2/s$	1.24/p

ipy = inches per year
ipm = inches per month
mdd = milligrams per square decimeter per day
p = metal density in g/cm^3

Such general corrosion results from the uniform breakdown of the passive film over the entire surface of the steel. Acid cleaning or pickling is an exaggerated example of general corrosion.

General corrosion may be reduced or even prevented by the proper selection of materials that resist the intended corrosive environment.

The end-use application should dictate whether an alloy with a known corrosion rate is suitable for service. For example, a rate of < 2 mpy would generally be necessary for a food container, whereas a rate of 20 mpy might be adequate for some industrial applications. Corrosion rates as high as 50 mpy can occasionally be tolerated, but higher rates are rarely economical.

Stainless steels are sometimes used at higher temperatures because of their improved oxidation resistance over ordinary steel. The maximum service temperature in still air varies from about 649/704°C (1200/1300°F) for the 12% chromium stainless and up to about 1093/1149°C (2000/2100°F) for 25% chromium stainless. Oxidation resistance is primarily dependent upon chromium content, but in the nickel-containing alloys, higher nickel contents are beneficial particularly in intermittent service.

Localized Corrosion

We will discuss these forms of localized corrosion:

1. Intergranular Corrosion
2. Pitting Corrosion
3. Crevice Corrosion
4. Galvanic Corrosion
5. Stress-Corrosion Cracking

Intergranular Corrosion

Intergranular corrosion is rarely a problem if the stainless steel is used in the “mill annealed” condition. A knowledge of intergranular corrosion is only necessary if the steel is to be heated to elevated temperatures [>427°C (>800°F)] during service or prior to service (during welding or stress relieving, for example).

The austenitic stainless steels, such as Type 304, become susceptible to intergranular corrosion in some environments after they are heated for short times in the range of about 482/816°C (900/1500°F) or are cooled slowly through that range. An example is shown in Figure 2. This susceptibility to intergranular corrosion is generally believed to be due to the precipitation of chromium carbides in the grain boundaries when the steel is heated in or through this temperature range. These grain boundary carbides are deleterious because they remove chromium from adjacent areas, making these areas more prone to attack in certain environments. Susceptibility to intergranular corrosion in austenitic stainless steels can be avoided by:

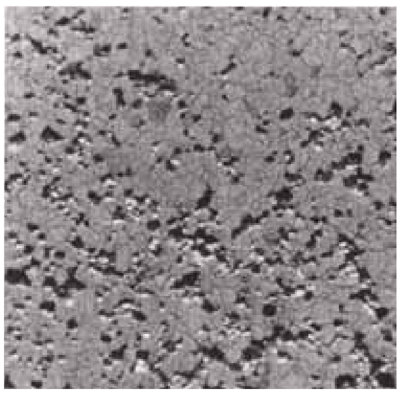


Figure 2 *Example of intergranular corrosion*

1. Using alloys only in the annealed condition [927/1093°C (1700/2000°F)], or annealing and quenching rapidly after exposure to the critical temperature range. The corrosion resistance of welded material can also be regained by annealing after welding.

2. Using alloys that have low carbon, such as Types 304L and 316L.

3. Using alloys that are "stabilized" by the addition of a carbide former such as columbium or titanium, such as Types 347, 321, and Carpenter 20Cb-3® stainless. The columbium and titanium combine with the carbon in these alloys, making the carbon unable to form the deleterious chromium-rich carbides. These alloys are preferably annealed in the range 871/982°C (1600/1800°F) to promote the formation of columbium or titanium carbide.

The ferritic stainless steels, such as Type 430, become susceptible to intergranular corrosion in some environments if heated above 927°C (1700°F) such as during welding. This problem can be overcome by reannealing at 704/816°C (1300/1500°F).

Pitting Corrosion

Under certain conditions of service, stainless steels that are apparently immune to attack by certain solutions will fail by corroding deeply in individual spots. This type of corrosion, shown in Figure 3, is known as pitting. Pitting can occur for several reasons. The most common cause of pitting is lack of cleanliness. If scale, corrosion products, and shop dirt are allowed to deposit on a stainless steel surface, then metal immediately underneath the deposit lacks access to oxygen. Oxygen is required to maintain the corrosion-resistant surface film. Corrosion initiates under the deposit and may be further accelerated by local chemistry changes in the corrodent beneath the deposit.

Figure 3 *Pit-type corrosion*

Pitting occurs much more readily in some environments than others with chlorides being the most common species likely to cause pitting. Stagnant conditions also promote pitting since they are more likely to allow deposits to become lodged on the metal surface. Stagnant conditions are also more likely to permit concentration of damaging species such as chlorides in the pitted areas.

Pitting is best avoided by maintaining clean surfaces and, if chlorides are present, preventing stagnant conditions. Cleaning stainless equipment with hydrochloric acid should be avoided unless all traces of acid can be immediately removed after the cleaning. The molybdenum-bearing grades such as Types 316, 317 and 20Cb-3 stainless have improved resistance to pitting compared with other stainless steels.

Crevice Corrosion

Crevices formed by metal-to-metal contact or at gaskets, for example, can lead to localized corrosion in the crevice (See Figure 4). Crevice corrosion is caused by lack of oxygen and buildup of acids and contaminants such as chlorides within the crevice. Similarly to pitting, crevice corrosion is more likely to occur in chloride solutions; the molybdenum-bearing grades are more resistant to it.

Galvanic Corrosion

Although classified here as a form of localized corrosion, galvanic corrosion may affect a larger surface area than pitting corrosion. Galvanic corrosion may occur when two dissimilar metals are in contact in an electrolyte (this includes most aqueous solutions).

Expect the corrosion resistance of stainless steel to be reduced when in contact with zirconium, noble metals, graphite, etc. On the other hand, it is improved at the expense of the other metal when in contact with iron, steel, aluminum, zinc or cadmium. Galvanic corrosion can be minimized or prevented by using, so far as possible, metals of the same or similar composition for complete assemblies when this condition is encountered. In some cases, a gasket can be used to form a separation between the two metals at the point of contact.

Figure 4 *Crevice Corrosion (gasket moved aside)*

Table 2 shows the galvanic behavior of stainless steels with other metals when tested in sea water. If two metals in this list are in contact in sea water, then the metal nearer the bottom of the list is the one most likely to corrode at the metal junction. The degree of corrosion is increased as the separation of the alloys in the list is increased.

Stainless steels are listed in this table in both the passive and active conditions. When the surface is active, the chromium rich passive film has been penetrated by the environment and increased corrosion is expected. Penetration of the passive film is more likely as chloride levels are increased, particularly when crevices are present.

The surface areas of the two dissimilar metals are also important—the higher the ratio of the areas of the noble metal to active metal, the greater will be the galvanic effect on the active metal.

In service, contact between two different stainless steels generally does not cause galvanic corrosion. In some environments, stainless may be considered, even if galvanic contact with other material will occur. Potential applications should be considered on a case-by-case basis.

TABLE 2

Galvanic Series of Metals and Alloys in Sea Water

ACTIVE ↑

Magnesium
Magnesium Alloys
Zinc
Aluminum
Cadmium
Steel or Iron
Cast Iron
Chromium-Iron (active)
18-8 Chromium-Nickel-Iron (active)
18-8-3 Chromium-Nickel-Molybdenum-Iron (active)
20Cb-3 Stainless (active)
Titanium (active)
Lead-Tin Solders
Lead
Tin
Nickel (active)
Brasses
Copper
Bronzes
Copper-Nickel Alloys
Silver Solder
Nickel (passive)
Chromium-Iron (passive)
18-8 Chromium-Nickel-Iron (passive)
18-8-3 Chromium-Nickel-Molybdenum-Iron (passive)
20Cb-3 Stainless (passive)
Titanium (passive)
Silver
Graphite
Zirconium
Gold
Platinum

NOBLE ↓

Stress-Corrosion Cracking

As the name suggests, this form of corrosion attack results from the combination of a selected corrosive environment and stresses in the material (Figure 5). The stresses may result from cold working, quenching after heat treatment, or from an externally applied stress.

Figure 5 *Micrograph of stress-corrosion cracking*

Stress-corrosion cracking in stainless steels occurs only in certain specific environments. Chloride solutions are the most well known of these. The stress-corrosion behavior of stainless steels is primarily dependent upon their nickel content and their yield strength. Low-yield-strength stainless steels are relatively immune to cracking in chlorides if they contain nickel less than about 0.5-1% (e.g., Types 405, 430). Low-yield-strength stainless steels become susceptible to cracking in hot chloride solutions [>66°C (>150°F)] as their nickel content is increased until they reach maximum susceptibility at about 8% nickel (e.g., Type 304). Further increasing nickel beyond about 30% (e.g., 20Cb-3® stainless) causes a marked increase in resistance to cracking. In summary, low-yield-strength stainless steels are resistant to chloride-stress-corrosion cracking if they contain either no nickel or greater than about 30% nickel.

Higher-strength stainless steels; i.e., martensitic and precipitation-hardening steels, differ from the low-strength stainless steels in that they can crack at room temperature, and even grades without nickel are susceptible. In general, the higher the yield strength of a high-strength stainless, the more susceptible it will be to stress-corrosion cracking. This is just a general rule; consult the appropriate data sheets for specific details.

High-strength materials can be cracked due to hydrogen embrittlement. This phenomenon is more likely to occur if the high-strength alloy is the protected metal in a galvanic couple. Hydrogen can be evolved in the corrosion process, particularly at the protected metal. If the hydrogen is not evolved as a gas, it may enter the metal as atomic hydrogen and embrittle the material. Generally, the effects of hydrogen embrittlement and stress-corrosion cracking are the same.

Low-yield strength stainless steels with about 8% nickel are often resistant to cracking in chlorides if the temperature is below about 50°C (120°F). Resistance at higher temperatures is possible in some environments. On the other hand, low pH, the use of sensitized or exposure to environments containing hydrogen sulfide can result in failures at lower temperatures. Sulfide stress cracking is characterized by cracking of low- or high-strength materials in the presence of hydrogen sulfide and water, in combination with a tensile stress. This form of cracking is generally expected to be due to a hydrogen embrittlement mechanism.

Stress-corrosion-cracking may be minimized by reducing fabrication stresses, removing harmful contaminants from the environment, or selecting materials that are resistant to this type of failure.

Factors Affecting Corrosion

Some of the factors that influence corrosion resistance, other than metal or alloy composition, are as follows:

Service Environment and Application

A. Bulk solution composition. This includes the solution pH and the concentration of its components.

B. The temperature of the corrodent. As a rule, the degree of corrosion increases with increase in temperature. There are numerous cases where metals satisfactory for cold solutions are entirely unsuitable for these same solutions at more elevated temperatures.

C. Heat transfer. In some applications, heat is transferred from the metal to the solution. The corrosion rate may be increased due to the higher metal temperature.

D. The presence of impurities in the corrosive medium. Although pure chemicals or solutions are seldom encountered in commercial work, the presence of even minor percentages of impurities is of utmost importance and should be considered when using published corrosion tables. While increased attack is expected when chlorides are present, some impurities can actually lower the corrosion rate.

E. Adherent deposits. Deposits on the metal surface can cause crevice corrosion, particularly in the presence of chloride ion impurities.

F. The degree of aeration to which a corrodent is exposed. Liquids kept in closed containers from which air or a circulation of air is excluded may cause different degrees of corrosion than these same liquids when freely exposed to the atmosphere. This applies also to the presence of atmospheric gases, which may sometimes change the corrosive behavior of metals to a marked degree.

G. Velocity of corrodent. Since published corrosion tables are usually based on static tests, the corrosion in actual service may differ due to the effect of velocity.

Material Condition and Fabrication

A. Surface condition. A smoother finish often improves corrosion resistance. This is especially true for lower alloy stainless steels in severe atmospheric exposures. Also, for optimum corrosion resistance, surfaces must be free of scale and foreign particles and finished parts should be passivated.

B. Metallurgical condition. Corrosion resistance, particularly stress-corrosion cracking, can depend upon whether a material is annealed, hardened or cold worked, etc.

C. Thermal treatment in fabrication. Welding or stress relieving can affect resistance to corrosion, particularly to stress-corrosion cracking and intergranular corrosion.

D. Fabrication design. Attack can occur at crevices or where dissimilar metals are in contact.

Corrosion Testing

Selection of appropriate corrosion tests requires consideration of the potential forms of corrosion, details of the service environment and the material composition and fabrication. Some of the factors affecting corrosion are presented above.

Corrosion evaluation methods can be divided into simulated service and accelerated tests. In a simulated service test, both environment and material condition are similar to that in service. Long-term exposures can be required for a proper evaluation. Accelerated tests are designed to detect the susceptibility of a material to one or more forms of corrosion in a relatively short period of time.

Intergranular Corrosion

The standard tests for intergranular attack are generally viewed as accelerated techniques and often are used to verify that the material received a good anneal. The ASTM standards are listed in Figure 6. Each ASTM designation is applicable to different alloys or material conditions: A 262 for austenitic stainless steels, A 763 for ferritic stainless steels and G 28 for wrought, nickel-rich, chromium-bearing alloys.

Pitting and Crevice Corrosion

ASTM G 48 describes accelerated tests for pitting and crevice corrosion in ferric chloride or ferric chloride-hydrochloric acid. Samples (with or without crevices) may be exposed at one constant temperature and evaluated by weight loss and appearance. Alternatively, the critical temperature for attack may be determined by exposing several sets of specimens at increasing temperatures and recording the temperature at which attack occurs. Critical pitting temperature can also be determined electrochemically using ASTM G 150.

Stress Corrosion Cracking

The boiling magnesium chloride test of ASTM G 36 has been used extensively to evaluate resistance to stress-corrosion cracking at elevated temperature, but this test is much more severe than most service environments. An alternative environment, which may be more useful to predict service experience, is found in ASTM G 123 and consists of boiling 25% NaCl acidified to pH 1.5 with phosphoric acid.

Cracking that occurs at lower temperatures can be studied using the salt spray test of ASTM B117 at 35°C (95°F). If hydrogen sulfide is present, sulfide-stress-cracking resistance can be evaluated using NACE TM0177 which involves exposing stressed samples to an acidified H2S environment.

Cracking is possible in other than chloride environments. For example, sensitized Type 304 can be cracked in polythionic acid, produced when hydrogen sulfide and sulfur dioxide are bubbled through water. The evaluation test is found in ASTM G 35.

Several methods are available to externally stress samples for exposure to corrosive environments. Sample configurations include U-bends (ASTM G 30), bent beams (ASTM G 39), C-rings (ASTM G 38), and tensile samples (ASTM G 49). C-rings and tensile samples can be notched to change the stress state and increase the likelihood that failure will occur in a predetermined area. Some notched samples can be fatigue pre-cracked to study crack propagation. Examples of such specimens are wedge open load, compact tension, cantilever beam and double cantilever beam. In addition, slow strain rate tests, which evaluate stress corrosion resistance by slowly pulling a specimen to failure in a corrosive environment, are found in ASTM G 129.

Test samples for the evaluation of weldments are described in ASTM G 58. These include samples using the residual stresses from welding as well as externally stressed or pre-cracked specimens.

A more recent test has been developed to measure SCC resistance of stainless alloys. The RSL (Rising Step Load) test, ASTM F 1624, provides an actual KIscc value by testing a pre-cracked sample via an incremental step loading technique. Using this test method, SCC resistance in 3.5% NaCl solution at room temperature can be quantified. Values for a sample tested in a solution are then compared to values for the material obtained in an air test to provide a value for overall degradation of the material due to SCC in a given environment.

Corrosion in Atmospheres

Three tests have been widely used for stainless steels. All are performed in controlled-atmosphere chambers. The mildest, 100% humidity at 35°C simulates storage or use in many damp environments. The 5% salt spray (sodium chloride) of ASTM B 117 is more aggressive and has been used to simulate exposure to road salt or marine environments. The Copper-Accelerated Acetic Acid-Salt Spray test (ASTM B 368) is an even more severe test in which 5% sodium chloride with a copper II chloride addition is acidified using acetic acid. This test and the Salt Spray test are not suggested for all grades of stainless steels.

***Figure 6** – ASTM Intergranular Corrosion Tests*

Alloy System	ASTM Standard	Test Media	Test Duration
Austenitic stainless steels	A 262-A	Oxalic acid etch	Etch test
	A 262-B	Ferric sulfate-sulfuric acid	120 hours
	A 262-C	Nitric acid (Huey test)	240 hours
	A 262-E	Copper sulfate - 16% sulfuric acid (copper contact)	24 hours
Wrought nickel-rich, chromium-bearing alloys	G 28-A	Ferric sulfate - sulfuric aid	24/120 hours
	G 28-B	Mixed acid-oxidating salt	24 hours
Ferritic stainless steels	A 763-W	Oxalic acid etch	Etch test
	A 763-X	Ferric sulfate - sulfuric acid	24/120 hours
	A 763-Y	Copper sulfate - 50% sulfuric acid	96/120 hours
	A 763-Z	Copper sulfate - 16% sulfuric acid (copper contact)	24 hours

Importance of Cleaning and Passivating

The corrosion-resisting qualities of stainless steels are inherent in the metal itself. However, contamination of the surface by adhering dirt or scale can have a deleterious effect. For this reason, surfaces must be free of scale, lubricants, foreign particles, and coatings applied for drawing and heading. After fabrication of parts, cleaning and/or passivation should be considered. Passivation maximizes the inherent corrosion resistance of stainless steel. Perhaps the best test to confirm that passivation has been effective is a 24-hour exposure to 100% humidity at 35°C. Learn more about cleaning and passivation.

Other resources: www.nace.org | www.astm.org

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Magnetic Properties of Stainless Steels

The magnetic behavior of stainless steels varies considerably, ranging from nonmagnetic in fully austenitic grades to hard or permanent magnetic behavior in the hardened martensitic grades. Stainless steels have not found widespread use solely as magnetic materials since their magnetic capability is almost always inferior to conventional magnetic materials. However, there are circumstances and applications where the magnetic or nonmagnetic behavior can significantly influence fabrication and use of these alloys.

Austenitic (nonmagnetic) Stainless Steels

All austenitic stainless steels are essentially nonmagnetic in the fully austenitic condition as occurs in well-annealed alloys. The DC magnetic permeabilities range from 1.003 to 1.005 when measured at magnetizing forces of 200 oersteds (16k A/m). The permeability increases with cold work due to deformation-induced martensite, a ferromagnetic phase. For certain grades such as Types 302 and 304, the increase in magnetic permeability can be appreciable, resulting in these grades being weakly ferromagnetic in the heavily cold-worked condition. The susceptibility of a particular grade to becoming ferromagnetic when heavily cold worked depends on the stability of the austenite, which, in turn, depends on chemical composition and homogeneity.

The effect of cold work on magnetic permeability is illustrated for several austenitic stainless steels in Figure 1. The relationship between ultimate tensile strength and magnetic permeability is shown in Figure 2. The rise in permeability correlates well with the increase in tensile strength or work-hardening behavior, which is another measure of austenite stability. The differing performance between grades is a reflection of their composition. In particular, nickel increases austenite stability, thereby decreasing the work-hardening rate and the rate of increase of magnetic permeability. Consequently, the higher nickel grades, such as Carpenter Stainless No. 10 (Type 384), exhibit lower magnetic permeabilities than the lower nickel grades such as Project 70+® Type 304/304L when cold worked in equivalent amounts. The high-manganese, high-nitrogen alloys, such as Carpenter 18Cr-2Ni-12Mn, are also noted for maintaining low permeability after heavy deformation.

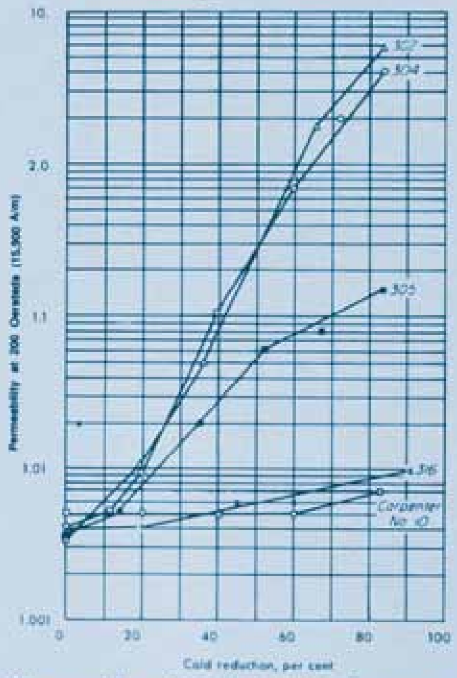
The magnetic permeabilities achievable in austenitic stainless steels are very low compared with conventional magnetic materials such as silicon-iron alloys. Therefore, their non magnetic behavior is more of a concern. Certain uses such as housings and components for magnetic detection equipment used for security, measuring and control purposes require that the steel be nonmagnetic. That is because the presence of even weakly ferromagnetic parts can adversely affect performance. Unless the austenitic stainless steel parts are used in the annealed condition and are not subjected to deformation during use, a higher nickel grade would be a prudent choice assuming it offered the appropriate corrosion resistance and strength.

For a given grade, the magnetic permeability can vary significantly depending on the chemistry and degree of cold work of the steel. Often a particular lot of an "unstable" grade such as Type 304 can perform satisfactorily. If the magnetic permeability of an austenitic stainless steel is of particular concern, it can be measured by relatively simple means as described in ASTM Standard Method A342.

Ferritic Stainless Steels

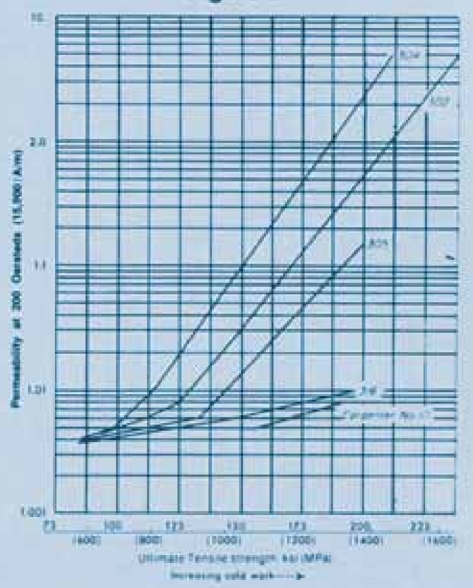
Ferritic stainless steels are ferromagnetic and have been used as soft magnetic components such as solenoid cores and pole pieces. Although their magnetic properties are not generally as good as conventional soft magnetic alloys, they are successfully used for magnetic components which must withstand corrosive environments. As such, they offer a cost-effective alternative to plated iron and silicon-iron components. In addition, the relatively high electrical resistivity of ferritic stainless steels has resulted in superior AC magnetic performance.

Figure 1



When cold working is employed, some normally nonmagnetic austenitic steels become substantially ferromagnetic

Figure 2



Magnetic permeability of austenitic alloys subjected to cold working can also be expressed as a function of tensile strength.

Soft magnetic properties, i.e., high magnetic permeability, low coercive force (H_c) and low residual induction (B_r), depend strongly on alloy chemistry, particularly impurities such as carbon, sulfur and nonmetallic inclusions, and stresses due to cold working. Magnetic permeability decreases and the coercive force increases. That is, the behavior is less magnetically soft, with increasing amounts of impurities and stress. As a result, well-annealed, high-purity alloys yield optimum magnetic performance. Carpenter produces two grades of ferritic stainless steels, Carpenter Stainless Type 430F Solenoid Quality, Carpenter Stainless Type 430FR Solenoid Quality, and the ChromeCore® family of alloys for consideration in soft magnetic alloy applications. These two grades are melted and processed for consistent magnetic properties.

Even if a ferritic stainless steel is not being used as a magnetic component, its magnetic behavior can be of significance to fabrication and use. Annealed ferritic stainless steels exhibit soft magnetic behavior, which means they do not have the ability to attract other magnetic objects when removed from an externally applied magnetic field. Cold working, however, increases the coercive force (H_c) of these steels changing their behavior from that of a soft magnet to that of a weak permanent magnet. If parts of cold worked ferritic stainless steel are exposed to a strong magnetic field such as occurs in magnetic particle inspection, the parts can be permanently magnetized and, therefore, able to attract other ferromagnetic objects. Apart from possibly causing handling problems, the parts would be able to attract bits of iron or steel which will, if not removed, impair corrosion resistance. It is therefore prudent to either electrically or thermally demagnetize such parts if they have been subjected to a strong magnetic field during fabrication. Magnetic properties of some ferritic stainless steels are listed in Table 1.

Martensitic and Precipitation Hardenable Stainless Steel

All martensitic and most precipitation hardenable stainless steels are ferromagnetic. Due to the stresses induced by the hardening transformation, these grades exhibit permanent magnetic properties if magnetized in the hardened condition. For a given grade, the coercive force tends to increase with increasing hardness, rendering these alloys more difficult to demagnetize. Although not used as permanent magnets to any significant extent, the previously mentioned potential difficulties of hardened ferritic stainless steels also apply to these steels. Magnetic properties of some martensitic steels are also shown in Table 1.

TABLE 1

Magnetic Properties of Some Ferritic and Martensitic Stainless Steels

Grade	Condition	Rockwell Hardness	Maximum Relative Permeability	Coercive Force (Hc)	
				Oersteds	A/M
Type 410 (Martensitic)	A H	B 85 C 41	750 95	6 36	480 2900
Type 416 (Martensitic)	A H	B 85 C 41	750 95	6 36	480 2900
Type 420 (Martensitic)	A H	B 90 C 50	950 40	10 45	800 3600
Type 430F Solenoid Quality (Ferritic)	A	B 78	1800	2	160
Type 430FR Solenoid Quality (Ferritic)	A	B 82	1800	2	160
Type 440B (Martensitic)	H	C 55	62	64	5100
Type 446 (Ferritic)	A	B 85	1000	4.5	360
Chrome Core® 12-FM	A	73	3100	2.5	200
Chrome Core 13-FM	A	75	2900	1.8	144
Chrome Core 13-XP	A	80	3200	1.6	128
Chrome Core 18-FM	A	86	1500	2.5	200

Above data determined on round bars 0.375" (9.53 mm) to 0.625" (15.88 mm) per ASTM A 341-Fahy permeameter.

A—fully annealed
H—heat treated for maximum hardness

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Fabricating Carpenter Stainless Steels

Due to the sheer volume of information available on the fabrication of stainless steels, this section will provide a general knowledge of the methods of fabrication. In several fields, Carpenter Technology Corp. has developed considerable information regarding certain methods of fabrication. This section will briefly discuss forging, blanking, punching, shearing, perforating, annealing and heat treating, cleaning and passivating, tumbling and ball burnishing, and machining and abrasive wheel grinding of Carpenter stainless steels.

The following industry associations and technical societies are good resources for additional information:

American Iron and Steel Institute
www.aist.org

ASM International
www.asminternational.org

ASTM International
www.astm.org

American Welding Society, Inc.
www.aws.org

Welding Information Center
www.weldinginfocenter.org

Forging Industry Association
www.forging.org

Wire Association International
www.wirenet.org

International Molybdenum Association
www.imoa.info

Forging Carpenter Stainless Steels

In all metalworking operations stainless steel can be easily worked when the characteristics of these alloys are understood. Stainless steels have good inherent forgeability, but there are important differences from the carbon and low-alloy steels.

Rotary Forging

Most importantly, stainless steels are much stronger at forging temperatures and thus require greater force or more blows under a hammer than is required for leaner alloys. The high temperature alloys are even harder and more resistant to flow in forging operations.

All stainless steels have much lower thermal conductivity than ordinary steel—thus the heat penetrates the steel more slowly. The best results are obtained in a muffle or semimuffle type of furnace with pyrometer control. Keep open flames away from the steel.

As shown in Table 1, the forging temperature depends upon the type of steel—austenitic, martensitic, ferritic, duplex or precipitation hardenable, with a few special cases. There is no simple rule to follow for thermal handling on either heating or cooling. The suggested forging temperatures should be attained by heating in furnaces held at those temperatures (all temperatures are furnace temperatures, not die temperatures). The furnace must not be run excessively hot and the steel withdrawn "on the fly" as it rushes up to the forging heat. This gives a wash heat on the surface and a cold center.

Other Resources: Nickel Development Institute | Stainless Steel Industry of North America | Stainless Steel World Forging Industry Association

TABLE 1

Forging Temperatures of Stainless Steels

Grade	Do Not Forge Below		Do Not Forge Above		Special Instructions
	°F	°C	°F	°C	
Type 302	1700	927	2300	1260	Slow preheat is *not* necessary. Cool forgings in air. Anneal after forging to restore corrosion resistance.
Type 304	700	927	2300	1260	
Type 304L	1700	927	2300	1260	
NeutroSorb PLUS® alloy	1800	982	2200	1204	
Forging temperature varies with Boron Content.					
Type 303	1700	927	2300	1260	
Type 303Se	1700	927	2300	1260	
Type 305	1700	927	2300	1260	
Type 309	1800	982	2250	1232	
Type 309S	1800	982	2250	1232	
Type 310	1800	982	2250	1232	
Type 310S	1800	982	2250	1232	
Type 384 (Stainless No. 10)	1700	927	2250	1232	
Type 316	1700	927	2300	1260	
Type 316L	1700	927	2300	1260	
Type 317	1700	927	2300	1260	
Type 321	1700	927	2300	1260	
Type 347	1700	927	2250	1232	
20Cb-3® stainless	1800	982	2250	1232	
Type 410	1650	899	2200	1204	Slow preheat is *not* necessary. Cool forgings in air. Do not quench. Anneal after forging to avoid cracking; cool to room temperature before annealing.
Type 414	1650	899	2200	1204	
Type 416 (No. 5)	1700	927	2250	1232	
Type 420	1650	899	2200	1204	Slow preheat is necessary. Cool forgings very slowly. Furnace cooling preferred. Anneal after forging to avoid cracking; cool to room temperature before annealing.
Type 420F	1650	899	2200	1204	
Type 431	1650	899	2200	1204	Slow preheat is *not* necessary. Cool forgings slowly. Anneal after forging to avoid cracking; cool to room temperature before annealing.
Type 440A	1700	927	2200	1204	Slow preheat is necessary. Cool forgings very slowly. Furnace cooling preferred. Anneal after forging to avoid cracking; cool to room temperature before annealing.
Type 440B	1700	927	2150	1177	
Type 440C	1700	927	2100	1149	
Type 440F	1700	927	2100	1149	
Pyromet® Alloy 355	1700	927	2100	1149	Slow preheat is *not* necessary. Air cool, equalize and overtemper.
Custom 455® stainless	1650	899	2300	1260	Slow preheat is *not* necessary. Cool forgings in air and anneal.
Custom 450® stainless	1650	899	2300	1260	
Custom 465® stainless	1650	899	2200	1204	
Custom 630 (17Cr-4Ni)	1850	1010	2200	1204	
Type 409Cb	1500	816	2050	1121	Slow preheat is necessary. Cool forgings in air. When reheating, use lower forging temperature and finish cold as possible for optimum grain refinement. Anneal after forging to restore corrosion resistance.
Type 430	1500	816	2050	1121	
Type 430F	1500	816	2100	1149	
7-Mo® stainless	1700	927	2000	1093	
7-Mo® PLUS stainless	2150	1177	2375	1302	Slow preheat is *not* necessary. Cool forgings in air. Anneal after forging to restore corrosion resistance.

Hold the heating furnace steady at the proper forging temperature and no hotter; allow the steel to soak out a little before withdrawing, and it will flow readily under the dies. In order not to slow down the forging operation and still run the furnace at a “slow” heat, more bars or billets can usually be heated at one time.

Most grades are subject to rapid grain growth at the forging heat. If all parts of the steel are thoroughly forged after heating, the grain structure will be refined again. If some parts of the forging get little reduction under the hammer, care must be exercised to limit grain growth by avoiding a long soak at temperature.

Surface preparation of forging bars and billets is generally more critical for stainless steels for several reasons. One example is the aircraft industry, which demands close tolerances for weight economy. This allows little or nothing for removing defects from finished parts. Any forging job will cost less if no defects must be removed because of poorly prepared stock.

Lastly, stainless steels require special heat treatments after forging to obtain best corrosion resistance and mechanical properties. (See Table 1) Briefly, the austenitic, ferritic and duplex grades should be annealed for optimum corrosion resistance; the martensitic grades are air-hardening and require slow cooling after forging plus subsequent annealing to prevent cracking; and the precipitation hardenable grades require a solution anneal for optimum aging response.

Carpenter has developed stainless steels that have optimum forgeability as opposed to, say, optimum machinability. The factors that contribute to good inherent forgeability in Carpenter stainless steel are as follows:

1. Controlled melting process for sounder centers, cleaner metal and less center segregation.
2. Balanced analysis for better metal flow, reduced hot shortness, and less in-process preparations.
3. Rare earth additions to highly alloyed austenitic grades such as 20Cb-3® stainless for reduced hot shortness and better yields.

Every metal fabricator who hot-works steels and alloys knows how important it is to determine the best temperature range for forging each grade. The more narrow the forging range, the more critical the problem becomes.

Many tests used to predict hot-working temperature ranges are helpful in that they offer a rough measure of forgeability over a given range, but they do not give specific values. This has forced forgers to rely on approximate temperatures which, in many cases, are not the best ones for the material being worked.

Hot tensile ductility is often used to determine the forging temperature range for a given alloy. Evaluation is performed using a Gleeble thermomechanical testing unit. The main feature of the unit is the ability to reproduce any desired thermal cycle on a test specimen via resistive heating.

Whereas inherent forging quality is melted into stainless steels, there is another equally important aspect to Carpenter forging quality: mechanical forgeability. This includes factors that contribute to soundness:

1. Disc inspection and sonic inspection of in-process billets and finished forging billets.
2. Adequate surface preparation both on in-process billets for manufacturing forging bars and also final surface preparation of forging bars and billets.
3. Quality control upset forging tests conducted on critical forging bar items.

Ask your Carpenter representative for additional information on Carpenter stainless steels for the forging industry. Technical information on hundreds of Carpenter alloys, as well as dozens of technical articles, is available free on Carpenter's technical information database at www.cartech.com/alloytechzone.html.

Other Resources: ASTM International

Relative Workability of Selectaloy Stainless Steels - Annealed Condition

E-Excellent   G-Good   F-Fair   P-Poor   NR-Not Recommended

Carpenter Stainless Steel	Ball Burnishing (Tumbling)	Blanking	Brazing (See Note No. 1)	Buffing (See Note No. 2)	Coining (Cold)	Deep Drawing and Stamping	Electrolytic Polishing	Embossing	Etching
Project 70+® Type 304/304L	E	G	G	E	G	G	E	G	Aqua Regia
Project 70+® Type 316/316L	E	G	G	E	G	G	E	G	Aqua Regia
20Cb-3® Stainless	E	G	G	E	G	G	E	G	Aqua Regia
Type 430	E	G	G	E	E	G	E	G	50-50 Hydro-chloric
Type 409Cb	E	G	G	E	E	G	E	G	50-50 Hydro-chloric
Type 410	E	G	G	E	G	F	E	G	50-50 Hydro-chloric
Type 420	E	G	F	E	G	P	G if hardened otherwise F	G	50-50 Hydro-chloric
Type 431	E	G	G	E	G	F	G	F	50-50 Hydro-chloric
Type 440C	E	G	F	E	F	NR	G if hardened	P	50-50 Hydro-chloric
Custom 450® Stainless	—	G	E to G	E	G to F	P to F	P to E	—	Special*
Custom 455® Stainless	—	G	F	E	F to G	P to F	G to E	—	Special*
Custom 465® Stainless	—	G	P to F	E	F to G	P to F	G to E	—	Special*

Note 1 - Brazing: Caution should be used in brazing or hard soldering stainless steels. See fabricating instructions.

Note 2 - Polishing: While the finish obtained on free-machining grades is good, there is a slight tendency to "pin feather drag."

Note 3 - Machining: For more complete information on machining, download the booklet "Guide to Machining Carpenter Specialty Alloys."

Note 4 - Punching (perforating): Generally, the free-machining grades and the ferritic/martensitic steels perforate very well. The austenitic grades tend to drag on the break. On all types, stepped punches are desirable.

Terms: Excellent, good, fair, etc., are relative among the several stainless steels. Grades marked "excellent" represent the best conditions. "Good" means that this operation presents no difficulties important enough to interfere with the selection of that particular steel, if its other properties are desirable. "Slight" means that the steel will stand a certain amount of such working but not as much as steels rated "good."

**50 ml Dist. H2O, 50 ml Ethyl Alcohol, 50 ml Methyl Alcohol, 50 ml HCl (37-38%), 2.5 ml H NO3, 1 gm cupric chloride, 3.5 gm ferric chloride.*

Carpenter Stainless Steel	Forging Hot	Forging Cold	Forming	Grinding (Ease)	Grinding (Is it Magnetic?)	Heading Hot	Heading Cold	Hobbing	Machinability % of 1212 (See Note No. 3)	Punching (Perforating) (See Note No. 4)
Project 70+® Type 304/304L	G	G	E	F	No	G	F	P	62	Yes
Project 70+® Type 316/316L	G	G	E	F	No	G	F	P	57	Yes
20Cb-3® Stainless	G	G	G	F	No	G	G	P	42	Yes
Type 430	G	G	G	F	Yes	G	E	G	57	Yes
Type 409Cb	G	G	G	F	Yes	G	E	G	57	Yes
Type 410	G	G	G	F	Yes	G	E	G	57	Yes
Type 420	G	Slight	F	F	Yes	G	F	G	52	Yes
Type 431	G	G	F	F	Yes	G	G	G	49	Yes
Type 440C	G	P	P	G	Yes	G	F	F	39	Yes
Custom 450® Stainless	E	F	G	G	Yes	E	G	F	43	Yes
Custom 455® Stainless	E	F	G	G	Yes	E	G	F	40	Yes
Custom 465® Stainless	E	F	G	G	Yes	E	G	F	38	Yes

Relative Workability of Selectaloy Stainless Steels—Annealed Condition (Continued)

E-Excellent G-Good F-Fair P-Poor NR-Not Recommended

Carpenter Stainless Steel	Press Brake Forming	Polishing Setup Wheels (See Note No. 2)	Riveting (Cold)	Roll Forming	Roll Threading	Shearing (Cold) (see Note No. 5)	Sawing (See Note No. 6)	Slitting	Soldering Soft
Project 70+® Type 304/304L	G	E	F	E	G	G	F	G	G
Project 70+® Type 316/316L	G	E	F	E	G	G	F	G	G
20Cb-3® Stainless	G	E	G	E	G	G	F	G	G
Type 430	G	E	E	E	E	G	F	G	G
Type 409Cb	G	E	E	E	E	G	F	G	G
Type 410	G	E	G	G	E	G	G	G	G
Type 420	F	E	F	F	F	F	F	F	G
Type 431	G	E	G	F	G	G	G	G	G
Type 440C	P	E	F	P	F	F	F	Not made as sheet or strip	F
Custom 450® Stainless	F	G	G	G	G	G	F	G	—
Custom 455® Stainless	F	G	G	G	G	G	F	G	—
Custom 465® Stainless	F	G	G	G	G	G	F	G	—

Note 5 - Shearing (cold): On all stainless, reduce the speed of the press to about 75% of normal, use shear angle, when possible, on punch or shear blade to relieve high pressures.

Note 6 - Sawing: Band saws for use with stainless have 14 teeth per inch, running at about 110 feet per minute—hacksaws, 6 to 10 teeth per inch and 60 strokes per minute. If band saws are used with over 15 and up to 18 teeth per inch, cut speed to 100 feet per minute.

Note 7 - Hard Soldering: If temperatures above 1400°F (760°C) are involved, the martensitic grades will harden and must be tempered subsequently.

Note 8 - Surface Hardening: Very high surface hardness can be obtained to a depth of .004 to .018" (0.10-0.45 mm) by nitriding. This will reduce corrosion resistance to some extent.

Note 9 - Spinning: Carpenter Stainless Type 304 is the best in the austenitic group. The martensitic/ferrite/age hardening steels do not work-harden as rapidly as the austenitic steels.

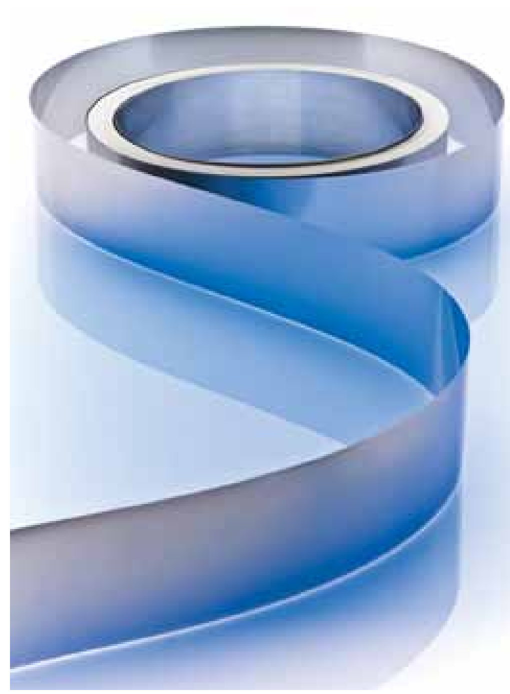
Note 10 - Welding: See fabrication instructions on page 53 for more complete information.

Download the Guide to Machining Carpenter Specialty Alloys

Carpenter Stainless Steel	Soldering Hard (See Note No. 7)	Surface Hardening (See Note No. 8)	Spinning (See Note No. 9)	Swaging	Upsetting (Hot)	Upsetting (Cold)	Welding (Fusion and Resistance) (See note No. 10)	In All Hot Working Operations, Look Out for . . .
Project 70+® Type 304/304L	G	G	G	G	G	F	E	Intergranular corrosion—anneal afterward.
Project 70+® Type 316/316L	G	G	G	G	G	F	E	Intergranular corrosion—anneal afterward.
20Cb-3® Stainless	G	G	G	G	G	G	G	Intergranular corrosion—anneal afterward.
Type 430	G	G	G	G	G	E	F	Grain Growth
Type 409Cb	G	G	G	G	G	E	F	Grain Growth
Type 410	G	G	G	G	G	G	G	Air Hardening
Type 420	G	G	P	F	G	F	F	Air Hardening
Type 431	F	G	F	G	G	G	F	Air Hardening
Type 440C	F	G	NR	Slight	G	F	NR	Air Hardening
Custom 450® Stainless	G	G	—	G	E	F	G	None
Custom 455® Stainless	F	G	—	G	E	F	F	Grain Growth
Custom 465® Stainless	F	P	—	G	E	F	P to F	Grain Growth

Blanking, Punching, Shearing and Perforating Carpenter Stainless Steels

The following four properties should help you successfully blank punch, shear and perforate stainless steels:



1. All stainless steels have higher tensile and shear strengths than mild steel even when dead soft annealed. This tells us that the press must have adequate power. The constant uniform pressure provided by hydraulic presses makes them desirable for these operations. On some jobs, slower speeds and higher pressures than are normal for mild steel will work better with stainless steels. This property also indicates that tools must be rugged and strong because they will wear faster. Tool steels that provide maximum wear resistance and good toughness, such as Carpenter's Hampden (D3), No. 610 (D2), Micro-Melt® A11*, and Micro-Melt A11-LVC tool steels, have displayed excellent results on long-run jobs.

** Micro-Melt A11 tool steel is equivalent in hardness, wear resistance and heat treating response to CPM 10V alloy. CPM and 10V are registered trademarks of Crucible Materials Corporation.*

2. All stainless steels excepting the free-machining types have a tendency to gall, or pick-up on the tools. This involves the tolerances in fitting punches and dies. Tool clearances for the straight chrome grades will approach that for ordinary steels. Galling and tool pick-up can be reduced or eliminated by properly mating the tools. A practice frequently followed is to allow very little clearance between the punch and die, then if it is too close, relieve the punch until the correct tolerance is obtained for the job. Evidence of too little clearance is the early tendency for the punch to gall or pick-up. Too much clearance will result in excessive burrs and a drawing action along the edge of the cut.

3. The austenitic chrome-nickel stainless steels, as annealed, are tough and gummy. There will be less breakout on these particular types. They will break more uniformly, however, if the alloys can be used at a slightly higher hardness. The straight chrome types will have a more normal breakout.

4. The austenitic chrome-nickel stainless steels work harden more rapidly but are more ductile than ordinary soft steels. This is not true of the straight chrome steels, which work harden at about the same rates as mild steel but are only about 80% as ductile.

This property indicates difficulty in **shaving** on the chrome-nickel types. The sheared edges are work hardened to such an extent that it is difficult to pick up a light cut. For shaving these grades, a more generous second cut must be taken to get under the hardened skin. This difficulty does not exist in the straight chrome types.

When **shearing** annealed stainless steel, increase the pressure or use heavier equipment than that required for mild steel. As a guide, the shear strength of annealed stainless is generally estimated at 75,000 to 100,000 psi (517 to 690 MPa) as compared to 50,000 to 70,000 psi (345 to 483 MPa) for mild steel and medium carbon steels. An increase in press capacity from 30% to 50% is usually ample for most jobs. In cold-worked or -hardened conditions, stainless develops very high mechanical properties and requires correspondingly greater pressures to shear.

Break-through varies with the type of stainless. The straight chrome types of the 400 Series work much the same as ordinary steels, while the chrome-nickel steels of the 300 Series show very little break-through. Therefore, on the 300 stainless steels, keep the blades very sharp and the adjustment close to avoid dragging. For example, when cutting 19 or 20 gauge stock, a clearance of 0.001/0.002" (0.025/0.051 mm) is usually suggested.

In **perforating**, follow the same practice used in blanking or punching by employing slow speeds, sharp tools and sufficient power. When the perforating punches are small, drawing compounds are useful.

For **punching or drilling** small holes, with the straight chrome steels (400 Series), it is not always economical to perforate when the diameter of the hole is less than the thickness of the metal. With chrome-nickel steels (300 Series), the minimum hole diameter should be 1-1\2 or 2 times the metal thickness.

Clean blanking, punching and shearing can only be expected in stainless steels that are uniformly annealed at the mill. All Carpenter stainless strip steels are continuously annealed in specially designed furnaces to promote uniformity from one end of the coil to the other.

Annealing and Heat Treating Carpenter Stainless Steels

Most consumers of stainless steel will not find it necessary to anneal or heat treat the parts they are fabricating. Most stainless products are furnished either as-annealed or as-heat treated from the mill, and further heat treatments are not usually necessary. The primary exceptions are where forging is done, where there is severe cold working done requiring subsequent annealing operations, or when martensitic or precipitation-hardening alloys must be hardened.

A NOTE ON HEAT TREATING ATMOSPHERES

It is possible to heat treat (anneal or harden) in the following environments:

1. Open atmospheres ranging from pure air to the normal products of combustion.
2. Special controlled atmospheres, some designed for heat treating carbon steels and those especially designed for stainless steels.
3. Vacuum.
4. Liquid salt baths ranging from neutral to carburizing or nitriding.

All forging operations should be followed by an annealing treatment, even in cases where subsequent heat treating for hardening is required. Annealing and heat treating procedures, temperatures, etc., can be found in the appropriate alloy data.

It is best to thoroughly clean all work to remove oil, grease, and other surface contamination prior to annealing or heat treating; failure to do so may cause carburization, difficult-to-remove scale, or other problems.

Open annealing is generally preferred since carburization is minimized and the type of scale produced is easily removed by simple procedures. However, when it is necessary to heat treat close to or at finished dimensions, either special atmospheres or salt baths are required to prevent the formation of scale and surface contamination. In most cases, atmospheres rich in hydrogen with extremely low moisture content are the best atmospheres for annealing stainless steels. Heat treating cleaned stainless steel parts in a dry hydrogen atmosphere will result in parts that appear to be as bright as they were prior to heat treatment. However, the problem of contamination in such atmospheres cannot be overlooked and good control is necessary. A properly maintained salt bath will also yield satisfactory results.

Vacuum annealing has the advantage of not exposing the heat-treated surface to any contamination whatsoever. It eliminates potential dangers from explosion. Also, some of the hardenable stainless steels can become contaminated with gases such as nitrogen and hydrogen. As is the case with bright atmospheres, a drawback is the inherently slower cooling rate with vacuum as opposed to liquid quenching media.

Caution: Atmospheres designed primarily for carbon and alloy steels generally carburize and oxidize stainless steels. Improperly purged salt baths may also either oxidize or carburize stainless. Pack hardening or pack annealing is definitely not recommended for stainless steel because damaging carburization cannot be avoided.

When hardening the martensitic stainless steels, a fairly good rule is to soak work at least 20 minutes at heat after being certain the entire charge is up to the heat treating temperature. Water quenching is to be avoided since it will not make the steel any harder than oil quenching and it also promotes cracking. Although these steels can be both air and oil hardened, oil quenching is generally recommended because it promotes maximum mechanical properties. Because of the slower cooling rates involved, bright hardening will generally result in the loss of a few points Rockwell C hardness compared with that which can be obtained by oil quenching.

Stainless steels can be surface hardened by both carburizing and nitriding, but corrosion resistance will be decreased. In some cases, corrosion resistance can be compromised when surface hardening is required.

Passivating and Electropolishing Stainless Steel Parts

Parts and components machined from stainless steels must be passivated to maximize their essential corrosion resistance. Good passivating practice can make the difference between satisfactory performance and premature failure. Poor practice can actually cause corrosion.

Two small instruments for orthopedic surgery made from Carpenter Custom 455® stainless and Custom 630 stainless. Each bright electropolished instrument contrasts with identical instruments covered by brown oxide from prior heat treatment. Control of finish between bright and dull can be maintained by judicious use of abrasive wheel and fine glass bead blasting. (Photo courtesy of Troy Innovative Instrument, Inc., Middlefield, OH)

The process of passivation is sometimes misunderstood. It is not a scale removal treatment, nor anything similar to a coat of paint. It is a post-fabrication method of maximizing the inherent corrosion resistance of the stainless steel from which the workpiece was made.

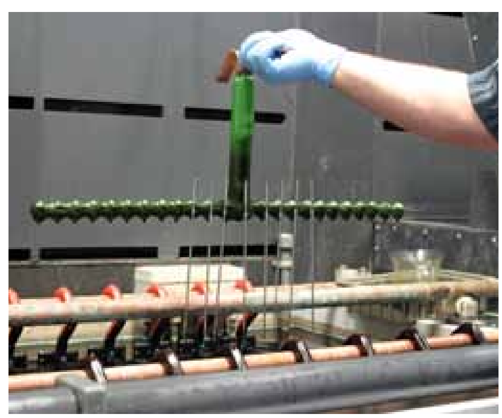
Not everyone agrees on the precise mechanics of how passivation works. It is certain, however, that a protective oxide film exists on the surface of passive stainless steel before it is fabricated. This invisible film is extremely thin, about 100,000 times thinner than a human hair!

Clean, freshly machined, polished or pickled stainless steel parts automatically acquire this protective film from exposure to oxygen in the atmosphere. Under the best conditions, this oxide film covers all part surfaces.

The need for passivation arises when parts are fabricated, either by cold forming or machining. Contaminants such as shop dirt or iron particles from cutting tools may be transferred to the surface of the stainless steel parts during fabrication. These foreign particles can reduce effectiveness of the original protective film. If they are not removed, corrosive attack may begin.

Under certain conditions, rust spots may appear on machined parts. This is actually corrosion of foreign particles from the tool steel, not the parent metal. Sometimes the crevice at the embedded tool steel particle or its corrosion products may cause attack of the part itself.

Likewise, small particles of iron-containing shop dirt may stick to the stainless part surface. Although the metal may appear shiny in the as-machined condition, the invisible particles of free iron can cause rusting on the surface after exposure to the atmosphere.



High strength, pin-like surgical instruments made from Carpenter Custom 455® stainless just removed from electropolishing tank. After a deionized water rinse, the instruments will have a lustrous finish. (Photo courtesy of Troy Innovative Instrument, Inc., Middlefield, OH)

Exposed sulfides, if ignored, also can be a problem. They derive from the addition of sulfur to stainless steels to improve machinability. Sulfides improve the alloy's ability to form chips that break away cleanly from the cutting tool during the machining process. If the part is not properly passivated, sulfides can act as initiation sites for corrosion on the surface of the fabricated product.

A two-step procedure can provide the best possible corrosion resistance. First is cleaning, a fundamental, but sometimes overlooked procedure. Second is passivating treatment in an acid or electrochemical bath.

Cleaning

Grease, coolant or other shop debris must be thoroughly cleaned from the surface to obtain the best possible corrosion resistance. Machining chips or other shop dirt can be wiped carefully off the part. A commercial degreaser or cleanser may be used to clean off machining oils or coolants. Foreign matter such as thermal oxides may have to be removed by grinding, or by methods such as acid pickling.

Occasionally, a machine operator might skip the cleaning, falsely assuming that by immersing a grease-laden part in an acid bath, both cleaning and passivating will take place at the same time. That doesn't happen. Instead, the contaminating grease reacts with the acid to form gas bubbles. These bubbles collect on the surface of the workpiece and interfere with passivation.

Even worse, contamination of the passivating solution, sometimes with high levels of chlorides, can cause "flash attack." Instead of obtaining the desired oxide film with a shiny, clean, corrosion-resisting surface, the flash attack produces a heavily etched or darkened surface. This is a deterioration of the very surface that passivation is designed to optimize.

Martensitic/Precipitation Hardened Stainless Grades

Parts made from martensitic stainless steels (Type 410, 420 and 440 series) are magnetic, with moderate corrosion resistance and high yield strengths. These alloys are hardened at a high temperature, then tempered to obtain the hardness and mechanical properties desired.

Precipitation hardenable (PH) stainless steels (Custom 630, 450, 455 and 465 stainless) offer a better combination of strength and corrosion resistance than the martensitic alloys. These PH grades are rough machined, aged at lower temperatures, then finish machined.

Workpieces made from the preceding stainless steels 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 condition can result in undersize parts with a pitted finish after the scale is removed by acid or abrasive methods. If cutting fluids are left on parts that are bright hardened, as in a vacuum furnace or protective atmosphere, surface carburization may occur, leading to a loss of corrosion resistance.

Passivating – Nitric Baths

After the stainless steel parts or components are thoroughly cleaned, they are ready for immersion in a passivating bath. More corrosion-resistant, chromium-nickel stainless steels can be passivated in a 20% by vol. nitric acid bath (Fig. 1).

As shown in the same table, less resistant stainless grades – straight chromium, high carbon-high chromium and precipitation hardened martensitic grades – can be passivated by adding sodium dichromate to the nitric acid bath to make the solution more oxidizing and capable of forming a passive film on the surface.

Another option is to increase the concentration of nitric acid to 50% by vol. The sodium dichromate addition and the higher nitric acid concentration both reduce the chance of undesirable flash attack. It should be understood here that the 50% nitric acid concentration is more oxidizing and therefore less aggressive to stainless steels than 20% nitric acid.

TABLE 1

Procedures for Passivating Stainless Steel Parts in Nitric Acid Bath

Grades	Passivation
- Chrome-Nickel Grades (300 Series) - Grades with 17% Chromium or more (except 440 Series)	20% by vol. nitric acid at 49/60°C (120/140°F) for 30 minutes.
- Straight Chromium grades (12-14% Chromium) - High Carbon–High-Chromium Grades (440 Series) - Precipitation Hardening Stainless	20% by vol. nitric acid + 3 oz. per gallon (22 g/liter) sodium dichromate at 49/60°C (120/140°F) for 30 minutes OR 50% by vol. nitric acid at 49/60°C (120/140°F) for 30 minutes.
1. 5% by wt. sodium hydroxide at 160/180°F (71/82°C) for 30 minutes. 2. Water rinse.	

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

Free-Machining Stainless Steels

The procedure for passivating free-machining stainless steels (Table 1) is somewhat different from that used with non-free-machining stainless alloys. That is because the sulfides of sulfur-containing free-machining grades are partially or totally removed during passivation in a typical nitric acid bath, creating microscopic discontinuities in the surface of the machined part. Even normally efficient water rinses can leave residual acid trapped in these discontinuities after passivation. Unless this acid is neutralized or removed, it can then attack the surface of the part.

Fig. 1: Left test cone is passivated using the A-A-A method. Results of conventional passivation shown on right. Both were exposed to salt spray.

To effectively passivate the free-machining stainless steels, Carpenter has developed the A-A-A (alkaline-acid-alkaline) process which neutralizes trapped acid. This passivation method can be done in less than two hours, as follows:

(a) After degreasing, soak the parts for 30 minutes in a 5% solution of sodium hydroxide at 160°F to 180°F (71°C to 82°). (b) Rinse the parts thoroughly in water (c) Immerse the parts for 30 minutes in a 20% by vol. nitric acid solution containing 3 ounces per gallon (22g/liter) of sodium dichromate at 120°F to 140° (49° to 60°C). (d) Remove the parts from bath and flush with water. (e) Immerse the parts in the sodium hydroxide solution for another 30 minutes. (f) Water rinse the parts again and dry them, completing the process.

The benefits of using the alkaline-acid-alkaline method are demonstrated in Fig. 2. The left test cone clearly shows the improved surface and resistance of free-machining stainless steel when passivated by the A-A-A method. The visible result of conventional passivation can be seen in the right test cone.

Passivating – Citric Baths

Citric acid passivation has been gaining favor with fabricators who wish to avoid the use of mineral acids or solutions containing sodium dichromate, and elude the disposal problems and greater safety concerns associated with their use. Citric acid is considered environmentally friendly in every respect. It is on the GRAS (Generally Regarded As Safe) list compiled by the FDA as a material that is safe for people to handle.

While citric acid passivation offers attractive environmental advantages, shops might want to continue the course if they are having success with mineral acid passivation and are having no safety issues. There may be no compelling need for those fabricators to change if they have a clean shop, well maintained and clean equipment, coolant free of iron-containing shop dirt and a process that yields good results.

Passivation in citric acid baths has been found useful for a large number of stainless steel families, including several individual stainless grades (Table 3). The conventional nitric acid passivation methods from Table 1 are included for convenience. Observe that the older nitric acid formulations are in volume percent, while newer citric acid concentrations are in weight percent. It is important to note that, in implementing these procedures, a careful balance of immersion time, bath temperature and concentration is critical to avoid the "flash attack" described earlier.

The passivation treatment varies depending on chrome content and machinability characteristics of the grades in each family. Note the columns referring to Process 1 or Process 2 in Table 4. Process 1 includes five steps: clean and degrease, rinse, passivate, rinse and dry. Process 2 includes seven steps: clean and degrease, rinse, passivate, rinse, neutralize, rinse and dry.

Laboratory tests have indicated that citric acid passivating procedures were more prone to "flash attack" than nitric acid procedures. Factors causing this attack included excessive bath temperature, excessive immersion time and bath contamination. Citric acid products containing corrosion inhibitors and other additives (e.g. wetting agents) are commercially available that reportedly reduce sensitivity to "flash attack".

The ultimate choice of passivation will depend on the acceptance criteria imposed by the manufacturer for whom the parts or components are to be made. For more information, refer to ASTM A 967 "Standard Specification for Chemical Passivation Treatments for Stainless Steel Parts." The specification can be accessed at www.astm.org.

TABLE 3

Passivation with Citric and Nitric Acids

Stainless Family	Example Stainless Steels	%CR	10w/o Citric Acid – passivated 30 minutes as below			Percent Nitric Acid–passivated 30 minutes at 120°F/140°F	
			°F	pH(a)	Process(b)	Volume %(c)	Process(b)
Austentic	Type 304/304L Type 316/316L Custom flow 302HQ Type 305 Nitrogen strengthened	15.0 -23.5	150		1	20%	1
Martensitic	Custom 630 (17Cr-4Ni) Custom 450®stainless Custom 455®stainless Custom 465®stainless	11.0 17.5	150		1	20%+$Na_2Cr_2O_7$	1
Ferritic	Type 430	≥16	150		1	20%+$Na_2Cr_2O_7$	1
Ferritic	Type 409Cb	<12	180-200		2	20%+$Na_2Cr_2O_7$ Use care: low Cr	1
Martensitic	Type 410 Type 420 TrimeRite®stainless	≤15	120- 130		2	20%+$Na_2Cr_2O_7$	1
Austenitic– FM	Type 303	17-19	150		2	20%+$Na_2Cr_2O_7$	2
Ferritic–FM	Types 430F & 430FR	≥16	NA	NA	NA	20%+$Na_2Cr_2O_7$	2
Ferritic–FM	Chrome Core® 18-FM	≥16	100		2	NA	NA
Ferritic–FM	Type 409Cb-FM	≤13	110	5	2	20%+$Na_2Cr_2O_7$	2
Martensitic	Type 416	≤13	110	5	2	Preferred vs. citric 20%+$Na_2Cr_2O_7$	2

FIGURE 4

Appropriate Processes for Passivating

Process 1	Process 2
1. Clean/degrease. 2. Water rinse. 3. Passivate as in Table 3. 4. Water rinse. 5. Dry.	1. Clean/degrease in 5% by weight sodium hydroxide at 160 to 180°F (71 to 82°C) for 30 minutes. 2. Water rinse. 3. Passivates as in Table 3. 4. Water rinse. 5. Neutralize in 5% by weight sodium hydroxide at 160 to 180°F (71 to 82°C) for 30 minutes. 6. Water rinse. 7. Dry.

Electropolishing

Electropolishing is an electrochemical process used to polish a metal surface by removing a microscopic amount of material from the workpiece. It is a frequently used method that more accurately conditions, rather than passivates the surface of a part. A part that has been electropolished requires no subsequent passivation.

This is the process of choice for parts and components that must have a very smooth, lustrous, mirror finish such as that required for surgical instruments. For bright-finish parts that reflect too much glare – as in the surgical suite – glass beads or a fine abrasive buffing pad may be used to tone down the surface finish.

High strength, pin-like surgical instruments made from Carpenter Custom 455® stainless just removed from electropolishing tank. After a deionized water rinse, the instruments will have a lustrous finish. (Photo courtesy of Troy Innovative Instrument, Inc., Middlefield, OH)

Electropolishing is accomplished by creating an electrochemical cell in which the material to be polished is the anode (stainless steel part). A cathode is formed to duplicate the geometry of the part surface. The anode and cathode are submerged in a heated electrolyte bath. For stainless steels, a variety of mixed acid solutions is suggested for the electrolyte bath, including glycolic, phosphoric and sulfuric. When a DC current is applied, an electrical charge dissolves metal ions from the part surface.

Since electropolishing removes surface material and contaminants, it improves the corrosion resistance of stainless parts so processed. In addition, electropolishing deburrs as it polishes the surface. Finally, the improved microfinish reduces product adhesion and contamination buildup.

Testing Treated Parts

Tests can be performed to determine how effective passivation has been in removing free iron and other exogenous matter from treated surfaces. These tests can be used on electropolished surfaces as well. Each of five test methods are described in detail in the previously mentioned ASTM A 967 specification. They are known as: A – water immersion test, B – high humidity test, C – salt spray test, D – copper sulfate test and E – potassium ferricyanide-nitric acid test.

It is essential that the test method employed is matched to the grade to be evaluated. A test that is too severe may reject perfectly good material, while one that is too lenient may accept unsatisfactory parts.

The 400 series precipitation-hardening and free-machining stainless steels are best evaluated in a cabinet capable of maintaining 100% humidity (samples wet) at 95°F (35°) for 24 hours. The cross section is usually the most critical surface, particularly for free-machining grades. One reason for this is that the sulfides, elongated in the direction of working, intersect this surface.

Critical surfaces should be positioned upward, but at 15 to 20 degrees from the vertical to allow any moisture to run off. Material that has been properly passivated will be virtually free of rust, although it may show some light staining.

Austenitic, non-free-machining stainless steels also may be evaluated by means of a humidity test. When so tested, liquid droplets of water should be present on the surface of samples, revealing free iron by the presence of rust formation.

A faster method is available using a solution from ASTM A380, "Standard Recommended Practice for Cleaning and Descaling Stainless Steel Parts, Equipment and Systems." This test consists of swabbing the part with a copper sulfate/ sulfuric acid solution, maintaining wetness for six minutes and observing whether there is any plating of copper.

Alternatively, the part may be immersed in the solution for six minutes. Copper plating occurs if iron is dissolved. This test should not be applied to surfaces of parts for use in food processing. Also, it should not be used for the martensitic or lower-chromium ferritic stainless steels of the 400 series because false-positive results are likely.

Historically, the 5% salt spray test at 95°F (35°C) also has been used to evaluate passivated samples. This test, too severe for some alloys, generally is not necessary to confirm that passivation has been effective.

Stainless steel components for the handle of a surgical instrument after they have been heat treated and passivated in this citric acid-base solution. (Photo courtesy of Troy Innovative Instrument, Inc., Middlefield, OH)

To help you with the passivation process, here is a checklist of good procedures and a second list of potential mistakes to be avoided.

Best Practice

1. Clean first, removing all particles of oxide or heat tint before passivating.
2. Assign certain machines to fabricate stainless steels only. Stay with the same preferred coolant to cut stainless steels, to the exclusion of all other metals.
3. Rack parts individually for treatment to avoid metal-to-metal contact. This is especially important with free-machining stainless steels where free flow of passivating and rinse solutions is needed to diffuse away corrosion products from sulfides and avoid pockets of acid.
4. Avoid chlorides which, in excess, can cause harmful flash attack. When possible, use only a good grade of water containing less than about 50 parts per million (ppm) of chlorides. Tap water is usually adequate, and in some cases up to several hundred ppm chlorides can be tolerated.
5. Replace baths on a regular schedule to avoid a loss in passivation potential that can result in flash attack and ruined parts. Baths should be maintained at proper temperature because out-of-control temperature may allow localized attack.
6. Maintain very specific schedules for solution replacement during high production runs to minimize the possibility of contamination. Use a control sample to test the bath's effectiveness. If the sample is attacked, it is time to change the bath.

Mistakes to Avoid

1. Do not passivate stainless steel parts that have been carburized or nitrided. Parts so treated may have their corrosion resistance reduced to the point where they are subject to attack in the passivating tank.
2. Don't use tooling with iron content (floor, equipment, coolant, etc.) that is not exceptionally clean. Steel grit can be avoided by using carbide or ceramic tools.
3. Don't forget that attack can occur in a passivating bath if parts are improperly heat treated. High-carbon, high-chromium martensitic grades must be hardened to become corrosion-resistant. Passivation is frequently performed after a subsequent temper using a temperature that maintains corrosion resistance.

4. Don't overlook the nitric acid concentration in the passivating bath. It should be checked periodically using a simple titration procedure below.

5. Don't passivate more than one stainless steel at a time. This discipline can prevent costly mixups and avoid galvanic corrosion.

TABLE 5

Simple titration test for checking nitric acid concentration of passivating bath. This test should be performed at regular intervals.

Titration Procedure
Concentration of nitric acid (percent) in a passivating bath can be determined with this method of titration, assuming excessive iron contamination has not occurred.
SUPPLIES 1. 0.5N standard sodium hydroxide solution (has limited shelf life). 2. Phenolphthalein indicator solution. 3. 1.0-ml pipettes, Class A. 4. 25-ml Schellbach burette with Teflon stopcock. 5. Burette support and clamp. 6. Casserole for acid sampling. 7. 250-ml Erlenmeyer flasks. 8. 4-ounce sample bottles.
PROCEDURE 1. Use casserole to transfer acid from tank to sample bottle. 2. Measure 1.0 ml of nitric acid solution into a 250-ml flask containing 100 to 150 ml of a good grade of water (drinking water will suffice) and a few drops of the phenolphthalein indicator. 3. Swirl flask and add sodium hydroxide slowly from a burette until the solution remains pink at least one-half minute.
CALCULATION *Ml titration X 3.24 = volume percent of nitric acid* NOTE: If the passivating solution contains sodium dichromate, the phenolphthalein indicator should be eliminated and the titration continuously monitored (pH meter) until a ph of 7.0 is obtained.

Tumbling and Ball Burnishing Carpenter Stainless Steels

Small stainless stampings can be given a fairly good finish and color in a tumbling barrel. Several things require emphasis:

1. **Be sure the parts are thoroughly cleaned before they are charged into the barrel.** During fabrication, the parts are covered with a lubricant which must be removed before tumbling. The best cleaning solution will depend upon the type of lubricant to be removed.

   (a) If a water-soluble lubricant, use alkali washing solution.

(b) If an oil-base lubricant, chemical degreasing will be required.

After the cleaning operation is completed, parts should not be exposed to shop dust and dirt.

2. **Most important is the type and condition of the water used for charging the barrel in normal operation and for rinsing the finished burnished pieces.** The formation of insoluble hard water curd from the soap always occurs if no attention is given to "water hardness." All hard water should be reduced to soft water before charging the barrel. This is quickly done by finding out from your water supplier the number of grains of hardness per gallon you have in your water. The water can then be softened by adding one ounce of trisodium phosphate per one grain of hardness per 100 gallons of water. This procedure will also prevent a coating of insoluble lime soap from forming on the surface of the burnishing balls. Avoid this coating, because once this deposit is present, no alkaline cleaning or rinsing in kerosene will remove it. Balls coated like this do not impart bright, clean luster finishes on the work.

3. **Absolute cleanliness is important.** In every step of the job, no "hangover" material should be left in the barrel or clinging in the load.

   For successful operation, wash the barrel and the balls before each loading. This requires roughly 30 minutes' spinning of the barrel, one-third full of water with one pound of soda ash, and one ounce of cyanide. Include the balls required for a normal load of work and discard the solution after the balls and barrel have been cleaned.

4. **No. 1 burnishing balls should be used.** Some manufacturers sell an especially good ball, particularly recommended for stainless steel. It pays to use them. On some parts with sharp angles or deep ridges, it may be desirable to use specially shaped burnishing materials, such as "jacks," "cones," "ovals," etc.

5. **Never use cheap yellow soap.** Only good white soap or soap flakes will be satisfactory.

6. **On some pieces, due to size and shape, the speed of the barrel can control the type of finish.** For example, small lock parts can be successfully run at 20 rpm. Some parts might be run as high as 27/32 rpm but, in general, the higher speeds do not give quite as good a finish as the slower speeds.

Machining and Abrasive Wheel Grinding of Carpenter Stainless Steels

The following industry associations and technical societies are good resources for additional information:
Precision Machined Products Association | www.pmpa.org

Machining

These three characteristics of stainless steel exert the most influence on machinability:

1. Relatively high mechanical properties (including yield strength)

2. High work-hardening rate

3. Ductility

These factors explain the material's tendency to form a built-up edge during machining. For example, the chips removed in machining exert high pressures on the nose of the tool and therefore tend to weld fast, producing what machinists call a "bug." This causes the tool to run hot, slows down the job and interferes seriously with the finish.

The austenitic stainless steels (300 Series) are not only troublesome because of "bugging" and chip disposal, but they work harden so that the tool, in passing over the work, will harden the surface and thus interfere with the next cut. The only remedy for this is to reduce the speed, increase the cut somewhat, if possible, and keep cutting. The tool must not be allowed to dwell on the work.

The best mechanical method for chip control is to grind the tools with a fairly steep top rake or lip angle. Tools with a 5º to 10º angle will generate less heat and be freer and cleaner cutting. Generous chip curlers or chip breakers are also a decided advantage. It is also helpful to stone the top of the tool smooth as an aid to skidding the chips. For general-purpose drilling, twist drill makers produce a drill for drilling stainless steel. It has a shorter flute and overall length than regular drills and is therefore heavier and stronger. As sold from stock, this type of drill is generally pointed with an included angle of 140º.

Where close tolerance and fine finish are necessary, consider using a shave tool with a light cut and fast speed. This tool should be sharply ground and stoned. Running at high speed while taking a light cut (0.002/0.008" or 0.05/0.20 mm) produces an excellent finish and holds to extremely close tolerance.

Sulfur-based cutting fluids have been recognized for years for their ability to cool and prevent seizing. As a result, properly blended sulfur-base fluids have become the standard cutting fluids for machining all types of stainless steels. Here is a handy rule-of-thumb to use regarding the mixture: If the chips are welding to the tool, keep adding sulfur-based oil. If tools are failing by rapid abrasion, add more paraffin-base oil.

The real answer to machinability came with Carpenter's development of free-machining stainless steel. Both sulfur and selenium have been successfully added to stainless alloys to secure free-cutting properties. Carpenter Stainless Type 416 was the first free-machining stainless steel. Later, Carpenter uses selenium in the manufacture of Carpenter Stainless Type 303 Se.

Since the 1970s, Carpenter has developed and improved upon a line of enhanced machinability stainless machining bar grades. The most recent enhancement is the Project 70+® stainless family. Users of Project 70+ machining bar have reported faster machining speeds, improved finishes and extended tool life.

More detailed information about machining Carpenter alloys is available in the guide, "Machining Carpenter Specialty Alloys."

Abrasive Wheel Grinding

Precision grinding is required on jobs in which you desire excellent surface finish, exceptionally close dimensions and geometric accuracy, or when heat-treated parts are too difficult to machine.

For this work, the grinding wheel is the heart of the job. Wheels for precision grinding may contain either aluminum oxide or silicon abrasives, which may be bonded by shellac, rubber, silicate, resinoid, etc. Avoid the use of grinding wheels containing iron oxide. Contamination of the stainless surface with iron oxide will cause rapid corrosion and rust pitting. Selection of the right wheel for a job can often be made from experience on previous work. On a new job, it is best to consult a wheel manufacturer for guidance in your selection.

The method of holding or supporting the work will vary with the type of machine used and job to be done. On special jobs, various types of work holders, chucks or collets are available or may be designed and produced in your own tool room.

Whether cylindrical, universal, surface, internal, centerless, thread or special grinders, grinding machines should be massive. Distortion and vibration cause many poor grinding jobs.

In general, the most efficient grinding speeds are in the range 5500/9000 surface feet per minute. The optimum speed within this range will depend upon the grade of stainless, type of grind, rigidity of the machine, and wheel selection.

The 300 Series austenitic stainless grades, being gummy, should be ground with a wheel having a porous bond to avoid early loading of the wheel. The straight chrome steels in the 400 Series can be ground with a harder wheel. It is seldom necessary to start with less than 60- to 70-grit wheels for the roughing cut. This should be followed with an 80- to 100- grit wheel having a soft or porous bond to provide faster cutting and prevent burning.

Note: When changing wheels from one size grit to another, it is important that the work be cleaned and all "wild" grit be removed. When the coarse grains are carried along to the finer grit wheels, deep scoring or scratching may occur.

Troubleshooting Grinding Problems

Traverse marking: Check the edges of your grinding wheel. They may be too sharp and should be slightly rounded off to avoid a "dragging edge." Such marking may also be caused by excessive spindle spring or too high a speed on finishing cuts. Lastly, traverse may be too fast for the work speed. This leaves a pattern on the work that can be corrected by slightly decreasing the traverse speed.

Loading or Glazing: The wheel may be too hard or not dressed often enough. Dressing may be too fine or dresser too dull.

Work "Out-of-Parallel": This condition is usually caused by mechanical faults such as "sloppy ways," improper setting of tailstock, or center not concentric with the work piece. Check accuracy of the dressing operation. If wheel is dressed off-center, it will not conform with surface of work part. After first cut is made, check for straightness, taper or chatter marks. Proper adjustments in setup at start of job will reduce rejects and save time in the long run.

Lubrication: Practically all grinding is done with water-base coolants because of their ability to dissipate heat rapidly and thus prevent spoiled work due to overheating. Exception: On thread grinding that requires a highly finished and smooth surface, sulfur-base oils—either straight or cut back with paraffin oil—may be used.

Lubrication serves to reduce friction between work and wheel, and cuts down the resistance of the metal to the abrasive. Further, it washes away the chips and abrasive particles that might otherwise score the surface and spoil the part. A steady flow of coolant retards loading of the wheel and prevents impregnation of particles into the metal.

Avoid highly alkalized lubricants, as they may deteriorate the wheel bonds. This condition can be safeguarded against to some degree by increasing the percentage of water in the mixture. This condition should be checked carefully, as premature decision may put the fault with the steel or wheels while the real problem lies elsewhere.

Other Resources: Precision Machined Products Association

Cold Heading, Warm Heading and Hot Heading Carpenter Stainless Steels

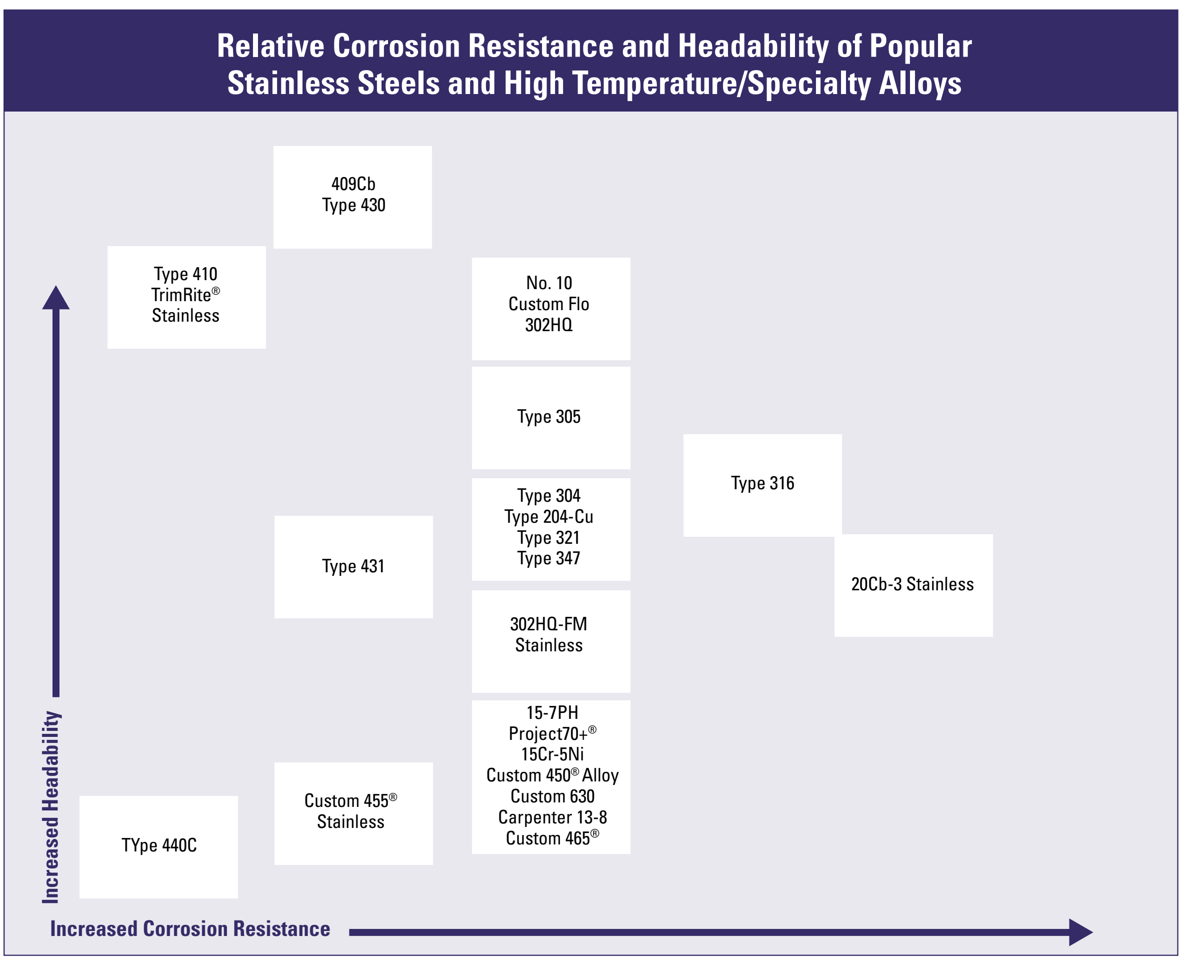
The following industry associations and technical societies are good resources for additional information:
Industrial Fasteners Institute | www.industrial-fasteners.org

Cold Heading

Stainless steels continue to be used in the manufacture of cold-headed parts. This group of alloys provides several benefits, including corrosion resistance and high strength at room and elevated temperatures. Most stainless steels can be cold headed. Carpenter Technology has played an important role in the development and production of stainless steel cold-heading wire.

Comparison of Cold Headability: The diagram below presents a simple comparison of cold headability and corrosion resistance of the popular cold-headed grades of stainless steel.

The relative headability of martensitic stainless steels such as Type 410 and ferritic stainless steels such as Type 430 is affected primarily by carbon content and yield strength. Type 410 and Type 430 are relatively easy to cold head and are comparable to low carbon alloy steels. Martensitic stainless steels can be hardened by heat treatment but ferritic stainless steels cannot. Both types will harden slightly by cold working. Both are widely used for fasteners.



The relative headability of the austenitic stainless steels is affected primarily by composition. That is, those higher in nickel, and in some cases copper, generally exhibit lower work-hardening rates because of the more stable austenitic structure. Stainless Type 305 was the original stainless grade developed for improved cold headability. The 12% nickel content accounts for this. Carpenter also produces Carpenter No. 10 (Type 384) and Carpenter 302HQ stainless, both of which exhibit low work-hardening rates and excellent cold headability for austenitic stainless steels. Typical austenitic stainless steels cannot be hardened by heat treatment; however, cold working will increase hardness. Carpenter 302HQ stainless has been used extensively to produce Phillips and other recessed-head fasteners.

Product Forms

Carpenter manufactures three basic wire product forms in addition to specially finished wire or rod for special applications. The three basic forms include:

1. Annealed and Cold Drawn to Finish Heading Wire
2. Cold Drawn and Annealed at Finish Heading Wire
3. Hot Rolled and Annealed at Finish Rod

Annealed and Cold Drawn to Finish Heading Wire is raw material in the finished condition. It is available in all sizes up to about 1.00" (25.4 mm) in diameter. Refer to Table I for specific size tolerances. Wire in this condition offers substantial surface integrity and the widest range of mill coatings. This product typically does not require additional sizing prior to entering the header.

TABLE 1

Standard Size Tolerances for Cold Drawn Heading Wire

Size Range	Tolerance
Up to 0.312" (7.92 mm) diameter	±0.001" (0.025 mm)
> 0.312" - 0.499" (7.92-12.67 mm) diameter	±0.0015" (0.038 mm)
> 0.500" (12.7 mm) diameter	±0.002" (0.051 mm)

Note: Half-standard tolerances may be ordered.

Table 2 lists typical ultimate tensile strength maximums for annealed and cold-drawn wire for sizes greater than 0.100" diameter.

TABLE 2

Typical Tensile Strength Maximums for Cold Drawn Heading Wire in Diameters >0.100" (2.54 mm)

Alloy	Typical Ultimate Tensile Strength	
	ksi	MPa
No. 10	85	586
Type 302HQ, Batch Annealed	83	572
Type 302HQ, Strand Annealed	96	662
Type 305	93	641
Type 316HQ	85	586
Type 316	93	641
Type 304	95	655
Type 410	90	621
Type 430	86	593
Type 431	115	793

Cold Drawn and Annealed at Finish Heading Wire is supplied cold reduced, annealed and coated. It offers the lowest mechanical properties and is suitable for redraw or heading. This product should be sized prior to entering the header. Cold drawn, annealed product is available in all sizes up to about 1.00" (25.4 mm) in diameter. Tolerances are double those available on annealed and cold drawn wire.

STARR® wire (Stainless, Annealed, ready for Redraw) is a modification of the basic cold drawn and annealed at finish form. Its manufacturing sequence typically includes additional operations to enhance surface quality. It is available in only a few stainless grades and is typically supplied with a cross sectional area about 5 percent over the cross sectional area of the finish drawn product. Typical maximum ultimate tensile strengths for annealed at finish wire are shown in Table 3.

TABLE 3

Typical Ultimate Tensile Strength Maximums for Annealed at Finish Wire in Diameters >0.100" (2.54mm)

Alloy	Typical Ultimate Tensile Strength	
	ksi	MPa
No. 10	78	538
Type 302HQ, Batch Annealed	75	517
Type 302HQ, Strand Annealed	88	607
Type 305	83	572
Type 316HQ	76	524
Type 316	85	586
Type 304	85	586
Type 410	82	565
Type 430	75	517
Type 431	105	724

Hot Rolled and Annealed at Finish Rod is the least finished condition and must be sized prior to entering the header. It is supplied annealed, descaled and coated. Of the three wire forms, rod has the roughest surface and the widest tolerances. Rod is available in a size range from about 7/32" (5.55625 mm) to 1-1/4" (31.75 mm) diameter. Tolerances may be as great as ±0.010" (.25mm) with a maximum of 0.015" (.381 mm) out-of-round in the larger diameters. See Table 4.

TABLE 4

Standard Rod Tolerances

Size Range	Tolerance
0.221" - 0.4375" (5.6 - 11.1 mm)	±0.006" (.15 mm)
0.453" - 0.625" (11.5 - 15.9 mm)	±0.007" (.18 mm)
0.641" - 0.875" (16.3 - 22.2 mm)	±0.008" (.20 mm)
0.891" - 1.000" (22.6 - 25.4 mm)	±0.009" (.23 mm)
>1.000" - 1.250" (25.4 - 31.75 mm)	±0.010" (.25 mm)

To reduce wire inventories and the number of wire sizes purchased, some headers draw wire or rod in front of the header with obvious savings.

While rod is the lowest cost wire stock, this may not be an advantage. Many fabricators report that rod necessitates more in-house capabilities. When redrawing rod, scrap losses may increase and present overall quality control problems that often negate initial raw material savings.

The best alternative for most headers is the use of wire that has been annealed and cold drawn to finish.

Coatings

Choice of the proper coating is influenced by the specific application; however, there are general considerations. The type of coating required depends on the alloy being formed, the degree of cold work needed, the temperature generated by the heading process, and the complexity of the part being formed. Additional factors influencing coating selection include availability and cost, compatibility with other mill coatings or fabricator lubricants, and the ease of coating removal from the finished parts.

For many years the most effective coating for stainless steel heading wire has been an electrolytically plated copper layer plus lime and soap drawn on during the final light draft made in finishing the wire. Today, however, coatings such as Carpenter's Ecolube® II coating may be used to eliminate the problems associated with disposal of cleaning acids containing metal ions. A key point to remember is that Carpenter, as a producer of stainless heading wire and rod and a variety of coatings, is fully equipped to help customers with coatings selection, as well as all other aspects of cold heading operations.

Coating classes are determined by selecting a coating option designated by a letter and a drawing option designated by a number. This is typically referred to as Carpenter's Alpha-Numeric Coating Classification System. The coating and drawing options are as follows:

TABLE 5

Carpenter's Alpha-Numeric Coating Classification System

(Must choose one Coating Option and *one* Drawing Option)	
Coating Options (Alpha)	**Drawing Options (Numeric)**
A - Uncoated	1 - Undrawn (Annealed at Finish)
B - Lime	2 - Drawn in Soap
C - Precoat	3 - Drawn in Grease
F - Ecolube® II coating	4 - Drawn in Molybdenum Disulfide-Bearing Soap
H - Copper + Lime	5 - Drawn Without Soap or Grease (Only coatings F, N, O, S)
K - Copper	
L - Copper + Precoat	
N - Copper + Moly Overcoat	
O - Copper + Ecolube II coating	
P - Special	
R - KnightCote® wire coating	
S - Copper + KnightCote wire coating	

Download a copy of our Wire Coating and Lubricant Options Fact Sheet.

Warm Heading

Warm heading is a modified form of cold heading performed at 93° to 427°C (200° to 800°F), which is below the recrystallization or transformation temperature of the metal being formed. Ductility is improved without changing the microstructure. Warm heading allows working difficult-to-form materials, requires less deformation pressure, reduces tooling loads by as much as 50 percent compared to cold forming, and generally prolongs tool life.

Warm heading is especially applicable to parts of unusual shape and forming high strength alloys that are resistant to heat and corrosion. Usually alloys that work harden rapidly can be upset without cracking. The method generally works well for making high strength bolts.

With warm heading, the wire is usually heated before it enters the feed rolls, or, when possible, between the feed rolls and the header machine frame. The most commonly used methods of heating are:

1. **Resistance heating -** A contact stand is installed between the wire reel and the feed rolls. A low-voltage, high-amperage circuit is then connected to the contact stand and the feed rolls. The electrical resistance of the metal itself serves to produce the heat.

2. **Gas heating -** A series of burners is mounted on an adjustable stand and the wire passes over them. Variations include use of a tube, surrounded by a series of ring burners, which is mounted on an adjustable stand, heating the wire as it passes through the tube.

3. **Induction heating -** An induction coil is installed in front of the feed rolls, and the wire is passed through the coil.

Close control of wire temperature is important since erratic heating may cause uneven flow, and may result in uncontrolled head dimensions. If the wire is overheated, for instance, the material will tend to blob instead of flow. Also, the lubricity of the wire coating may be destroyed, and smearing may occur at the cutoff station. Close temperature control, on the other hand, improves plasticity and headability by reducing both the strength and work hardening of the material being formed. Consequently, less forming pressure is required to fill the cavity of the die or hammer, with a resulting improvement in sharper corners and shoulders and, in some cases, elimination of stress cracking.

Surprisingly good warm heading results for the stainless steels are achieved in the temperature range between 177° to 232°C (350° and 450°F). Temperatures over 316°C (600°F) should generally be avoided.

Hot Heading

Hot heading or upset forging can be done on conventional heading equipment similar to cold heading machinery or on forging machines. Hot heading is generally performed on the larger diameters which cannot be obtained in coils. The same general principles applying to conventional forging should be utilized.

Download Carpenter's Heading Hints booklet

Drawing, Forming, and Spinning Carpenter Stainless Steels

The production of stainless parts by cold forming is as common today as that for ordinary steels and nonferrous metals. In drawing, roll forming, spinning, etc., operators who have handled many stainless jobs prefer its consistent uniformity as compared with other metals. Because stainless steel is a high-strength material, it can be handled routinely on a profitable mass-production basis.

Anyone who has formed metals knows that differences exist between them, whether aluminum, brass, carbon steel or stainless steels. In the cold forming of stainless steels, these facts are worth knowing:

Drawing

The Press: The shear strength of annealed stainless steel is generally estimated at 517 to 690 MPa (75,000 to 100,000 psi), which is about 50 to 75 percent stronger than mild steel. Hence, more press power is required, or the job must be transferred to a heavier press. A more economical solution would be to take advantage of the high strength of stainless by changing to a lighter gauge material. If this can be done, the parts can often be formed on the same size press and with the same power used for mild steels. Regardless of press considerations, each stainless job should be figured on the basis of required mechanical properties to determine the lightest gauge stock necessary for the job.

Speeds and Clearances: It is natural to want to use the fastest possible speeds commensurate with production of the maximum number of quality parts. On some jobs, normal press speeds may be desirable; on others, slightly slower speeds may produce less downtime, fewer rejects and get the job out faster. "Stretching" of the metal must always be avoided.

On "shallow draws" with straight chrome steels of the 400 Series, press speeds and die clearances will be about the same as for mild steels. Deep draws and heavy gauges may require slower speeds. If the job is new and speeds cannot be estimated from past experience, a safe starting speed is 35 to 40 feet per minute.

A characteristic property of the chrome-nickel stainless steels is their rapid rate of cold work hardening. On deep drawn or severe forming jobs, parts must be annealed in process so that the operation can be continued. This increases production costs, is troublesome, and slows down the job.

The solution to this problem came with the development of Carpenter Stainless Type 305. This grade shows such a small rate of cold work hardening that it is now practical to run many jobs on automatic transfer presses. With Type 305, savings can often be made in production by reducing process annealing, using considerably faster press speeds, and reducing the number of presses and man-hours required when using the regular 18-8 grades.

Where regular 18-8 grades (Types 302, 304, etc.) are preferred, deeper draws can be made in one operation if slower press speeds are used and the radii on the draw ring are increased. Why? Because slower press speeds and a more generous radius on the draw ring work harden the metal more moderately and allow it to be pulled into the die without stretch or fracture.

To prevent wrinkling and buckling, use heavier pad pressure with thicker rubbers, heavier springs, or more air pressure in your air cushions.

Dies and Tools: The blanking, piercing and punching of stainless steels require the use of good tool steels that have nongalling characteristics. Carpenter K-W (F2) should be considered for tools that are not too intricate. If the design or shape of the tool prohibits the use of a water-hardening tool steel, consider Hampden (D3) tool steel or No. 610 (D2) tool steel with a nitrided case. Other alloys to consider are powder tool steels, such as Carpenter Micro-Melt® A11 or A11-LVC tool steel.

It has been found that hard bronze, showing about 340/360 Brinell, is an excellent material for draw rings. Centrifugal castings are to be preferred where possible. If hard bronze is not available, No. 610 (D2) tool steel with a nitrided surface may be considered.

Make allowance for greater "spring back" in dies when fabricating stainless steel. Generally, a slightly larger radius on draw rings is recommended to avoid stretching the metal. This allows it to flow more freely into the die and tends to cut down work hardening. The dies or draw rings should be polished and stoned and kept smooth at all times. Use a fine stone rather than a wheel in "finish stoning" the draw rings. The small amount of extra work involved is well repaid with longer die life and smoother stampings.

Lubricants: Because of their high strength, stainless steels exert more pressure on the tools and develop more heat. Unless proper lubricants are used, the film will break down and stretching and galling will result. Improper lubrication will gall or score the tools rapidly. A constant film must stay on the metal while drawing. While lead and linseed oil mixed to the consistency of 600W oil is reasonably satisfactory. So is a 50:50 mixture of lithopone and water-free soluble oil. Both of these are a little difficult to wash off, especially if left lying around. The lead compounds, being insoluble, will load up the cleaning tanks. For making a few experimental pieces, castor oil is usually easy to procure and is a good lubricant. For very light draws, lithopone and kerosene or soap solutions may be all that are needed.

Forming

Brakes: The same bending and forming equipment that is used for mild steel can be used on stainless steels. In hand or power brakes, more power is required than for mild steel. The dies should be polished and free from imperfections. If the press brake operation is essentially drawing, lubricants are necessary, and the same ones used for drawing are satisfactory. Greater allowance must be made for "spring back" in the tool design.

Rolls: Roll forming of stainless strip into channel, molding and trim is a commonplace operation today. Stainless, possessing greater strength, will work differently from cold-rolled steel, so when long runs are required be sure the rolls are made from materials that will prove adequate for your production requirements. Good examples of this are the high-production jobs like auto body and fender trim. For jobs like these, Carpenter Hampden or No. 610 die steels for the male rolls, and hard cast bronze for the female rolls should be considered.

More leverage is required in spinning stainless than with mild steel or copper. The speeds used are also slower. In general, stainless steels of the 400 Series can be spun at 60/70% of the speed used for mild steel. Most of the steels in the 300 Series should be spun somewhat slower because of their faster work-hardening properties. Exceptions are Carpenter Stainless Type 305 and No. 10, which work harden more slowly, and therefore can be worked faster and longer before process annealing may be necessary. Many shops find it good practice to leave 1/2" of unworked metal on the rim to prevent cracking and splitting.

Lubricants are very important in spinning. Lubricants that are too heavy will not stay on the blank and will accumulate under the tool. If too thin, they will not properly lubricate. Soap suspensions and hydraulic greases are useful. Proprietary compounds, prepared especially for spinning, are available and will produce good results.

When intermediate annealing is necessary, always clean the parts thoroughly, removing all traces of lubricants and other foreign matter before placing them in the furnace.

Soldering and Brazing Carpenter Stainless Steels

Soldering and brazing differ only in the temperatures used to melt the alloy being used to join the material being soldered or brazed. The material being joined is not melted by these joining processes.

Soft Soldering: Soft soldering of stainless steel is not much of a problem when the requirements of the job are understood. The biggest problem is breaking through the passive film with a flux so that the solder will wet the stainless.

Soft solders are weak compared with stainless steel. Consequently, if strength is required, the edges should first be riveted or spot-welded, then soldered for a tight seal.

Stainless steel must be perfectly clean before soldering is attempted. Cleaning can be accomplished by pickling with acid or with mechanical polishing. Do not expect the flux to do the cleaning.

Stainless steel is resistant to the corrosive attack of most soldering fluxes, and unless the flux etches the surface, it will not function. On smooth surfaced parts, such as cold rolled strip, it will be difficult to get the flux to spread and completely cover the surface. Therefore, the soldering area should first be roughened by acid etching (50:50 muriatic acid and water) or mechanical polishing. This rough surface will take the flux quickly and the solder will flow evenly.

Use fluxes prepared especially for soldering stainless steel. Apply the flux with a brush to the area to be soldered and rub until the surface is wet. All flux must be properly and completely removed after soldering to avoid continued corrosion. Be sure to remove all splattered flux with soap and water.

Stainless steels are slower to absorb heat, and it is, therefore, necessary to use a larger and heavier iron. The iron need not be hotter, but it should be bigger and possess more heat capacity. That way, the iron will heat a sufficient area to allow the solder to flow freely. "Tinning" the joint will also assist in making the solder flow more evenly. Keep moving as fast as the solder fills the joint.

Ordinary half-and-half solder applied from the top of a well-tinned copper is satisfactory but for brighter, stronger joints, use 67 percent tin and 33 percent lead dairy solder. In general, the higher the lead content, the more quickly the joint will darken on exposure to air.

Hard Soldering or Brazing: This process is also called silver soldering and is applicable to all types of stainless steels. The temperature range in which this process is applied is typically from 621 to 816°C (1150 to 1500°F), although brazing may be performed at temperatures up to above 1093°C (2000°F), depending on the composition of the brazing material. The straight chromium martensitic steels will air harden if heated above 788°C (1450°F). Exercise care to limit the heating of ferritic steels to the minimum required for flow of the solder in order to avoid grain growth and embrittlement in these grades. The chrome-nickel austenitic steels are necessarily heated in the carbide precipitation range, which may affect their corrosion resistance.

Lap-type joints are used in silver brazing. Joint clearances should be between 0.002" and 0.005" (0.051 and 0.127 mm) for best distribution of filler metal in the joint by capillary attraction. Silver brazing alloys for stainless steel contain from about 50 percent to 75 percent silver. The best color match is obtained with the alloys containing higher percentages of silver. A flux is generally required to make a satisfactory joint. However, for certain processes, particularly the straight silver-copper filler metals, if brazing is done in a vacuum or in inert atmosphere, flux may not be needed.

The bi-metallic nature of the joint makes it very difficult to predict the corrosion resistance of silver-brazed joints in stainless steel. Give consideration to crevice corrosion whenever the fluid contains small amounts of chlorine compounds. Cleaning of the flux after brazing is essential to prevent corrosion failure. The most common method of cleaning flux is with a hot water rinse of long enough duration to dissolve all the flux.

NOTE: American Welding Society Specification AWS A5.8 for Brazing Filler Metal prescribes requirements for filler metals which are added when making a braze. www.aws.org

Welding of Stainless Steels

The main methods of welding stainless steels are arc welding and resistance welding. Other techniques include electron beam welding, laser welding and solid state welding such as friction welding. Oxyacetylene welding is not recommended due to the possibility of carbon pickup. Depending on the technique, arc welding may be done autogenously or with filler metal; the other methods are primarily done without filler metal.

Protection from Atmosphere

Because of the propensity to form refractory chromium oxide at elevated temperatures, the welding process must be protected from the atmosphere. As will be discussed in the following sections, this can be accomplished with an inert shielding gas, a vacuum, or a slag cover. The gas shielded (and vacuum) processes produce higher quality welds from the standpoint that the welds are less susceptible to contamination from oxygen, nitrogen and carbon. In general, stainless steels containing significant quantities of highly reactive elements, such as Ti or Al, are welded with the gas-shielded processes.

For further information on welding processes, excellent sources are AWS Welding Handbook and ASM Handbook, 10th ed., Vol. 6, Welding, Brazing and Soldering.

Preweld Cleaning

To provide high quality welds, pay special attention to cleaning prior to welding. This includes removal of all cutting fluids, oils, paints, oxide, etc. In addition, eliminate sources of moisture because water can introduce porosity or hydrogen. Because the gas-shielded processes do not use a flux, precleaning is particularly important with these processes. Do not use copper or lead tools, such as mallets for aligning pieces, prior to welding due to the possibility of transferring metal to the weld area. Transfer of metal could lead to liquid-metal embrittlement. (Due to the lack of metal transfer, the proper use of copper chill bars and clamping fixtures does not pose a problem.)

Besides lead, other low-melting-point metals to be avoided include cadmium, zinc and tin, which may be present in protective coatings. If grinding is necessary prior to welding, aluminum oxide wheels should be used rather than silicon carbide since embedded silicon carbide could decompose and increase the carbon content of the weld.

Postweld Cleaning

Another important step is removal of surface discoloration or oxide to provide optimum corrosion resistance for the weldment. Slags and fluxes must be removed after each weld bead is made using stainless steel chipping tools, wire brushes, or files. Carbon steel tools must not be used because of possible iron contamination, which will degrade corrosion resistance. For the same reason, grinding wheels previously used for carbon steels should not be used for stainless steels.

Welding Martensitic Stainless Steels

General Considerations: In some cases, such as large sections or a high degree of restraint, welding materials in the annealed condition may be advantageous to better accommodate shrinkage stresses in the base material. However, the starting condition (annealed, hardened + tempered, etc.) has less effect on weldability than the air-hardening capability of these alloys. This capability can lead to cold cracking of the brittle martensite in the weld and heat-affected zone (HAZ) from constriction stresses. The susceptibility to cracking increases with the hardness capability, which increases with the carbon content.

For this reason, higher-carbon grades such as Type 420 and the Type 440 series are not generally suggested for welding, although it may be necessary to do so. Type 420 is, however, commonly used as an overlay material.

The following table summarizes the relationship between carbon level and welding practice. These are guidelines only and vary somewhat from reference to reference:

Carbon	Typical Grade	Preheat	Heat Input	Post-Weld Handling
<0.10	T410S	Not necessary	Standard	Non required
0.10-0.20	T410	400-500°F	Standard	Slow cool/heat treat
0.20-0.50	T420	500°F	Standard	Heat treat
>0.50	T440 series	500°F	High	Heat treat before weld cools below 500°F

Since hydrogen plays a role in cold cracking, welding practices should focus on avoiding sources of hydrogen, for example, moisture. Fluxes and covered electrodes must be kept dry. Low-hydrogen welding techniques include the insert-gas processes, GTAW and GMAW, as well as EBW and LBW.

Filler Metals: Standard matching filler metals include E/ER410 and ER420. Higher-carbon filler metals are not typically available. E/ER410NiMo, a low-carbon Ni-bearing grade, is also available and may be used for its good combination of as-welded strength and toughness. When mechanical properties (or physical properties, such as thermal expansion) matching those of the base metal are not needed, an austenitic filler metal, such as AWS E/ER308, E/ER309 or E/ER310 can be used. E/ER312, which has a high ferrite potential, may be used for higher-carbon grades, where dilution could otherwise result in a fully austenitic weld prone to hot cracking. The austenitic filler metal can also improve weldability by yielding, and thereby reducing strains in the heat-affected zone (HAZ); in addition, austenite has a higher solubility for hydrogen, reducing diffusion of hydrogen to the less tolerant base metal. Austenitic welds have good toughness, and their use may allow elimination of a postweld heat treatment, assuming the limited ductility and toughness of the HAZ are acceptable for the application. Slow cooling of the weld will help minimize cold cracking in this case.

Free-Machining Grades: Free-machining grades such as Type 416, 416Se, 420F and 440F are not usually recommended for welding because of their crack sensitivity. However, if they must be welded, an austenitic filler metal such as E/ER308, E/E309, or preferably the high-ferrite E/ER312 can be used. Dilution of the weld metal with the free-machining agent (S or Se) should be minimized by keeping heat input to a minimum. Avoid pickup of hydrogen, which could react with the free-machining agent to produce porosity in the weld.

Welding Ferritic Stainless Steels

General Considerations: The main problems associated with the welding of ferritic grades are in the development of coarse grains in fully ferritic alloys. Coarse grains will reduce ductility and toughness and the formation of austenite at elevated temperatures which, depending upon the alloy, can transform to brittle martensite upon cooling to room temperature. We will distinguish between the original, conventional ferritic grades and the newer grades developed to minimize these problems.

Austenite formation depends on the balance of ferrite and austenite formers, particularly chromium and carbon+nitrogen in the conventional ferritic grades. The risk of cracking from the transformation of this limited amount of austenite to martensite is significantly less than for the martensitic grades. However, if left untempered, the martensite can reduce ductility and toughness. On the positive side, the presence of some austenite at elevated temperatures will limit grain growth. In fact, this represents an earlier method of reducing grain growth. A further complication is that rapid cooling from temperatures above 900°C (1650°F) can result in sensitization and embrittlement.

To minimize the above problems, newer grades of ferritic stainless steels have significantly reduced carbon and nitrogen, and are usually stabilized with titanium and/or niobium (columbium). This minimizes austenite formation and sensitization. The titanium or niobium carbides also serve to restrict grain growth.

Grain growth can still occur, but with low carbon and nitrogen, the degradation of ductility and impact strength is reduced. However, excessive levels of stabilizers can cause hot cracking. In addition, titanium and niobium behave differently. Autogenous welds in titanium-stabilized ferritics typically have an equiaxed zone at weld centerline, while niobium-stabilized alloys typically have a columnar zone, which is more prone to cracking.

Another development used in Type 409 (11.5Cr-Ti) and Type 409Cb (11.5Cr-Nb) is the addition of a small amount of nickel so that austenite will form, limiting grain growth. However, because the martensite so formed is a nickel martensite with low carbon and nitrogen, it has reasonable toughness, allowing the part to be used in the as-welded condition.

Although martensitic hardening is significantly reduced or even eliminated in ferritic grades, preheating to 150-230°C (300-450°F) may still be advisable for thicker sections; for parts where a high degree of restraint is present; for higher-chromium grades, like Type 443 (21Cr-1Cu) and Type 446, which typically have low toughness even at room temperature; and for grades whose balance (lower chromium and/or higher carbon+nitrogen) will result in significant martensite upon cooling to room temperature. On the other hand, excessive preheat should be avoided since it can contribute to grain growth. Heat input during welding must be sufficient to ensure complete fusion, but excessive heat input must be avoided to help minimize grain growth.

When making full penetration welds, nitrogen should not be used as a backing gas to protect the root side of the weld, because the nitrogen will degrade toughness, ductility and corrosion resistance. Welding practices should also focus on eliminating sources of hydrogen, e.g. moisture, to avoid cracking or porosity.

Filler Metals: Matching filler metals such as E/ER430 are available. Austenitic filler metals, such as E/ER309, may also be used if there are concerns about weld ductility or toughness, particularly in the as-welded condition. If the carbon level of the ferritic grade is low, an austenitic L grade should be used to avoid increasing the carbon level of the ferrite. In addition, if the weldment is to be annealed, an L grade should be used, since the annealing temperature for conventional ferritics is in the sensitization range for standard (higher-carbon) austenitic alloys. E/ER316L filler metal may be used for the chromium-molybdenum ferritic grades.

Use of an austenitic filler metal will be undesirable for applications requiring magnetic performance, since the austenite will create a magnetic "air gap." Another concern is the large difference in thermal expansion between the austenite and ferrite, which may induce stresses leading to cracking. For a closer match in thermal expansion, a suitable nickel-base filler metal can be used.

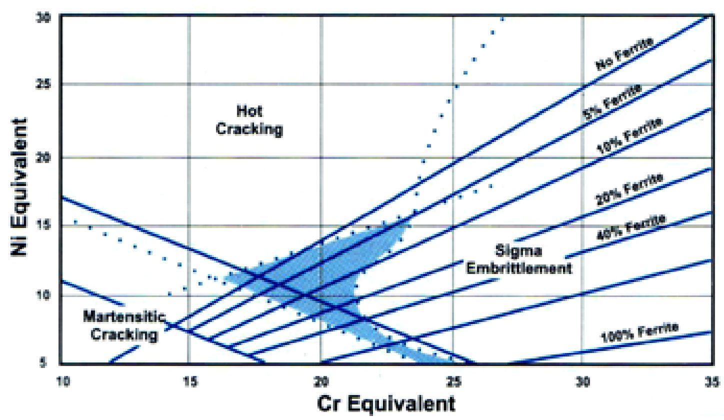
Postweld Handling: Postweld annealing may be needed to restore intergranular corrosion resistance and enhance ductility, particularly for conventional higher-carbon/nitrogen, non-stabilized alloys, such as Type 430 with autogenous welds or matching filler metal. Annealing may also be needed to optimize magnetic properties.

Free-Machining Grades: Free-machining grades such as Type 430F are not usually recommended for welding because of their crack sensitivity. However, if they must be welded, an austenitic filler metal such as E/E309 or E/ER312 can be used. Dilution of the weld metal with the free-machining agent (S or Se) should be minimized by keeping heat input to a minimum. Avoid pickup of hydrogen, which could react with the free-machining agent to produce porosity in the weld.

Welding Austenitic Stainless Steels

Consider these issues when welding austenitic stainless steels:

1. The high coefficient of thermal expansion, low thermal conductivity and high elevated-temperature strength of austenitic stainless steels can result in a greater propensity for distortion during welding and greater residual stresses in the welded part. Alignment of the pieces to be welded is important. Also, avoid excessive heat input. Copper chill bars and backing bars can assist in heat removal.
2. Sensitization occurs in the range of 425-870°C (800-1600°F), depending on carbon level. Sensitization is precipitation of chromium carbides at grain boundaries, which results in a chromium-depleted zone. This can lead to intergranular corrosion, also known as “weld decay,” in certain environments. The propensity toward sensitization can be reduced by using a low-carbon grade or a grade stabilized with titanium or niobium (columbium).
3. Fully austenitic alloys are susceptible to hot cracking. Hot cracking can take several forms, most notably solidification cracking. The relationship between composition and the propensity for weld hot cracking is shown in the diagram, which is based on the Schaeffler diagram. Alloys having compositions (Cr and Ni equivalents) falling within the shaded zone are resistant to weld hot cracking. This corresponds to alloys containing some ferrite in the as-cast condition, as opposed to those that are fully austenitic as cast.



Besides cracking, another defect that may occur in welds is porosity, which commonly results from moisture or contamination from greases, oils, etc. However, it may also be seen in nitrogen-strengthened grades that are close to the solubility limit for nitrogen. The latter problem can be aggravated in electron-beam welding due to the use of a vacuum; however, it is difficult to autogenously weld high-nitrogen grades (about 0.3% nitrogen and above) via any technique without encountering porosity. As a further complication, loss of nitrogen will increase ferrite content, adversely affecting cryogenic impact properties. To minimize nitrogen loss, a good gas cover must be maintained.

Filler Metals: Matching filler metals are commonly available for a wide range of austenitic stainless steels. E/ER308 or E/ER308L are the standard filler metals for the 18-8 austenitics, like Types 302, 304, 304L, 302HQ, 305, etc. The carbon level of the filler metal should be matched to the carbon level of the base metal.

Because titanium is so reactive, E/ER347 is commonly used for both 347 and 321. ER321 can be used for GMAW with good inert gas shielding. Shielding is important in any case, since nitrogen pick-up from the atmosphere can decrease the ferrite content of the weld.

Nickel-base filler metals with over-matched molybdenum levels are often used for high-molybdenum superaustenitic grades to avoid localized corrosion in the weld due to segregation of molybdenum. For the high-nitrogen austenitics, E/ER2209 (22Cr-13Ni-5Mn with reduced nickel and nitrogen) is commonly used, although other matching fillers may be available.

Preheating austenitic grades is unnecessary, and, in fact, undesirable because it may aggravate hot cracking and sensitization. In addition, dilution of the filler metal with the base metal is also to be avoided since excessive dilution can result in a fully austenitic weld, which is prone to cracking.

Fully austenitic, highly alloyed grades like Type 310 (25Cr-20Ni), Type 330 (18.5Cr-35Ni-1.25Si) and 20Cb-3® stainless require special considerations to avoid hot cracking. Since ferrite is not an option, welding consumables should contain low residuals including sulfur, phosphorus and silicon. For that reason, a special low-residual filler metal, E/ER320LR (20Cb-3LR) was developed by Carpenter specifically for 20Cb-3® stainless.

Ferrite may also be undesirable in the welds of lower-alloyed grades for a variety of reasons. These include its effect on magnetic behavior, cryogenic toughness, corrosion resistance, and possible transformation to sigma phase.

Besides control of solidification mode and residual elements, hot cracking can be minimized by reducing the thermal or mechanical stresses imposed on the weld during solidification. Techniques to accomplish this include keeping the heat input low, limiting interpass temperature to 300°F (150°C) maximum, and minimizing joint restraint. The latter must be balanced against the need to prevent distortion during welding. Keeping the heat input low also aids in avoiding sensitization by allowing a faster cooling rate.

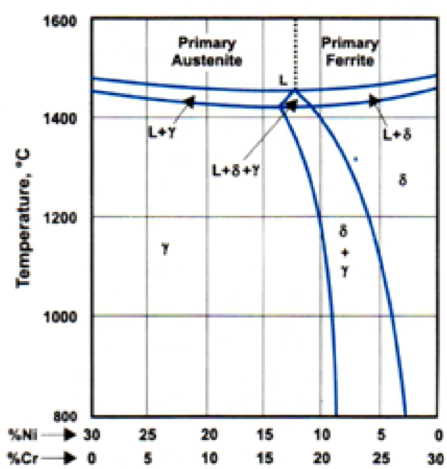
Another technique is the use of stringer beads, i.e., many narrow beads laid in a straight line rather than the fewer, wider beads produced by weaving from side to side (transverse oscillation). Finally, lower current and a slow travel speed provide a weld pool shape (elliptical versus tear-drop shaped) that is less prone to hot cracking.

Differences in cooling rate of weldments can affect the ferrite content needed to avoid hot cracking. For example, the rapid cooling rate of electron beam or laser beam welds with their narrow weld zone can shift the solidification mode from primary ferrite to primary austenite. This can also occur at higher welding speeds in conventional arc processes.

Postweld Handling: Postweld annealing may be needed to restore intergranular corrosion resistance, depending on the carbon content and cooling rate of the weldment. Even the low-carbon grades (up to 0.03%) can be sensitized if cooled extremely slowly through or held for very long periods in the sensitization range.

However, that is unlikely under normal circumstances. Therefore, the "L" grades, e.g. Type 304L versus Type 304, can often be used as-welded. If an anneal is not needed after welding, weldments may be stress-relieved, if necessary, for several hours at 370-425°C (700-800°F).

Low-temperature sensitization, i.e., sensitization after long-term exposure at temperatures lower than the traditional sensitization range, such as 400°C (750°F), has been observed even in L grades. Use stabilized grades or L grades with increased nitrogen in this situation.



Stabilized grades may need a stabilization anneal if they are going to be exposed to the sensitization range in use. This is because titanium or niobium (columbium) carbides will be solutioned in a zone adjacent to the weld. If they are not reprecipitated with a stabilization anneal, grain boundary chromium carbide will be precipitated upon subsequent elevated-temperature exposure. This can result in "knife-line" attack if the weldment is then exposed to an appropriate corrosive environment.

Autogenous welds in high-molybdenum superaustenitic grades may require an anneal to alleviate molybdenum segregation in the weld, which will otherwise reduce localized corrosion resistance.

Free-Machining Grades: Free-machining grades are not usually recommended for welding because of their crack sensitivity. However, if they must be welded, an austenitic filler metal such as E/ER312 can be used for higher-carbon grades or E/ER308L for lower-carbon grades. Dilution of the weld metal with the free-matching agent (S or Se) should be minimized by keeping heat input to a minimum.

Welding Precipitation-Hardenable Stainless Steels

General Considerations: Martensitic and semi-austenitic precipitation-hardenable stainless steels pose no particular problems in welding. They are usually welded in the solution-treated or annealed condition. They may be welded in an overaged condition if you anticipate unusual welding stresses from highly restrained conditions or heavier sections. Shielding gas must be carefully maintained for those alloys containing reactive age-hardening agents, such as aluminum in Carpenter 13-8 and titanium in Custom 455 stainless.

Preheating is not needed in order to avoid cracking. However, stress concentrations such as notches or partial penetration welds should be avoided.

Filler Metals: When a filler metal is needed, a matching composition, if available, should be used for mechanical properties similar to those of the base metal. The most readily available "matching" filler metal is E/ER630 (17Cr-4Ni). If high weld strength is not needed, an austenitic alloy such as E/ER308L can be used. E/ER308 can be used for the higher-carbon semi-austenitic alloys.

Postweld Handling: If welded in the solution-treated condition, martensitic PH grades can be used as welded, if appropriate for the grade, or directly aged after the alloy has cooled to room temperature. However, for the optimum combination of strength, ductility and corrosion resistance, the alloy should be solution-treated before aging. If welded in the overaged condition, the part must be solution treated before aging to higher strength levels.

If welded in the annealed condition, semi-austenitic grades will require a conditioning treatment prior to aging, or tempering in the case of Pyromet 350 and 355. As for the martensitic grades, the optimum combination of properties is obtained by following the complete heat treating cycle, starting with an anneal.

Welding Duplex Stainless Steels

One of the main concerns when welding duplex stainless grades is the phase balance after welding. Corrosion resistance and mechanical properties of modern duplex grades depend in part upon a balance of approximately 50% austenite and 50% ferrite.

However, as shown in the diagram, alloys that are duplex at lower temperature will transform to ferrite at suitably elevated temperatures. In addition, the molten metal will solidify as primary ferrite, with austenite precipitating out of the ferrite. The precipitation or reprecipitation of austenite is dependent upon cooling rate, with faster cooling rates, as may be encountered in welds, restricting the precipitation of austenite. Conversely, very slow cooling rates may allow the precipitation of undesirable phases in these highly alloyed grades.

The proper phase balance can be restored by annealing autogenous welds or welds with matching filler metal.

However, annealing is not always possible. Therefore, use the following procedures to help maintain the desired phase balance:

1. Avoid low heat inputs due to the faster solidification rates that accompany them. Welding techniques that

result in a fast solidification rate, such as short-circuiting GMAW, electron-beam welding and laser-beam welding, should be avoided if possible.

2. Avoid too high a heat input, particularly with the more highly alloyed duplex grades because of their propensity to form detrimental intermetallic phases. In this case, heat input may be reduced for subsequent passes. Stringer beads are preferred.

3. Enriched-nickel filler metals will assist in ensuring that the weld metal contains the proper balance of austenite and ferrite when postweld heat treating is not possible. (Matching filler metals should be used if a postweld heat treatment is to be performed.)

Because of the sensitivity of these grades to welding technique, qualification of welding procedures must be more rigorous than for other types of stainless steels, and besides mechanical property testing includes phase balance assessment, microstructural evaluation and corrosion testing.

Dissimilar Welds

Because of the potential for cracking, alloy or carbon steel consumables must not be used when welding alloy or carbon steel to stainless steels, and 400 series stainless consumables must not be used when welding 400 series stainless to austenitic stainless.

When welding an austenitic stainless steel to a martensitic or ferritic stainless steel or to a carbon or alloy steel, the non-austenitic side of the joint is first "buttered" or coated with an austenitic weld rod such as E/ER309 or 312, which has sufficiently high alloy content to prevent martensite formation and contains sufficient ferrite to prevent hot cracking. Preheat is used as necessary, and the steel can be heat treated after buttering as needed. Then the joint can be made using the austenitic filler normally used for the austenitic stainless steel side of the weld.

When welding a martensitic or ferritic stainless steel to carbon or alloy steel, both sides of the joint can be "buttered" or coated with an austenitic weld rod such as E/ER309, using preheat and heat treating after buttering as necessary. Then the joint can be made without the need for preheat. Alternatively, the joint can be made using austenitic filler without the initial overlays; however, control of dilution is critical in this case.

For more information, visit the American Welding Society at www.aws.org.

Other Resources: Welding Information Center

Galling and Carpenter Stainless Steels

Adhesive wear results from two metals being rubbed together under a load sufficient to break through the oxide film, allowing the mating surfaces to come into contact at the high points. When the cohesive force between the two metals exceeds the strength of either metal, adhesion or cold welding occurs. Under low stress, this adhesion usually results in a complex process, which wears away one or both of the mating surfaces at a slow rate. At higher stresses, cold welding occurs more rapidly and over a greater area of the mating surfaces. This higher degree of cold welding is referred to as galling and may cause equipment to seize or freeze up. If not dealt with at the outset, galling can be a worrisome and recurring problem, particularly in the application of stainless steels.

Prevention

The probability of galling occurring between two metals can be minimized or prevented via:

1. Control of surface roughness,
2. Use of lubricants,
3. Decreasing the contact load, and
4. Alloy selection.

Of these four measures, contact load may be the least subject to manipulation but, nevertheless, must be controlled to the extent that excessive loads are avoided. Control of surface roughness, coupled with the use of a high-quality lubricant such as a moly-disulfide reinforced grease, is all that may be required in many applications to prevent galling.

The ideal surface is one that is free of machining burrs, fins and tears and is not overly rough or overly smooth. For most applications, a surface roughness in the range of 15 to 50 micro-inches (rms) is best.

Alloy Selection

Most stainless steels are more susceptible to galling than carbon and alloy steels. However, not all stainless steels are equally susceptible and, in fact, some are quite resistant to galling. That is, resistant grades have a high **threshold galling stress (TGS).**

Threshold galling stress as discussed here is determined by a laboratory test following methods in ASTM G98. Threshold galling is the stress required to produce galling when a 1/2" (12.7 mm) diameter button is rotated against a flat plate with no lubrication. A single revolution of the button is normally used. However, when evaluating galling-resistant alloys, such as Gall-Tough® stainless, a procedure with three alternating revolutions is used to simulate more severe service. The button and plate may be the same or different alloys. Because of the many possible extraneous factors such as lubrication, temperature, roughness and others, TGS is not necessarily the lowest or, conversely, the highest stress that will produce galling in actual practice. Nevertheless, TGS has proven to be a valuable guide in selecting stainless steels with increased resistance to galling.

Threshold Galling Stress for Carpenter Alloys

To help the user and engineer select alloys for applications where galling could occur, Carpenter has applied the above procedure to determine TGS for numerous stainless steels. For some alloys, TGS was determined in two ways. In the first test, both button and base plate were the same alloy. In the second, base plate and button were two different alloys or conditions. Results from the various test are shown in Tables 1, 2, and 3. Note that Tables 2 and 3 present results for single-rotation tests, while Table 1 presents results for triple-rotation tests.

Large differences in TGS are seen among the various alloys and, of course, the resistance to galling increases with the TGS. Differences less than 2 to 4 ksi (14 to 28 MPa) between alloys, however, are not considered to be significant for the single-rotation test.

Observations Based on Our Data

Contrary to popular belief, cold working does not increase the resistance of an austenitic stainless steel to galling and, in fact, can be deleterious. On the other hand, increasing hardness via heat-treating is generally beneficial.

Martensitic stainless steels such as Type 410 and Type 416 in the annealed or tempered conditions are similar or less resistant to galling than annealed austenitic stainless steels such as Type 304 and 316.

The addition of free-machining additives to both the 300 and 400 series stainless steels and the restriction of nickel in the nitrogen-strengthened alloys increase resistance to galling.

The TGS for a combination of two different alloys frequently lies between the values for the individual alloys in a self-mated condition.

Gall-Tough stainless has the highest TGS of any stainless steel produced by Carpenter and should be considered for those applications now using alloys such as Types 302, 304, 316 and 22Cr-13Ni-5Mn where galling has been a problem or is likely to be a problem.

For questions and comments on this section, please visit our Facebook or Twitter account!

TABLE 1

Triple-Rotation Threshold Galling Stress Results for Various Stainless Steels

Self-Mated, Unlubricated Ground Finish

Alloy	Condition	Rockwell Hardness	Threshold Galling Stress	
			ksi	MPa
Gall-Tough® stainless	Mill Annealed	B 92	15*	103*
Gall-Tough	Cold Drawn	C 38	15*	103*
Gall-Tough PLUS® stainless	Mill Annealed	B 95	7	48
Type 440C	Tempered 400°F	C 56	2	14
Custom 455® stainless	H 950	C 46	<1*	<7**
Type 304	Annealed	B 76	<1**	<7**
Type 316	Annealed	B 80	< 1**	7
18Cr-2Ni-12Mn	Annealed	B 95	2	14
Type 430	Annealed	B 77	<1**	<7**
Type 420	Tempered 400°F	C 51	1	7

** Testing at higher stress not performed*
*** Galled at lowest stress evaluated*

TABLE 2

Single-Rotation Threshold Galling Stress Results for Dissimilar[1] Stainless Steel Couples

Unlubricated Ground Finish

Alloy[2]	Condition	Rockwell Hardness	Threshold Galling Stress		Alloy[2]	Condition	Rockwell Hardness	Threshold Galling Stress	
			ksi	MPa				ksi	MPa
Gall-Tough® Stainless	Annealed	B 96	15.0	104	Type 410	Tempered 600°F	C 42	5.0	34
Type 410	Tempered 500˚F	C 42			Type 440C	Tempered 500°F	C 55		
Project 70+® Type 304	Cold Drawn	C 27	4.0	28	Type 410	Tempered 600°F	C 42	1.0	7
Project 70+ Type 304	Annealed	B 86			Custom 450 Stainless	H 900	C 43		
Project 70+ Type 304	Annealed	B 86	4.0	28	Project 70+ Type 416	Tempered 1000°F	C 32	11.0	76
Type 440C	Tempered 500°F	C 55			Project 70+ Type 416	Annealed	B 83		
Project 70+ Type 304	Annealed	B 86	3.0	21	Project 70+ Type 416	Tempered 600°F	C 37	23.0	159
Custom 450® Stainless	H 900	C 43			Type 440C	Tempered 500°F	C 55		
Project 70+ Type 316	Annealed	B 82	8.0	55	Type 440C	Tempered 500°F	C 55	5.0	34
Project 70+ Type 316	Cold Drawn	C27			Type 630	H 900	C 45		
Project 70+ Type 316	Annealed	B 82	2.0	14	Type 440C	Tempered 500°F	C 55	12.0	83
Type 440C	Tempered 500°F	C 55			Custom Flo 302 HQ	Annealed	B 74		
22Cr-13Ni-5Mn	Hot-Worked Unann.	C 32	6.0	41	Custom 455® Stainless	H 950	C 48	18.0	124
Project 70+ Type 304	Annealed	B 89			Project 70+ Type 304	Annealed	B 86		
22Cr-13Ni-5Mn	Annealed	B 97	3.0	21	Custom 455 Stainless	H 950	C 48	11.0	76
Project 70+ Type 304	Annealed	B 89			Custom 630	H 900	C 45		
18Cr-2Ni-12Mn	Annealed	C 23	15.0*	103*	Custom 455 Stainless	H 950	C 48	8.0	55
Project 70+ Type 304	Annealed	B 86			Custom 630	H 1050	C 38		
Type 430	Annealed	B 98	10.0	69	Carpenter 13-8	H 1000	C 46	9.0	62
18Cr-2Ni-12Mn	Annealed	C 23			Custom 630	H 900	C 45		
7-Mo® Stainless	Annealed	C 25	1.5	10	Carpenter 13-8	H 1000	C 46	2.0	14
Project 70+ Type 316	Cold Drawn	C 27			Custom 630	H 1025	C 38		
7-Mo Stainless	Aged 1300°F 24 hrs.	C 41	5.0	34	Carpenter 13-8	H 1150	C 35	15.0*	104*
Project 70+ Type 316	Annealed	B 82			Al-bronze	Annealed	C 23		

(1) Dissimilar means that the button and block are either different materials or the same material in different conditions.
(2) The first material listed for each dissimilar couple is the button.
** Did not gall at 15 ksi.*

TABLE 3

Single-Rotation Threshold Galling Stress Results for Various Stainless Steels

Self-Mated, Unlubricated Ground Finish

Alloy	Condition	Rockwell Hardness	Threshold Galling Stress	
			ksi	MPa
Austenitic Stainless Steels				
Gall-Tough® Stainless	Annealed	B 95	15.0*	104*
Gall-Tough PLUS Stainless	Annealed	B 9??	15.0*	104*
22Cr-13Ni-5Mn	2050°F ANL	B 97	5.0	34
21Cr-6Ni-9Mn	Annealed	B 96	7.0	48
18Cr-2Ni-12Mn	Annealed	C 23	14.0	97
Type 204Cu	Annealed	B 88	5.0	34
Project 70+® Type 304/304L	Annealed	B 89	8.0	55
Project 70+ Type 304/304L	Cold Drawn	C 27	2.5	17
Project 70+ Type 316/316L	Annealed	B 82	7.0	48
Project 70+ Type 316/316L	Cold Drawn	C 27	5.0	34
Custom Flo 302 HQ	Annealed	B 74	5.0	34
Project 70+ Type 303	Annealed	B 85	15.0*	104*
20Cb-3® Stainless	Annealed	B 87	2.0	14
Martensitic Stainless Steels				
TrimRite® Stainless	Tempered 400°F	C 50	15.0*	103*
TrimRite Stainless	Tempered 500°F	C 47	9.0	62
Type 410	Annealed	B 87	1.0	7
Type 410	Tempered 500°F	C 43	3.0	21
Type 416	Annealed	B 95	3.0	21
Type 416	Tempered 600°F	C 37	9.0	62
Type 416	Tempered 1000°F	C 32	6.0	41
Type 420	Tempered 400°F	C 51	15.0*	104*
Type 420	Tempered 500°F	C 49	8.0	55
Type 440C	Tempered 500°F	C 55	15.0*	104*

Alloy	Condition	Rockwell Hardness	Threshold Galling Stress	
			ksi	MPa
Precipitation Hardenable Stainless Steels				
Custom 455® Stainless	H 950	C 48	13.0	90
Custom 455 Stainless	H 1050	C 43	8.5	59
Custom 455 Stainless	H 1150	C 36	4.0	28
Custom 450® Stainless	Solution Annealed	C 29	10.0	69
Custom 450 Stainless	H 900	C 43	8.0	55
Custom 450 Stainless	H 1050	C 38	2.5	17
Custom 450 Stainless	H 1150	C 33	2.0	14
Custom 630 Stainless	H 900	C 45	10.0	69
Custom 630 Stainless	H 1150	C 34	5.0	34
Ferritic and Duplex Stainless Steels				
182-FM	Cold Drawn	B 98	5.0	34
Type 430F	Annealed	B 92	2.0	14
Type 430	Annealed	B 98	1.5	10
7-Mo® Stainless	Annealed	C 25	1.0	7
7-Mo Stainless	Aged 1300°F 24 hrs.	C 41	7.0	48

** Did not gall at 15 ksi*

For more information on fabricating stainless steel, download a variety of publications from the SSINA at www.ssina.com, and visit their FAQ page.

MetalMass™ App

Carpenter Technology Corporation has created a free and simple to use application to help you estimate the total weight and cost of long-product metallic alloy materials.

To use this calculator, just enter:

- Shape
- Alloy Family or Density
- Cross-Sectional size
- Length
- Unit Cost

To learn more or to download this app, please visit www.cartech.com/metalmass.html or iTunes.

Tables

Approximate Estimated Weights – Steel Bar per Lineal Foot

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

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

Approximate Estimated Weights – Steel Bar per Lineal Foot (continued)

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

Size in Inches	Round	Square	Hexagon	Octagon
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
3	24.03	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

Approximate Estimated Weights – Steel Bar per Lineal Foot (continued)

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

Size in Inches	Round	Square	Hexagon	Octagon
5-15/16	94.14	119.9	103.9	99.26
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

Approximate Estimated Weights – Steel Bar per Lineal Foot (continued)

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

Approximate Estimated Weights in Pounds per Foot – Stainless Cold-Rolled Strip

This table applies to chrome-nickel grades. For simple chrome grades, deduct 1.7% from weight.

Thickness		Width - Inches															
No. B.W.G.	Decimal Equivalent	1/16	1/8	3/16	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	13/16	7/8	15/16	1
7	.180″	.0394	.0788	.1182	.1575	.1969	.2363	.2757	.3150	.3544	.3938	.4332	.4725	.5119	.5513	.5907	.6300
8	.165″	.0361	.0722	.1083	.1444	.1805	.2166	.2527	.2887	.3249	.3610	.3971	.4331	.4693	.5054	.5415	.5775
9	.148″	.0324	.0648	.0972	.1295	.1620	.1943	.2268	.2590	.2915	.3238	.3562	.3885	.4209	.4533	.4857	.5180
10	.134″	.0293	.0587	.0880	.1173	.1466	.1760	.2052	.2345	.2639	.2933	.3225	.3518	.3811	.4106	.4398	.4690
11	.120″	.0263	.0525	.0788	.1050	.1313	.1575	.1838	.2100	.2363	.2625	.2888	.3150	.3413	.3675	.3938	.4200
12	.109″	.0239	.0477	.0716	.0954	.1193	.1431	.1670	.1908	.2147	.2385	.2624	.2862	.3101	.3339	.3578	.3815
13	.095″	.0208	.0416	.0624	.0831	.1040	.1247	.1455	.1663	.1871	.2078	.2287	.2494	.2703	.2910	.3118	.3325
14	.083″	.0182	.0363	.0545	.0726	.0908	.1089	.1271	.1453	.1634	.1815	.1998	.2179	.2361	.2542	.2724	.2905
15	.072″	.0158	.0315	.0473	.0630	.0788	.0945	.1103	.1260	.1418	.1575	.1733	.1890	.2048	.2205	.2363	.2520
16	.065″	.0142	.0285	.0427	.0569	.0712	.0854	.0997	.1138	.1281	.1423	.1566	.1707	.1850	.1992	.2135	.2275
17	.058″	.0127	.0254	.0381	.0508	.0635	.0762	.0889	.1015	.1143	.1270	.1397	.1523	.1650	.1777	.1904	.2030
18	.049″	.0107	.0214	.0321	.0429	.0535	.0643	.0749	.0858	.0964	.1072	.1179	.1287	.1393	.1501	.1607	.1715
19	.042″	.0092	.0184	.0276	.0368	.0460	.0552	.0644	.0735	.0828	.0920	.1012	.1103	.1196	.1288	.1379	.1470
20	.035″	.0077	.0153	.0230	.0306	.0383	.0459	.0536	.0613	.0689	.0765	.0842	.0919	.0995	.1071	.1148	.1225
21	.032″	.0070	.0140	.0210	.0280	.0350	.0420	.0490	.0560	.0630	.0700	.0770	.0840	.0910	.0980	.1050	.1120
22	.028″	.0061	.0123	.0184	.0245	.0307	.0368	.0430	.0490	.0552	.0613	.0675	.0735	.0797	.0858	.0920	.0980
23	.025″	.0055	.0110	.0165	.0219	.0275	.0329	.0385	.0438	.0494	.0548	.0604	.0657	.0713	.0767	.0822	.0875
24	.022″	.0048	.0096	.0144	.0193	.0240	.0289	.0336	.0385	.0432	.0481	.0529	.0578	.0625	.0674	.0722	.0770
25	.020″	.0044	.0088	.0132	.0175	.0220	.0263	.0307	.0350	.0395	.0438	.0482	.0525	.0570	.0613	.0657	.0700
26	.018″	.0039	.0079	.0118	.0158	.0197	.0237	.0276	.0315	.0355	.0395	.0434	.0473	.0513	.0553	.0592	.0630
27	.016″	.0035	.0070	.0105	.0140	.0175	.0210	.0245	.0280	.0315	.0350	.0385	.0420	.0455	.0490	.0525	.0560
28	.014″	.0030	.0061	.0091	.0123	.0152	.0184	.0213	.0245	.0274	.0306	.0336	.0368	.0397	.0429	.0459	.0490
29	.013″	.0028	.0057	.0085	.0114	.0142	.0171	.0199	.0228	.0256	.0285	.0313	.0342	.0370	.0398	.0427	.0455
30	.012″	.0026	.0053	.0079	.0105	.0132	.0158	.0185	.0210	.0238	.0264	.0291	.0315	.0343	.0369	.0396	.0420
31	.010″	.0022	.0044	.0066	.0088	.0110	.0132	.0154	.0175	.0198	.0219	.0242	.0263	.0286	.0308	.0330	.0350
32	.009″	.0020	.0040	.0060	.0079	.0100	.0119	.0140	.0158	.0180	.0198	.0220	.0237	.0260	.0277	.0297	.0315
33	.008″	.0018	.0035	.0053	.0070	.0088	.0105	.0123	.0140	.0158	.0175	.0193	.0210	.0228	.0246	.0263	.0280
34	.007″	.0015	.0031	.0046	.0062	.0077	.0093	.0108	.0123	.0139	.0154	.0170	.0185	.0201	.0215	.0231	.0245
35	.005″	.0011	.0022	.0033	.0044	.0055	.0066	.0077	.0088	.0099	.0110	.0121	.0132	.0143	.0154	.0165	.0175
36	.004″	.0009	.0018	.0027	.0035	.0045	.0053	.0063	.0070	.0080	.0088	.0098	.0105	.0115	.0123	.0132	.0140
For Interpolation	.001″	.0002	.0004	.0006	.0009	.0010	.0013	.0015	.0018	.0019	.0022	.0023	.0027	.0028	.0030	.0032	.0035

Approximate Estimated Weights in Pounds per Foot – Stainless Cold-Rolled Strip (continued)

This table applies to chrome-nickel grades. For simple chrome grades, deduct 1.7% from weight.

Thickness		Width-Inches											
No. B.W.G.	Decimal Equivalent	1	2	3	4	5	6	7	8	9	10	11	12
7	.180″	.6300	1.260	1.890	2.520	3.150	3.780	4.410	5.040	5.670	6.300	6.930	7.560
8	.165″	.5775	1.155	1.733	2.310	2.888	3.465	4.043	4.620	5.198	5.775	6.353	6.930
9	.148″	.5180	1.036	1.554	2.072	2.590	3.108	3.626	4.144	4.662	5.180	5.698	6.216
10	.134″	.4690	0.938	1.407	1.876	2.345	2.814	3.283	3.752	4.221	4.690	5.159	5.628
11	.120″	.4200	0.840	1.260	1.680	2.100	2.520	2.940	3.360	3.780	4.200	4.620	5.040
12	.109″	.3815	0.763	1.145	1.526	1.908	2.289	2.671	3.052	3.434	3.815	4.197	4.578
13	.095″	.3325	0.665	0.998	1.330	1.663	1.995	2.328	2.660	2.993	3.325	3.658	3.990
14	.083″	.2905	0.581	0.872	1.162	1.453	1.743	2.034	2.324	2.615	2.905	3.196	3.486
15	.072″	.2520	0.504	0.750	1.008	1.260	1.512	1.764	2.016	2.268	2.520	2.772	3.024
16	.065″	.2275	0.455	0.683	0.910	1.138	1.365	1.593	1.820	2.048	2.275	2.503	2.730
17	.058″	.2030	0.406	0.609	0.812	1.015	1.218	1.421	1.624	1.827	2.030	2.233	2.436
18	.049″	.1715	0.343	0.515	0.686	0.858	1.029	1.201	1.372	1.544	1.715	1.887	2.058
19	.042″	.1470	0.294	0.441	0.588	0.735	0.882	1.029	1.176	1.323	1.470	1.617	1.764
20	.035″	.1225	0.245	0.368	0.490	0.613	0.735	0.858	0.980	1.103	1.225	1.348	1.470
21	.032″	.1120	0.224	0.336	0.448	0.560	0.672	0.784	0.896	1.008	1.120	1.232	1.344
22	.028″	.0980	0.196	0.294	0.392	0.490	0.588	0.686	0.784	0.882	0.980	1.078	1.176
23	.025″	.0875	0.175	0.263	0.350	0.438	0.525	0.613	0.700	0.788	0.875	0.963	1.050
24	.022″	.0770	.1540	.2310	.3080	.3850	.4620	0.5390	.6160	.6930	.7700	.8470	0.924
25	.020″	.0700	.1400	.2100	.2800	.3500	.4200	.4900	.5600	.6300	.7000	.7700	0.840
26	.018″	.0630	.1260	.1890	.2520	.3150	.3780	.4410	.5040	.5670	.6300	.6930	0.756
27	.016″	.0560	.1120	.1680	.2240	.2800	.3360	.3920	.4480	.5040	.5600	.6160	0.672
28	.014″	.0490	.0980	.1470	.1960	.2450	.2940	.3430	.3920	.4410	.4900	.5390	0.588
29	.013″	.0455	.0910	.1365	.1820	.2275	.2730	.3185	.3640	.4095	.4550	.5005	0.546
30	.012″	.0420	.0840	.1260	.1680	.2100	.2520	.2940	.3360	.3780	.4200	.4620	0.504
31	.010″	.0350	.0700	.1050	.1400	.1750	.2100	.2450	.2800	.3150	.3500	.3850	0.420
32	.009″	.0315	.0630	.0945	.1260	.1575	.1890	.2205	.2520	.2835	.3150	.3465	0.378
33	.008″	.0280	.0560	.0840	.1120	.1400	.1680	.1960	.2240	.2520	.2800	.3080	0.336
34	.007″	.0245	.0490	.0735	.0980	.1225	.1470	.1715	.1960	.2205	.2450	.2695	0.294
35	.005″	.0175	.0350	.0525	.0700	.0875	.1050	.1225	.1400	.1575	.1750	.1925	0.210
36	.004″	.0140	.0280	.0420	.0560	.0700	.0840	.0980	.1120	.1260	.1400	.1540	0.168
For Interpolation	.001″	.0035	.0070	.0105	.0140	.0175	.0210	.0245	.0280	.0315	.0350	.0385	0.042

Approximate Estimated Weights - Flat Rolled Steel per Lineal Foot

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

Thickness in Inches	Width - Inches										
	1/2	5/8	3/4	7/8	1	1-1/8	1-1/4	1-3/8	1-1/2	1-5/8	1-3/4
1/16	.1060	.1381	.1594	.1859	.212	.2391	.2656	.292	.319	.346	.372
1/8	.2125	.2656	.3188	.3720	.4250	.4782	.2656	.585	.638	.692	.744
3/16	.319	.399	.478	.558	.638	.717	.5312	.875	.957	1.04	1.15
1/4	.425	.531	.636	.743	.850	.957	1.06	1.17	1.28	1.38	1.49
5/16	.531	.664	.797	.929	1.06	1.20	1.33	1.46	1.59	1.73	1.86
3/8	.638	.797	.957	1.116	1.28	1.43	1.59	1.76	1.92	2.08	2.23
7/16	.744	.929	1.116	1.302	1.49	1.68	1.86	2.05	2.23	2.42	2.60
1/2	.850	1.06	1.275	1.487	1.70	1.92	2.12	2.34	2.55	2.72	2.98
9/16	.957	1.20	1.434	1.674	1.92	2.15	2.39	2.63	2.87	3.11	3.35
5/8	1.06	1.33	1.594	1.859	2.12	2.39	2.65	2.92	3.19	3.46	3.72
11/16	1.17	1.46	1.753	2.045	2.34	2.63	2.92	3.22	3.51	3.80	4.09
3/4	1.28	1.60	1.913	2.232	2.55	2.87	3.19	3.51	3.83	4.15	4.47
13/16	1.38	1.73	2.072	2.417	2.76	3.11	3.45	3.80	4.14	4.49	4.84
7/8	1.49	1.86	2.232	2.604	2.98	3.35	3.72	4.09	4.47	4.84	5.20
15/16	1.60	1.99	2.391	2.789	3.19	3.59	3.99	4.39	4.78	5.18	5.58
1	1.70	2.13	2.55	2.98	3.40	3.83	4.25	4.68	5.10	5.53	5.95
1-1/8	1.91	2.39	2.868	3.347	3.83	4.304	4.78	5.26	5.74	6.22	6.70
1-1/4	2.12	2.66	3.19	3.72	4.25	4.79	5.31	5.85	6.38	6.91	7.44
1-3/8	2.34	2.92	3.51	4.09	4.67	5.26	5.84	6.43	7.02	7.60	8.18
1-1/2	2.55	3.19	3.83	4.47	5.10	5.74	6.38	7.02	7.65	8.29	8.93
1-5/8	2.76	3.45	4.15	4.84	5.52	6.22	6.90	7.60	8.29	8.98	9.67
1-3/4	2.98	3.72	4.45	5.21	5.95	6.70	7.44	8.19	8.92	9.67	10.42
1-7/8	3.19	3.99	4.79	5.58	6.38	7.17	7.97	8.77	9.57	10.36	11.15
2	3.40	4.25	5.10	5.95	6.80	7.65	8.50	9.35	10.20	11.05	11.90

Approximate Estimated Weights - Flat Rolled Steel per Lineal Foot (continued)

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

Thickness in Inches	Width - Inches										
	2	2-1/4	2-1/2	2-3/4	3	3-1/4	3-1/2	3-3/4	4	4-1/4	4-1/2
1/16	.425	.478	.531	.584	.638	.691	.744	.80	.85	.90	.96
1/8	.850	.96	1.06	1.17	1.28	1.38	1.49	1.59	1.70	1.81	1.91
3/16	1.28	1.44	1.59	1.75	1.91	2.07	2.23	2.39	2.55	2.71	2.87
1/4	1.70	1.92	2.12	2.34	2.55	2.76	2.98	3.19	3.40	3.61	3.83
5/16	2.12	2.39	2.65	2.92	3.19	3.45	3.72	3.99	4.25	4.52	4.78
3/8	2.55	2.87	3.19	3.51	3.83	4.15	4.47	4.78	5.10	5.42	5.74
7/16	2.98	3.35	3.72	4.09	4.46	4.83	5.20	5.58	5.95	6.32	6.70
1/2	3.40	3.83	4.25	4.67	5.10	5.53	5.95	6.38	6.80	7.22	7.65
9/16	3.83	4.30	4.78	5.26	5.74	6.22	6.70	7.17	7.65	8.13	8.61
5/8	4.25	4.78	5.31	5.84	6.38	6.91	7.44	7.97	8.50	9.03	9.57
11/16	4.67	5.26	5.84	6.43	7.02	7.60	8.18	8.76	9.35	9.93	10.52
3/4	5.10	5.75	6.38	7.02	7.65	8.29	8.93	9.57	10.20	10.84	11.48
13/16	5.50	6.21	6.90	7.60	8.29	8.98	9.67	10.36	11.05	11.74	12.43
7/8	5.95	6.69	7.44	8.18	8.93	9.67	10.41	11.16	11.90	12.65	13.39
15/16	6.38	7.18	7.97	8.77	9.57	10.36	11.16	11.95	12.75	13.55	14.34
1	6.80	7.65	8.50	9.35	10.20	11.05	11.90	12.75	13.60	14.45	15.30
1-1/8	7.65	8.61	9.57	10.52	11.48	12.43	13.39	14.34	15.30	16.26	17.22
1-1/4	8.50	9.57	10.63	11.69	12.75	13.81	14.87	15.94	17.00	18.06	19.13
1-3/8	9.35	10.52	11.69	12.85	14.03	15.20	16.36	17.53	18.70	19.87	21.04
1-1/2	10.20	11.48	12.75	14.03	15.30	16.58	17.85	19.13	20.40	21.68	22.95
1-5/8	11.05	12.43	13.81	15.19	16.58	17.96	19.34	20.72	22.10	23.48	24.87
1-3/4	11.90	13.40	14.88	16.37	17.85	19.34	20.83	22.32	23.80	25.29	26.78
1-7/8	12.75	14.34	15.94	17.53	19.13	20.72	22.31	23.91	25.50	27.10	28.69
2	13.60	15.30	17.00	18.70	20.40	22.10	23.80	25.50	27.20	28.90	30.60

Approximate Estimated Weights - Flat Rolled Steel per Lineal Foot (continued)

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

Thickness in Inches	Width - Inches										
	4-3/4	5	5-1/4	5-1/2	5-3/4	6	6-1/4	6-1/2	6-3/4	7	7-1/4
1/16	1.01	1.06	1.116	1.169	1.222	1.275	1.328	1.381	1.434	1.487	1.540
1/8	2.02	2.13	2.232	2.338	2.444	2.550	2.656	2.762	2.869	2.975	3.081
3/16	3.03	3.19	3.35	3.51	3.67	3.83	3.99	4.14	4.30	4.46	4.62
1/4	4.04	4.25	4.46	4.67	4.89	5.10	5.31	5.53	5.74	5.95	6.16
5/16	5.05	5.31	5.58	5.84	6.11	6.38	6.64	6.90	7.17	7.44	7.70
3/8	6.06	6.38	6.69	7.02	7.34	7.65	7.97	8.29	8.61	8.93	9.25
7/16	7.07	7.44	7.81	8.18	8.56	8.93	9.29	9.67	10.04	10.41	10.78
1/2	8.08	8.50	8.93	9.35	9.77	10.20	10.63	11.05	11.48	11.90	12.32
9/16	9.09	9.57	10.04	10.52	11.00	11.48	11.95	12.43	12.91	13.39	13.86
5/8	10.10	10.63	11.16	11.69	12.22	12.75	13.28	13.81	14.34	14.87	15.40
11/16	11.11	11.69	12.27	12.85	13.44	14.03	14.61	15.20	15.78	16.36	16.94
3/4	12.12	12.75	13.39	14.03	14.67	15.30	15.94	16.58	17.22	17.85	18.49
13/16	13.12	13.81	14.50	15.19	15.88	16.58	17.27	17.95	18.65	19.34	20.03
7/8	14.13	14.87	15.62	16.36	17.10	17.85	18.60	19.34	20.08	20.83	21.57
15/16	15.14	15.94	16.74	17.53	18.33	19.13	19.62	20.72	21.51	22.32	23.11
1	16.15	17.00	17.85	18.70	19.55	20.40	21.25	22.10	22.95	23.80	24.65
1-1/8	18.17	19.13	20.08	21.04	21.99	22.95	23.91	24.87	25.82	26.78	27.73
1-1/4	20.19	21.25	22.32	23.38	24.44	25.50	26.56	27.62	28.69	29.75	30.81
1-3/8	22.21	23.38	24.54	25.71	26.88	28.05	29.22	30.39	31.56	32.72	33.89
1-1/2	24.23	25.50	26.78	28.05	29.33	30.60	31.88	33.15	34.43	35.70	36.98
1-5/8	26.25	27.63	29.01	30.39	31.77	33.15	34.53	35.91	37.99	38.67	40.05
1-3/4	28.27	29.75	31.24	32.73	34.22	35.70	37.19	38.68	40.17	41.65	43.14
1-7/8	30.28	31.87	33.47	35.06	36.65	38.25	38.85	41.44	43.03	44.63	46.22
2	32.30	34.00	35.70	37.40	39.10	40.80	42.50	44.20	45.90	47.60	49.30

Approximate Estimated Weights - Flat Rolled Steel per Lineal Foot (continued)

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

Thickness in Inches	Width - Inches										
	7-1/2	7-3/4	8	8-1/4	8-1/2	8-3/4	9	9-1/2	10	10-1/2	11
1/16	1.594	1.647	1.70	1.753	1.806	1.859	1.913	2.019	2.135	2.232	2.338
1/8	3.188	3.294	3.40	3.506	3.612	3.720	3.826	4.037	4.250	4.463	4.876
3/16	4.78	4.94	5.10	5.26	5.42	5.58	5.74	6.06	6.38	6.70	7.02
1/4	6.36	6.58	6.80	7.01	7.22	7.43	7.65	8.08	8.50	8.92	9.34
5/16	7.97	8.23	8.50	8.76	9.03	9.29	9.56	10.10	10.62	11.16	11.68
3/8	9.57	9.88	10.20	10.52	10.84	11.16	11.48	12.12	12.75	13.39	14.03
7/16	11.16	11.53	11.90	12.27	12.64	13.02	13.40	14.14	14.88	15.62	16.36
1/2	12.75	13.18	13.60	14.03	14.44	14.87	15.30	16.16	17.00	17.85	18.70
9/16	14.34	14.82	15.30	15.78	16.26	16.74	17.22	18.18	19.14	20.08	21.02
5/8	15.94	16.47	17.00	17.53	18.06	18.59	19.13	20.19	21.35	22.32	23.38
11/16	17.53	18.12	18.70	19.28	19.86	20.45	21.04	22.21	23.38	24.54	25.70
3/4	19.13	19.77	20.40	21.04	21.68	22.32	22.96	24.23	25.50	26.78	28.05
13/16	20.72	21.41	22.10	22.79	23.48	24.17	24.86	26.24	27.62	29.00	30.40
7/8	22.32	23.05	23.80	24.55	25.30	26.04	26.78	28.26	29.75	31.34	32.72
15/16	23.91	24.70	25.50	26.30	27.10	27.89	28.69	30.28	31.88	33.48	35.06
1	25.50	26.35	27.20	28.05	28.90	29.75	30.60	32.30	34.00	35.70	37.40
1-1/8	28.68	29.64	30.60	31.56	32.52	33.47	34.43	36.34	38.25	40.17	42.08
1-1/4	31.88	32.94	34.00	35.06	36.12	37.20	38.26	40.37	42.50	44.63	46.76
1-3/8	35.06	36.23	37.40	38.57	39.74	40.91	42.08	44.41	46.75	49.08	51.42
1-1/2	38.26	39.53	40.80	42.08	43.35	44.63	45.90	48.45	51.00	53.55	56.10
1-5/8	41.44	42.82	44.20	45.58	46.96	48.34	49.73	52.49	55.25	58.02	60.78
1-3/4	44.63	46.12	47.60	49.09	50.58	52.07	53.56	56.53	59.50	62.48	65.45
1-7/8	47.82	49.40	51.00	52.60	54.20	55.79	57.38	60.56	63.75	66.94	70.12
2	51.00	52.70	54.40	56.10	57.80	59.50	61.20	64.60	68.00	71.40	74.80

Approximate Estimated Weights - Flat Rolled Steel per Lineal Foot (continued)

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

Fractional Inches			Decimal Inches	Millimeters
1/64			.015625	
	1/32		.03125	
			.03937	1
3/64			.046875	
		1/16	.0625	
5/64			.078125	
			.07874	2
	3/32		.09375	
7/64			.109375	
			.11811	3
		1/8	.125	
9/64			.140625	
	5/32		.15625	
			.15748	4
11/64			.171875	
		3/16	.1875	
			.19685	5
13/64			.203125	
	7/32		.21875	
15/64			.234375	
			.23622	6
		1/4	.250	
17/64			.265625	
			.27559	7
	9/32		.28125	
19/64			.296875	
		5/16	.3125	
			.31496	8
21/64			.328125	
	11/32		.34375	
			.35433	9
23/64			.359375	
		3/8	.375	
25/64			.390625	
			.3937	10
	13/32		.40625	
27/64			.421875	
			.43307	11
		7/16	.4375	
29/64			.453125	
	15/32		.46875	
			.47244	12
31/64			.484375	
		1/2	.500	
			.51181	13

Fractional Inches			Decimal Inches	Millimeters
33/64			.515625	
	17/32		.53125	
35/64			.546875	
			.55118	14
	9/16	.5625		
37/64			.578125	
			.59055	15
	19/32		.59375	
		5/8	.625	
			.62992	16
41/64			.640625	
	21/32		.65625	
43/64			.671875	
		11/16	.6875	
45/64			.703125	
			.70866	18
47/64			.734375	
			.74803	19
		3/4	.750	
49/64			.765625	
			.7874	20
51/64			.796875	
		13/16	.8125	
			.82677	21
	27/32		.84475	
55/64			.859375	
			.86614	22
		7/8	.8750	
			.90551	23
	29/32		.90625	
59/64			.921875	
		15/16	.9375	
61/64			.953125	
	31/32		.96875	
			.98425	25
63/64			.984375	

Hardness Conversion Tables – Austenitic Steels

These charts have been established following ASTM standards A370, E10, and E140.

Approximate Hardness Conversions for Austenitic Steels

Rockwell		Brinell	Superficial		
C	A		15N	30N	45N
48	74.4	---	84.1	66.2	52.1
47	73.9	---	83.6	65.3	50.9
46	73.4	---	83.1	64.5	49.8
45	72.9	---	82.6	63.6	48.7
44	72.4	---	82.1	62.7	47.5
43	71.9	---	81.6	61.8	46.4
42	71.4	---	81.0	61.0	45.2
41	70.9	---	80.5	60.1	44.1
40	70.4	---	80.0	59.2	43.0
39	69.9	---	79.5	58.4	41.8
38	69.3	---	79.0	57.5	40.7
37	68.8	---	78.5	56.6	39.6
36	68.3	---	78.0	55.7	38.4
35	67.8	---	77.5	54.9	37.3
34	67.3	---	77.0	54.0	36.1
33	66.8	---	76.5	53.1	35.0
32	66.3	---	75.9	52.3	33.9
31	65.8	---	75.4	51.4	32.7
30	65.3	---	74.9	50.5	31.6
29	64.8	---	74.4	49.6	30.4
28	64.3	---	73.9	48.8	29.3
27	63.8	---	73.4	47.9	28.2
26	63.3	---	72.9	47.0	27.0
25	62.8	---	72.4	46.2	25.9
24	62.3	---	71.9	45.3	24.8
23	61.8	---	71.3	44.4	23.6
22	61.3	---	70.8	43.5	22.5
21	60.8	---	70.3	42.7	21.3
20	60.3	---	69.8	41.8	20.2

Hardness Conversion Tables (continued)

Approximate Hardness Conversions for Austenitic Steels

Rockwell		Brinell*		Superficial		
B	A	Dia.(mm)	Number	15T	30T	45T
100	61.5	3.79	256	91.5	80.4	70.2
99	60.9	3.85	248	91.2	79.7	69.2
98	60.3	3.86	240	90.8	79.0	68.2
97	59.7	3.97	233	90.4	78.3	67.2
96	59.1	4.02	226	90.1	77.7	66.1
95	58.5	4.08	219	89.7	77.0	65.1
94	58.0	4.14	213	89.3	76.3	64.1
93	57.4	4.20	207	88.9	75.6	63.1
92	56.8	4.24	202	88.6	74.9	62.1
91	56.2	4.30	197	88.2	74.2	61.1
90	55.6	4.35	192	87.8	73.5	60.1
89	55.0	4.40	187	87.5	72.8	59.0
88	54.5	4.45	183	87.1	7231	58.0
87	53.9	4.51	178	86.7	71.4	57.0
86	53.3	4.55	174	86.4	70.7	56.0
85	52.7	4.61	170	86.0	70.0	55.0
84	52.1	4.64	167	85.6	69.3	54.0
83	51.5	4.70	163	85.2	68.6	52.9
82	50.9	4.74	160	84.9	67.9	51.9
81	50.4	4.79	156	84.5	67.2	50.9
80	49.8	4.84	153	84.1	66.5	49.9
79	49.2	4.88	150	83.8	65.8	48.9
78	48.6	4.93	147	83.4	65.1	47.9
77	48.0	4.98	144	83.0	64.4	46.8
76	47.4	5.01	142	82.6	63.7	45.8
75	46.9	5.06	139	82.3	63.0	44.8
74	46.3	5.09	137	81.9	62.4	43.8
73	45.7	5.13	135	81.5	61.7	42.8
72	45.1	5.18	132	81.2	61.0	41.8
71	44.5	5.22	130	80.8	60.3	40.7
70	43.9	5.26	128	80.4	59.6	39.7
69	43.3	5.29	126	80.1	58.9	38.7
68	42.8	5.33	124	79.7	58.2	37.7
67	42.2	5.37	122	79.3	57.5	36.7
66	41.6	5.41	120	78.9	56.8	35.7
65	41.0	5.45	118	78.6	56.1	34.7
64	40.4	5.50	116	78.2	55.4	33.6
63	39.8	5.54	114	77.8	54.7	32.6
62	39.3	5.56	113	77.5	54.0	31.6
61	38.7	5.61	111	77.1	53.3	30.6
60	38.1	5.63	110	76.7	52.6	29.6

** 3000 kgf load, 10 mm ball*

Hardness Conversion Tables – Non-Austenitic Steels

Approximate Hardness Conversions for Non-Austenitic Steels

Rockwell		Brinell*		Superficial			Approx. Tensile
C	A	Dia.(mm)	Number	15T	30T	45T	
68	85.6	---	---	93.2	84.4	75.4	---
67	85.0	---	---	92.9	83.6	74.2	---
66	84.5	---	---	92.5	82.8	73.3	---
65	83.9	2.26	739	92.2	81.9	72.0	---
64	83.4	2.28	722	91.8	81.1	71.0	---
63	82.8	2.31	706	91.4	80.1	69.9	---
62	82.3	2.34	688	91.1	79.3	68.8	---
61	81.8	2.37	670	90.7	78.4	67.7	---
60	81.2	2.40	654	90.2	77.5	66.6	---
59	80.7	2.44	634	89.8	76.6	65.5	351
58	80.1	2.47	615	89.3	75.7	64.3	338
57	79.6	2.51	595	88.9	74.8	63.2	325
56	79.0	2.55	577	88.3	73.9	62.0	313
55	78.5	2.59	560	87.9	73.0	60.9	301
54	78.0	2.63	543	87.4	72.0	59.8	292
53	77.4	2.67	525	86.9	71.2	58.6	283
52	76.8	2.71	512	86.4	70.2	57.4	273
51	76.3	2.75	496	85.9	69.4	56.1	264
50	75.9	2.79	482	85.5	68.5	55.0	255
49	75.2	2.83	468	85.0	67.6	53.8	246
48	74.7	2.87	455	84.5	66.7	52.5	238
47	74.1	2.91	442	83.9	65.8	51.4	229
46	73.6	2.94	432	83.5	64.8	50.3	221
45	73.1	2.98	421	83.0	64.0	49.0	215
44	72.5	3.02	409	82.5	63.1	47.8	208
43	72.0	3.05	400	82.0	62.2	46.7	201
42	71.5	3.09	390	81.5	61.3	45.5	194
41	70.9	3.13	381	80.9	60.4	44.3	188
40	70.4	3.17	371	80.4	59.5	43.1	182
39	69.9	3.21	362	79.9	58.6	41.9	177
38	69.4	3.24	353	79.4	57.7	40.8	171
37	68.9	3.29	344	78.8	56.8	39.6	166
36	68.4	3.32	336	78.3	55.9	38.4	161
35	67.9	3.37	327	77.7	55.0	37.2	156
34	67.4	3.41	319	77.2	54.2	36.1	152
33	66.8	3.45	311	76.6	53.3	34.9	149
32	66.3	3.49	304	76.1	52.1	33.7	146
31	65.8	3.55	294	75.6	51.3	32.5	141
30	65.3	3.59	286	75.0	50.4	31.3	138
29	64.6	3.64	279	74.5	49.5	30.1	135
28	64.3	3.69	271	73.9	48.6	28.9	131
27	63.8	3.73	264	73.3	47.7	27.8	128
26	63.3	3.78	258	72.8	46.8	26.7	125
25	62.8	3.81	253	72.2	45.9	25.5	123
24	62.4	3.86	247	71.6	45.0	24.3	119
23	62.0	3.89	243	71.0	44.0	23.1	117
22	61.5	3.93	237	70.5	43.2	22.0	115
21	61.0	3.98	231	69.9	42.3	20.7	112
20	60.5	4.02	226	69.4	41.5	19.6	110

**3000 kfg load, 10 mm ball. A tungsten carbide ball must be used above HB 450. Brinell testing is not recommended above HB 630..*

Hardness Conversion Tables – Non-Austenitic Steels (continued)

Approximate Hardness Conversions for Non-Austenitic Steels

Rockwell		Brinell*		Superficial			Approx. vTensile
B	A	Dia.(mm)	Number	15T	30T	45T	
100	61.5	3.91	240	93.1	83.1	72.9	116
99	60.9	3.96	234	92.8	82.5	71.9	114
98	60.2	4.01	228	92.5	81.8	70.9	109
97	59.5	4.06	222	92.1	81.1	69.9	104
96	58.9	4.11	216	91.8	80.4	68.9	102
95	58.3	4.17	210	91.5	79.8	67.9	100
94	57.6	4.21	205	91.2	79.1	66.9	98
93	57.0	4.26	200	90.8	78.4	65.9	94
92	56.4	4.32	195	90.5	77.8	64.8	92
91	55.8	4.37	190	90.2	77.1	63.8	90
90	55.2	4.43	185	89.9	76.4	62.8	89
89	54.6	4.48	180	89.5	75.8	61.8	88
88	54.0	4.53	176	89.2	75.1	60.8	86
87	53.4	4.58	172	88.9	74.4	59.8	84
86	52.8	4.62	169	88.6	73.8	58.8	83
85	52.3	4.67	165	88.2	73.1	57.8	82
84	51.7	4.71	162	87.9	72.4	56.8	81
83	51.1	4.75	159	87.6	71.8	55.8	80
82	50.6	4.79	156	87.3	71.1	54.8	77
81	50.0	4.84	153	86.9	70.4	53.8	73
80	49.5	4.88	150	86.6	69.7	52.8	72
79	48.9	4.93	147	86.3	69.1	51.8	70
78	48.4	4.98	144	86.0	68.4	50.8	69
77	47.9	5.03	141	85.6	67.7	49.8	68
76	47.3	5.06	139	85.3	67.1	48.8	67
75	46.8	5.09	137	85.0	66.4	47.8	66
74	46.3	5.13	135	84.7	65.7	46.8	65
73	45.8	5.18	132	84.3	65.1	45.8	64
72	45.3	5.22	130	84.0	64.4	44.8	63
71	44.8	5.27	127	83.7	63.7	43.8	62
70	44.3	5.31	125	83.4	63.1	42.8	61
69	43.8	5.35	123	83.0	62.4	41.8	60
68	43.3	5.39	121	82.7	61.7	40.8	59
67	42.8	5.43	119	82.4	61.0	39.8	58
66	42.3	5.48	117	82.1	60.4	38.7	57
65	41.8	5.50	116	81.8	59.7	37.7	56
64	41.4	5.54	114	81.4	59.0	36.7	---
63	40.9	5.59	112	81.1	58.4	35.7	---
62	40.4	5.63	110	80.8	57.7	34.7	---
61	40.0	5.68	108	80.5	57.0	33.7	---
60	39.5	5.70	107	80.1	56.4	32.7	---
59	39.0	5.73	106	79.8	55.7	31.7	---
58	38.6	5.78	104	79.5	55.0	30.7	---
57	38.1	5.80	103	79.2	54.4	29.7	---
56	37.7	5.85	101	78.8	53.7	28.7	---
55	37.2	5.88	100	78.5	53.0	27.7	---
22	61.5	3.93	237	70.5	43.2	22.0	115
21	61.0	3.98	231	69.9	42.3	20.7	112
20	60.5	4.02	226	69.4	41.5	19.6	110

**3000 kgf load, 10 mm ball*

Conversion Tables

Decimal Equivalents of Millimeters

MM	Inches
25	.98425
26	1.02362
27	1.06299
28	1.10236
29	1.14173
30	1.18110
31	1.22047
32	1.25984
33	1.29921
34	1.33858
35	1.37795
36	1.41732
37	1.45669
38	1.49606
39	1.53543
40	1.57480
41	1.61417
42	1.65354
43	1.69291
44	1.73228
45	1.77165
46	1.81102
47	1.85039
48	1.88976
49	1.92913
50	1.96850
51	2.00787
52	2.04724
53	2.08661
54	2.12598
55	2.16535
56	2.20472
57	2.24409
58	2.28346
59	2.32283
60	2.36220
61	2.40157
62	2.44094
63	2.48031

MM	Inches
64	2.51968
65	2.55905
66	2.59842
67	2.63779
68	2.67716
69	2.71653
70	2.75590
71	2.79527
72	2.83464
73	2.87401
74	2.91338
75	2.95275
76	2.99212
77	3.03149
78	3.07086
79	3.11023
80	3.14960
81	3.18897
82	3.22834
83	3.26771
84	3.30708
85	3.34645
86	3.38582
87	3.42519
88	3.46456
89	3.50393
90	3.54330
91	3.58267
92	3.62204
93	3.66141
94	3.70078
95	3.74015
96	3.77952
97	3.81889
98	3.85826
99	3.89763
100	3.93700
62	2.44094
63	2.48031
61	40.0
60	39.5
59	39.0
58	38.6
57	38.1
56	37.7
55	37.2
22	61.5
21	61.0
20	60.5

Temperature Conversions

Table compiled by Albert Sauveur. To use, simply refer to figure in middle column; if in degrees Centigrade, read Fahrenheit equivalent in right-hand column; if in degrees Fahrenheit, read Centigrade equivalent in left-hand column.

-459.4 to 0		
C		F
-273	-459.4	---
-268	-450	---
-262	-440	---
-257	-430	---
-251	-420	---
-246	-410	---
-240	-400	---
-234	-390	---
-229	-380	---
-223	-370	---
-218	-360	---
-212	-350	---
-207	-340	---
-201	-330	---
-196	-320	---
-190	-310	---
-184	-300	---
-179	-290	---
-173	-280	---
-169	-273	-459.4
-168	-270	-454
-162	-260	-436
-157	-250	-418
-151	-240	-400
-146	-230	-382
-140	-220	-364
-134	-210	-346
-129	-200	-328
-123	-190	-310
-118	-180	-292
-112	-170	-274
-107	-160	-256
-101	-150	-238
-96	-140	-220
-90	-130	-202
-84	-120	-184
-79	-110	-166
-73	-100	-148
-68	-90	-130
-62	-80	-112
-57	-70	-94
-51	-60	-76
-46	-50	-58
-40	-40	-40
-34	-30	-22
-29	-20	-4
-23	-10	14
-17.8	0	32

0 to 50		
C		F
-17.8	0	32.0
-17.2	1	33.8
-16.7	2	35.6
-16.1	3	37.4
-15.6	4	39.2
-15.0	5	41.0
-14.4	6	42.8
-13.9	7	44.6
-13.3	8	46.4
-12.8	9	48.2
-12.2	10	50.0
-11.7	11	51.8
-11.1	12	53.6
-10.6	13	55.4
-10.0	14	57.2
-9.4	15	59.0
-8.9	16	60.8
-8.3	17	62.6
-7.8	18	64.4
-7.2	19	66.2
-6.7	20	68.0
-6.1	21	69.8
-5.6	22	71.6
-5.0	23	73.4
-4.4	24	75.2
-3.9	25	77.0
-3.3	26	78.8
-2.8	27	80.6
-2.2	28	82.4
-1.7	29	84.2
-1.1	30	86.0
-0.6	31	87.8
0.0	32	89.6
0.6	33	91.4
1.1	34	93.2
1.7	35	95.0
2.2	36	96.8
2.8	37	98.6
3.3	38	100.4
3.9	39	102.2
4.4	40	104.0
5.0	41	105.8
5.6	42	107.6
6.1	43	109.4
6.7	44	111.2
7.2	45	113.0
7.8	46	114.8
8.3	47	116.6
8.9	48	118.4
9.4	49	120.2
10.0	50	122.0

51 to 100		
C		F
10.6	51	123.8
11.1	52	125.6
11.7	53	127.4
12.2	54	129.2
12.8	55	131.0
13.3	56	132.8
13.9	57	134.6
14.4	58	136.4
15.0	59	138.2
15.6	60	140.0
16.1	61	141.8
16.7	62	143.6
17.2	63	145.4
17.8	64	147.2
18.3	65	149.0
18.9	66	150.8
19.4	67	152.6
20.0	68	154.4
20.6	69	156.2
21.1	70	158.0
21.7	71	159.8
22.2	72	161.6
22.8	73	163.4
23.3	74	165.2
23.9	75	167.0
24.4	76	168.8
25.0	77	170.6
25.6	78	172.4
26.1	79	174.2
26.7	80	176.0
27.2	81	177.8
27.8	82	179.6
28.3	83	181.4
28.9	84	183.2
29.4	85	185.0
30.0	86	186.8
30.6	87	188.6
31.1	88	190.4
31.7	89	192.2
32.2	90	194.0
32.8	91	195.8
33.3	92	197.6
33.9	93	199.4
34.4	94	201.2
35.0	95	203.0
35.6	96	204.8
36.1	97	206.6
36.7	98	208.4
37.2	99	210.2
37.8	100	212.0

Temperature Conversions (continued)

110 to 600		
C		F
43	110	230
49	120	248
54	130	266
60	140	284
66	150	302
71	160	320
77	170	338
82	180	356
88	190	374
93	200	392
99	210	410
100	212	413.6
104	220	428
110	230	446
116	240	464
121	250	482
127	260	500
132	270	518
138	280	536
143	290	554
149	300	572
154	310	590
160	320	608
166	330	626
171	340	644
177	350	662
182	360	680
188	370	698
193	380	716
199	390	734
204	400	752
210	410	770
216	420	788
221	430	806
227	440	824
232	450	842
238	460	860
243	470	878
249	480	896
254	490	914
260	500	932
266	510	950
271	520	968
277	530	986
282	540	1004
288	550	1022
293	560	1040
299	570	1058
304	580	1076
310	590	1094
316	600	1112

610 to 1000		
C		F
321	610	1130
327	620	1148
332	630	1166
338	640	1184
343	650	1202
349	660	1220
354	670	1238
360	680	1256
366	690	1274
371	700	1292
377	710	1310
382	720	1328
388	730	1346
393	740	1364
399	750	1382
404	760	1400
410	770	1418
416	780	1436
421	790	1454
427	800	1472
432	810	1490
438	820	1508
443	830	1526
449	840	1544
454	850	1562
460	860	1580
466	870	1598
471	880	1616
477	890	1634
482	900	1652
488	910	1670
493	920	1688
499	930	1706
504	940	1724
510	950	1742
516	960	1760
521	970	1778
527	980	1796
532	990	1814
538	1000	1832

1010 to 1500		
C		F
543	1010	1850
549	1020	1868
554	1030	1886
560	1040	1904
566	1050	1922
571	1060	1940
577	1070	1958
582	1080	1976
588	1090	1994
593	1100	2012
599	1110	2030
604	1120	2048
610	1130	2066
616	1140	2084
621	1150	2102
627	1160	2120
632	1170	2138
638	1180	2156
643	1190	2174
649	1200	2192
654	1210	2210
660	1220	2228
666	1230	2246
671	1240	2264
677	1250	2282
682	1260	2300
688	1270	2318
693	1280	2336
699	1290	2354
710	1310	2390
716	1320	2408
721	1330	2426
727	1340	2444
738	1360	2480
743	1370	2498
749	1380	2516
754	1390	2534
760	1400	2552
766	1410	2570
771	1420	2588
777	1430	2606
782	1440	2624
788	1450	2642
793	1460	2660
799	1470	2678
804	1480	2696
810	1490	2714
816	1500	2732

Temperature Conversions (continued)

1510 to 2000		
C		F
821	1510	2750
827	1520	2768
832	1530	2786
838	1540	2804
843	1550	2822
849	1560	2840
854	1570	2858
860	1580	2876
866	1590	2894
871	1600	2912
877	1610	2930
882	1620	2948
888	1630	2966
893	1640	2984
899	1650	3002
904	1660	3020
910	1670	3038
916	1680	3056
921	1690	3074
927	1700	3092
932	1710	3110
938	1720	3128
943	1730	3146
949	1740	3164
954	1750	3182
960	1760	3200
966	1770	3218
971	1780	3236
977	1790	3254
982	1800	3272
988	1810	3290
993	1820	3308
999	1830	3326
1004	1840	3344
1010	1850	3362
1016	1860	3380
1021	1870	3398
1027	1880	3416
1032	1890	3434
1038	1900	3452
1043	1910	3470
1049	1920	3488
1054	1930	3506
1060	1940	3524
1066	1950	3542
1071	1960	3560
1077	1970	3578
1082	1980	3596
1088	1990	3614
1093	2000	3632

2000 to 2500		
C		F
1093	2000	3632
1099	2010	3650
1104	2020	3668
1110	2030	3686
1116	2040	3704
1121	2050	3722
1127	2060	3740
1132	2070	3758
1138	2080	3776
1143	2090	3794
1149	2100	3812
1154	2110	3830
1160	2120	3848
1166	2130	3866
1171	2140	3884
1177	2150	3902
1182	2160	3920
1188	2170	3938
1193	2180	3956
1199	2190	3974
1204	2200	3992
1210	2210	4010
1216	2220	4028
1221	2230	4046
1227	2240	4064
1232	2250	4082
1238	2260	4100
1243	2270	4118
1249	2280	4136
1254	2290	4154
1260	2300	4172
1266	2310	4190
1271	2320	4208
1277	2330	4226
1282	2340	4244
1288	2350	4262
1293	2360	4280
1299	2370	4298
1304	2380	4316
1310	2390	4334
1316	2400	4352
1321	2410	4370
1327	2420	4388
1332	2430	4406
1338	2440	4424
1343	2450	4442
1349	2460	4460
1354	2470	4478
1360	2480	4496
1366	2490	4514
1371	2500	4532

2510 to 3000		
C		F
1377	2510	4550
1382	2520	4568
1388	2530	4586
1393	2540	4604
1399	2550	4622
1404	2560	4640
1410	2570	4658
1416	2580	4676
1421	2590	4694
1427	2600	4712
1432	2610	4730
1438	2620	4748
1443	2630	4766
1449	2640	4784
1454	2650	4802
1460	2660	4820
1466	2670	4838
1471	2680	4856
1477	2690	4874
1482	2700	4892
1488	2710	4910
1493	2720	4928
1499	2730	4946
1504	2740	4964
1510	2750	4982
1516	2760	5000
1521	2770	5018
1527	2780	5036
1532	2790	5054
1538	2800	5072
1543	2810	5090
1549	2820	5108
1554	2830	5126
1560	2840	5144
1566	2850	5162
1571	2860	5180
1577	2870	5198
1582	2880	5216
1588	2890	5234
1593	2900	5252
1599	2910	5270
1604	2920	5288
1610	2930	5306
1616	2940	5324
1621	2950	5342
1627	2960	5360
1632	2970	5378
1638	2980	5396
1643	2990	5414
1649	3000	5432

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