CARPENTER
Specialty Alloys

Alloys for Corrosive Environments

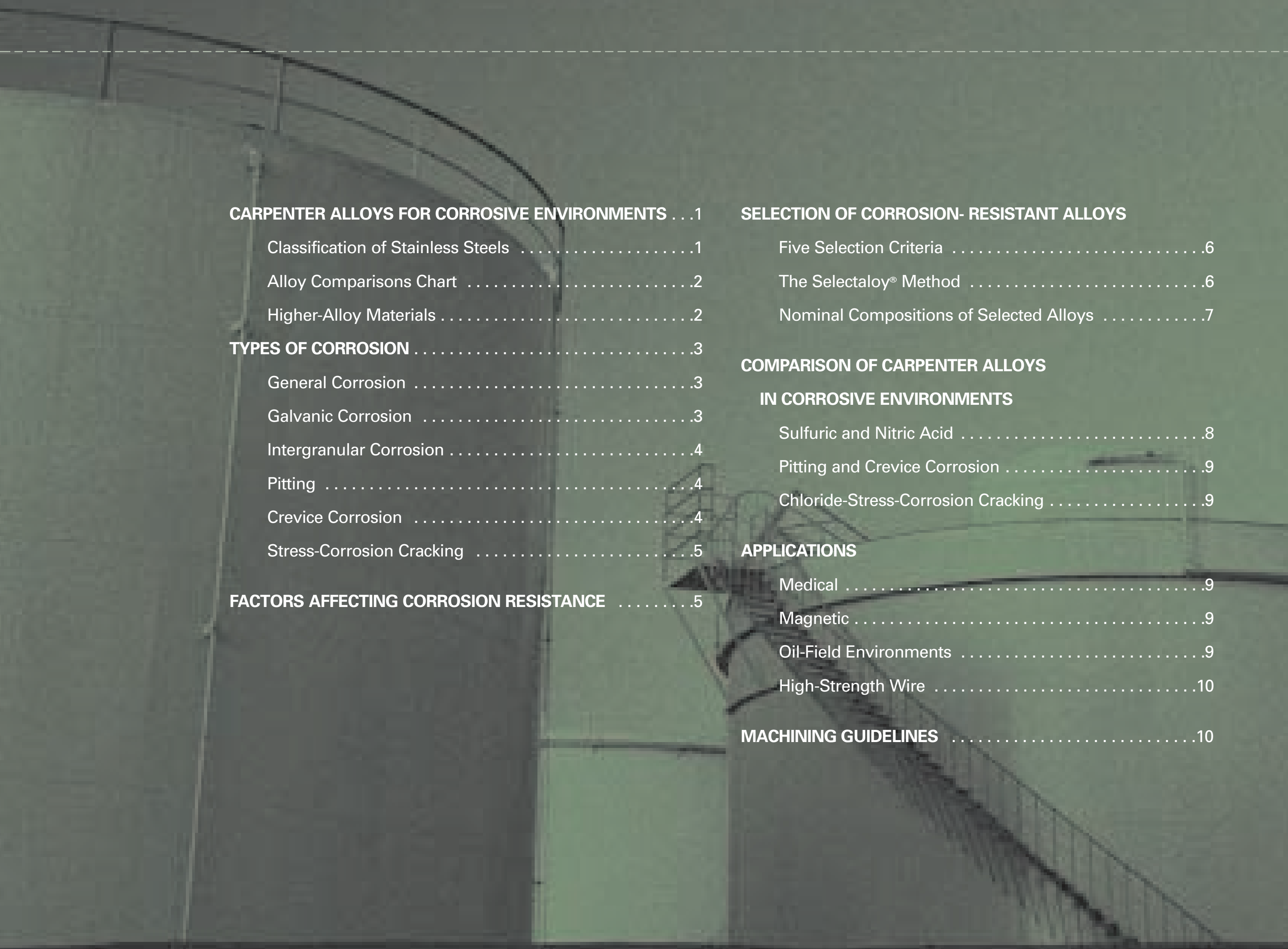
Specialty Alloys Operations produces hundreds of types of stainless steels, high temperature (iron-nickel-cobalt-base) alloys, magnetic alloys and other specialty materials. SAO is an ISO-registered business unit of Carpenter Technology Corporation.

Carpenter alloys may be found wherever critical material challenges exist, including a wide range of corrosive environments. This booklet may be helpful in selecting the appropriate material for your application.

Corrosion is the deterioration that occurs when a metal reacts with its environment. One way to effectively control corrosion is to select a construction material with the required level of corrosion resistance from alloys such as stainless steels and other highly alloyed metals. Since no single alloy is suitable for every application, you also need to consider factors such as strength, availability and ease of fabrication. Table 1 on page 2 can help put this material selection process into perspective.

In addition, free detailed, searchable technical information is available through Carpenter's Web site, **www.cartech.com**. Of course, neither the booklet nor the technical information is meant to replace the expertise of a corrosion engineer, but they can provide useful starting points on the subject of corrosives.

If you would like to discuss any of Carpenter's specialty metal alloys, get in touch with a Carpenter regional metallurgist or application engineer. Visit us at **www.cartech.com** or call 800-654-6543 in the U.S.



SELECTION OF CORROSION- RESISTANT ALLOYS

COMPARISON OF CARPENTER ALLOYS IN CORROSIVE ENVIRONMENTS

APPLICATIONS

Typically, stainless steels are alloys of iron to which a minimum of about 11% chromium has been added to provide a passive film to resist “rusting” when the material is exposed to the weather. This invisible film is self-forming and self-healing in environments where the stainless steel is resistant.

To obtain greater corrosion resistance, more chromium is added to the alloy. Stainless steels can contain chromium contents of 15%, 17%, 20% and even higher. This element provides resistance to oxidizing environments, such as nitric acid, and provides resistance to pitting and crevice attack. These and other forms of corrosion are discussed in the next section.

Other alloying elements are added for improved corrosion resistance or higher strength. Molybdenum is probably the most effective element for improving pitting and crevice corrosion resistance. Nickel provides resistance to reducing environments and affects resistance to stress corrosion cracking. Nitrogen may also be added to increase strength and, together with other elements, improve resistance to pitting or crevice attack.

Copper is added to improve resistance to general corrosion in sulfuric acid and to strengthen some precipitation-hardenable grades. In sufficient amounts, however, copper reduces pitting resistance of some alloys.

Columbium and titanium act to stabilize carbon. That is, they form carbides and reduce the carbon available to form chromium carbides, which can be deleterious to corrosion resistance. These elements, along with aluminum, can also be used to age harden iron- and nickel-base alloys.

CLASSIFICATION OF STAINLESS STEELS

Conventional ferritic stainless steels, such as Type 430, are alloys of iron and chromium. Ferritic stainless steels possess a body-centered cubic lattice structure, are magnetic and can be strengthened only moderately by cold work. These steels have low solubility for interstitial elements such as carbon and nitrogen which can form intergranular precipitates and reduce corrosion resistance. They tend to be embrittled in the vicinity of 885°F (475°C) and form sigma phase at about 1400°F (760°C). Care must be exercised in fabrication of many of these grades if the corrosion resistance, ductility and impact strength are to be maintained.

Austenitic stainless steels contain chromium and one or more elements to stabilize the austenitic face-centered cubic lattice structure. Nickel is conventionally added for this purpose, but manganese, nitrogen, carbon and copper also stabilize austenite. Molybdenum, columbium, and titanium are not austenite stabilizers but are among the elements that may be added to produce desired corrosion resistance or strength properties.

Annealed austenitic stainless steels typically have low strength but possess good ductility and toughness. The strength can be increased by cold working or by alloying with nitrogen (e.g. as in 22Cr-13Ni-5Mn stainless or 25Ni-20Cr-6Mo alloy). The austenitic grades have a higher solubility for interstitial elements than the ferritic stainless steels. They are not susceptible to 885°F (475°C) embrittlement and do resist the formation of sigma phase. The austenitic grades are generally easier to fabricate than the ferritic grades and are often used when heavier sections or welding are involved. Examples of austenitic stainless steels range from 18% Cr-8% Ni types to highly alloyed materials such as 20Mo-6® HS stainless steel.

Duplex stainless steels are alloys containing both austenite and ferrite, often in about equal proportions. These materials typically contain chromium and molybdenum for resistance to uniform or general corrosion and for resistance to pitting attack in chloride media. Nickel and nitrogen are added to stabilize the austenite phase. Generally, these materials have annealed yield strengths about twice that of the conventional austenitic stainless steels and also possess good ductility and impact strength. Duplex stainless steels are susceptible to 885°F (475°C) embrittlement and to the formation of sigma phase, but tend to be more resistant to the deleterious effects of these phenomena than ferritic stainless steels. Examples include 7-Mo PLUS® stainless and Carpenter 2205 stainless steel.

Martensitic stainless steels contain relatively lower levels of chromium with sufficient carbon to permit martensite formation with rapid cooling. Martensite is a body-centered tetragonal structure that provides increased strength and hardness over annealed stainless with other lattice structures. Martensitic grades, such as Type 410, are tempered after hardening to increase toughness. Other elements, such as nickel and

TABLE 1–ALLOY COMPARISONS

IMPROVING LEVELS OF CORROSION RESISTANCE	CHLORIDE PITTING AND CREVICE CORROSION	CHLORIDE STRESS CORROSION CRACKING	SULFURIC ACID	MEDICAL (ORTHOPEDIC)	MAGNETIC APPLICATIONS (Water and mild Chemicals)	OIL FIELD ENVIRONMENTS	HIGH STRENGTH WIRE (Cold drawn or cold drawn & aged)
OUTSTANDING	C-276 Custom Age 625 PLUS®[1] and Pyromet® 625	C-276 Custom Age 625 PLUS[1] and Pyromet® 625 Ni-Cu 400[2]	C-276 20Cb-3®	BioDur® CCM Plus® CCM Alloys MP35N[4] Carpenter L-605	Chrome Core® 29	C-276 Custom Age 625 PLUS[1] and Pyromet® 625	C-276 MP35N[1, 4] Custom Age 625 PLUS[1] 20Mo-6 HS
SUPERIOR	20Mo-6® and 25Ni-20Cr-6Mo	20Mo-6® and 825 PLUS[1] 20Mo-4® 20Cb-3®	Custom Age 625 PLUS[1] and Pyromet® 625 20Mo-4® 20Mo-6® Ni-Cu 400[2]	BioDur 108 and 22Cr-13Ni-5Mn	Chrome Core 18-FM Types 430F and 430FR	Pyromet® 718	Pyromet® 718[1]
EXCELLENT	20Mo-4®, 7-Mo PLUS® and 2205 22Cr-13Ni-5Mn	25Ni-20Cr-6Mo 7-Mo PLUS® and 2205		Type 316, BioDur 316LS Gall-Tough® PLUS	Chrome Core 13-FM Chrome Core 12 Chrome Core 12-FM	825 PLUS[1] 25Ni-20Cr-6Mo 20Mo-4® 20Cb-3®	825 PLUS[1]
GOOD	825 PLUS[1] Ni-Cu 400[2] 20Cb-3® Type 316	22Cr-13Ni-5Mn Type 316	25Ni-20Cr-6Mo 7-Mo PLUS® 22Cr-13Ni-5Mn 2205 Type 316	Types 304, 304L Gall-Tough®	Chrome Core 8 Chrome Core 8-FM	22Cr-13Ni-5Mn Type 316, A-286[1] and 2205 15-15LC® Mod and 15-15HS[3] Custom 450®	22Cr-13Ni-5Mn A-286[1]

[1] Aged Condition. [2] Resistance varies considerably with aeration or oxidizing impurities. [3] Candidates for drilling applications. [4] MP35N is a registered trademark of SPS Technologies, Inc. MP is a registered trademark of SPS Technologies, Inc.

molybdenum, may be added for improved corrosion resistance and mechanical properties.

Precipitation-hardening stainless steels contain chromium and nickel and are strengthened by aging due to the presence of elements such as copper, columbium, titanium or aluminum. Molybdenum may be added for corrosion resistance, and columbium may be used to stabilize carbon. Examples of the martensitic precipitation-hardenable grades include Custom 450®, Custom 455® and Custom 465® stainless steels.

HIGHER-ALLOY MATERIALS

Some environments require corrosion resistance greater than that provided by the conventional stainless steels. High levels of elements such as nickel, molybdenum, copper and chromium may be used to obtain resistance for a wide variety of applications, including medical implant, oil field and chemical process environments. Many of these highly alloyed materials can be viewed as extensions of the austenitic stainless steels. Many are hardenable only by cold work, such as Pyromet® 625 and Nickel-Copper 400 alloy. Some materials, such as Custom Age 625 PLUS® alloy, are age hardenable and additions such as columbium, titanium and aluminum are used for that purpose.

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 can be relatively high. Localized corrosion includes intergranular corrosion, stress corrosion cracking, pitting and crevice corrosion. All metals and alloys are subject to these two basic types of corrosion.

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”; i.e., a regular rate of metal loss over the entire surface. General corrosion is portrayed in Figure 1 showing two samples of stainless steel, one that has not been corroded and one that has experienced severe general corrosion.

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.

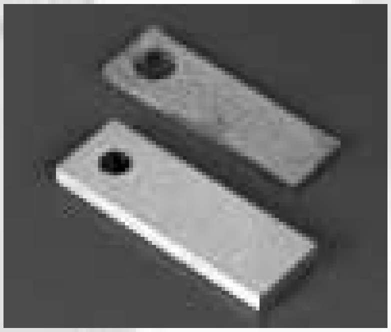


Figure 1: Examples of uncorroded test piece and severe general corrosion.

GALVANIC CORROSION

Galvanic corrosion may occur when two dissimilar metals are in contact in an electrolyte (this includes most aqueous solutions).

The general corrosion resistance of stainless steel is expected to be reduced when in contact with noble metals or 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.

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 top of the list is the one more 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.

Although the more resistant alloy of a galvanic couple is protected from general corrosion, it may be susceptible to crack-

TABLE 2–
GALVANIC SERIES OF METALS AND ALLOYS

INCREASING CORROSION ↑

CORRODED END (ANODIC, OR LEAST NOBLE)
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)
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)
Silver
Graphite
Zirconium
Gold
Platinum
PROTECTED END (CATHODIC, OR MOST NOBLE)

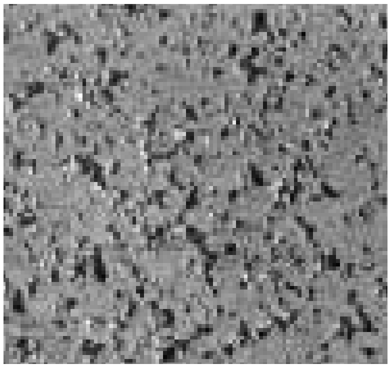


Figure 2: Intergranular Corrosion

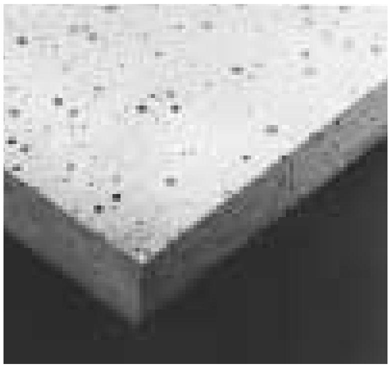


Figure 3: Pit-type Corrosion

Figure 4: Crevice Corrosion (O-Ring moved)

ing due to hydrogen embrittlement. This phenomenon is of more concern with high-strength materials. See the section on stress-corrosion cracking on page 5.

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.

INTERGRANULAR CORROSION

Intergranular corrosion is very rarely a problem if the material is used in the “mill-annealed” or equivalent condition. A knowledge of intergranular corrosion is only necessary if the alloy is to be heated to elevated temperatures [above about 800°F (427°C)] 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 900/1500°F (482/816°C), 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 or duplex alloys can be avoided by:

a. Using only in the annealed (1700/2100°F, 927/1149°C) or equivalent condition, 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.

b. Using alloys with low carbon, such as Type 304L and Type 316L.

c. Using alloys that are “stabilized” by the addition of a carbide former such as columbium or titanium; e.g., Type 347, Type 321 and 20Cb-3® stainless. The columbium and titanium combine with the carbon in these alloys, preventing the formation of deleterious chromium-rich carbides. These alloys are preferably annealed in the range 1600/1850°F (871/1010°C) to promote the formation of columbium or titanium carbide.

PITTING

Under certain conditions of service, stainless steels which 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. A common cause of pitting is lack of surface cleanliness. If scale, corrosion products, shop dirt, etc., are allowed to deposit on a stainless steel surface, then metal immediately underneath the deposit often does not have ready access to oxygen, which is required to maintain the corrosion-resistant surface film. Corrosion can initiate under the deposit and may be further accelerated by local chemistry changes in the corrodent beneath the deposit.

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, and they are more likely to permit concentration of damaging species, such as chlorides, in the pitted areas. Molybdenum-bearing grades are used for their improved pitting resistance.

CREVICE CORROSION

Crevices formed by metal-to-metal contact or at gaskets, etc., can lead to localized corrosion in the crevice (see Figure 4). Lack of oxygen and buildup of acids and contaminants (e.g., chlorides) within the crevice are the causes of this problem. Like pitting, crevice corrosion is more likely to occur in chloride solutions, and the molybdenum-bearing grades are more resistant to it. Higher-nickel alloys may be required to resist pitting, crevice corrosion and general attack in low-pH, chloride environments.

Figure 5: Micrograph of stress-corrosion cracking.

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.

Stress-corrosion cracking in stainless steels and higher alloys 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 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 more susceptible to cracking in hot chloride solutions 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 more 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 rule is generally applicable to other alloy systems (e.g. nickel-base materials).

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 120°F (about 50°C). Resistance at higher temperatures is possible in some environments. On the

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. Contact Carpenter for information regarding passivation.

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

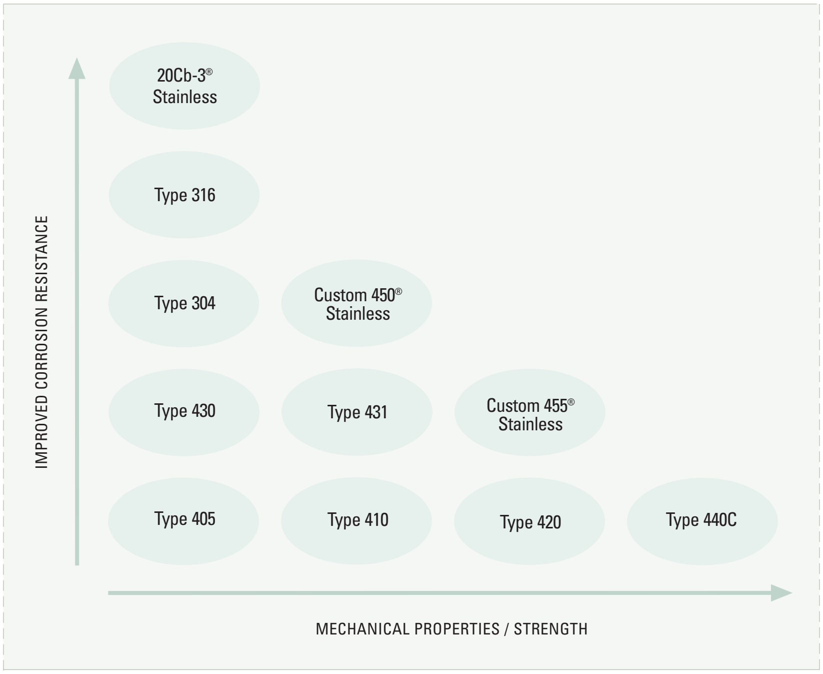
C. Thermal treatment in fabrication. Welding or stress relieving can affect resistance to corrosion, particularly to stress-corrosion cracking and intergranular corrosion.

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

other hand, low pH, the use of sensitized material 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.

Figure 6: Selectaloy® Diagram



SELECTION OF CORROSION-RESISTANT ALLOYS

These five criteria, listed in order of importance, may assist you in selecting corrosion-resistant alloys:

1. **Corrosion Resistance.** First, choose candidate materials to resist corrosion in the service environment. Cost-effective alloys will have sufficient resistance to provide the desired service life without incurring the unnecessary expense of "overalloying."
2. **Mechanical Properties.** Along with alloy strength, consider hardness, fatigue, impact and stress rupture properties. Together with the corrosion resistance factor, the mechanical properties designate the specific alloy type for the application.
3. **Fabrication Operations.** After considering corrosion resistance and mechanical properties, examine the processing that the alloy will need to undergo. Alloys react differently to machining, welding, cold heading, deep drawing, brazing and other fabricating operations.
4. **Total Cost.** Determine the overall value analysis of the material, including initial alloy price, installed cost, and the effective life expectancy of the finished product. Both the material and fabrication cost must be considered for cost-effective design. Finished parts of a more expensive alloy may actually cost less due to reduced expense in fabrication.
5. **Product Availability.** Consider availability of the raw material and minimum purchase requirements in choosing the most economical and practical material.

THE SELECTALOY® METHOD

The Carpenter Selectaloy method was designed to assist engineers in the selection of appropriate stainless steels for a variety of applications. Figure 6 can guide you in selecting an alloy based on the combination of corrosion resistance and strength requirements. Variations of certain alloys may be selected to optimize properties such as headability, machinability or galling resistance as shown in Figure 7.

Two properties may be improved in one alloy. For example, Type 302HQ-FM is designed to optimize cold headability and machinability.

Additional grades are available to provide the best material for a wide variety of corrosive environments and applications. Typical compositions appear in Table 3 and include the following:

Figure 7: Alloy Families Designed for Improved Fabricability or Utility

	TYPE 304 COLD HEADING	TYPE 304 MACHINABILITY	TYPE 410 MACHINABILITY	TYPE 304 GALLING	TYPE 316 GALLING
▲ IMPROVED PROPERTY	Carpenter No. 10	Project 70+® Type 303	No. 5-F*	Gall-Tough®	Gall-Tough PLUS
			Project 70+ Type 416		
	Type 302HQ	Type 303			
	Type 305	Type 303 Se	Type 416		
	Type 304	Type 304	Type 410	Type 304	Type 316

*Not hardenable

- The high-alloy austenitic stainless steels provide resistance to general corrosion and several forms of localized attack, along with high levels of ductility and toughness.
- Duplex stainless 7-Mo PLUS® and Carpenter 2205 stainless provide excellent corrosion resistance, and have about twice the yield strength of the typical austenitic stainless steels.
- The nickel-base alloys provide resistance to very severe environments. For example, Custom Age 625 PLUS® alloy may be considered a candidate for service in elevated-temperature oil field environments that may contain brine, hydrogen sulfide, carbon dioxide and elemental sulfur.
- TrimRite® stainless has been used for high-strength self-tapping fasteners, cutlery, conveyor chain, valve parts and instruments.

TABLE 3–NOMINAL COMPOSITIONS OF SELECTED ALLOYS

	Percent by Weight (Balance Iron)												
	C	Mn	Si	S	Cr	Ni	Mo	Cu	Cb	Ti	Al	N	Other
Selected Martensitic and Precipitation Hardenable Stainless Steels													
TrimRite®	0.2	0.5	0.4	–	14	0.6	0.6	–	–	–	–	–	–
Custom 450®	0.03	0.5	0.4	–	15	6.5	0.75	1.5	0.6	–	–	–	–
Custom 455®	0.01	0.3	0.3	–	12	8.5	–	2	0.3	1.1	–	–	–
Custom 465®	0.01	0.1	0.1	–	11.5	11	1	–	–	1.6	–	–	–
Austenitic Stainless Steel													
Project 70+® Type 303	0.02	1.8	0.4	0.35	18	9	–	–	–	–	–	–	–
Type 305	0.02	0.8	0.5	–	18.5	12	–	–	–	–	–	–	–
Custom Flo 302HQ	0.01	1.5	0.4	–	18	9.5	–	3.8	–	–	–	–	–
Carpenter No. 10	0.02	0.8	0.4	–	16	17.5	–	–	–	–	–	–	–
Gall–Tough®	0.1	5.5	3.5	–	16	5	–	–	–	–	–	0.12	–
15–15LC® Modified	0.04	18	0.4	–	17.5	1	1	–	–	–	–	0.5	–
15–15HS	0.02	18	0.4	–	19	2	1	–	–	–	–	0.6	–
Type 316	0.05	1.7	0.5	–	17.5	12.5	2.5	–	–	–	–	–	–
Gall–Tough PLUS	0.9	7.5	3.8	–	17.5	8.5	0.7	–	–	–	–	0.15	–
22Cr–13Ni–5Mn	0.02	5.0	0.4	–	22	12.5	2.3	–	0.2	–	–	0.3	V
25Ni–20Cr–6Mo	0.02	0.5	0.4	–	20.3	25.0	6.5	1	–	–	–	0.2	–
20Cb–3®	0.02	0.4	0.3	–	20	33.0	2.2	3.2	0.5	–	–	–	–
20Mo–6® HS	0.05	0.8	0.3	–	24	36.5	5.7	1.1	–	–	–	0.3	–
Soft Magnetic Ferritic Stainless													
Chrome Core® 29	0.02	0.4	0.5	–	28.5	–	–	–	–	–	–	–	–
Chrome Core 18-FM	0.01	0.4	0.9	0.3	17.5	0.2	1.8	–	0.25	–	–	–	–
Type 430FR	0.02	0.4	1.3	0.3	17.5	–	0.3	–	–	–	–	–	–
Chrome Core 13-FM	0.02	1	1.5	0.3	13	–	0.3	–	–	–	–	–	–
Chrome Core 12-FM	0.02	0.4	0.5	0.3	12	–	0.3	–	–	–	–	–	–
Chrome Core 8-FM	0.02	0.4	0.5	0.3	8	–	0.3	–	–	–	–	–	–
Duplex Stainless Steel													
7–Mo PLUS®	0.02	0.4	0.3	–	26.5	4.8	1.5	–	–	–	–	0.2	–
Carpenter 2205	0.02	0.4	0.3	–	22	5.5	3	–	–	–	–	0.2	–
Nickel or Cobalt–Base Alloys													
Pyromet® 625	0.04	0.05	0.05	–	22	62	9	–	3.9	–	0.2	–	–
Carpenter Alloy 825 PLUS	0.02	0.5	0.4	–	21	42	3	2.2	–	2.1	0.3	–	–
Custom Age 625 PLUS®	0.01	0.05	0.05	–	20.5	61.0	8.5	–	3.4	1.3	0.2	–	–
Pyromet 718	0.03	0.05	0.1	–	18.5	52.5	3	–	5	1	0.5	–	–
Carpenter C–276	0.005	0.4	0.03	–	16	57	16	–	–	–	–	–	W, V
MP35N*	0.005	0.1	0.1	–	20	35	9.5	–	–	0.75	–	–	35%Co
Carpenter L–605	0.08	1.5	0.2	–	20	10	–	–	–	–	–	–	15%W, 51%Co
BioDur® CCM®	0.05	0.7	0.7	–	28	–	6	–	–	–	–	0.15	65%Co
BioDur 108	0.04	23	0.3	–	21	–	0.7	–	–	–	–	1.0	–

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

Carpenter has developed a method similar to the Selectaloy® system to facilitate selection of the corrosion-resistant alloys listed in Table 3. These charts, showing susceptibility to attack in pertinent environments or by specific forms of corrosion, begin on this page.

The typical strength level is plotted on the horizontal axis, but other strengths can be obtained for each alloy by varying the processing. Annealed strength levels are used in most cases, except when other conditions are typical. For example, Custom Age 625 PLUS® alloy is aged, and high-strength wire is either cold drawn or cold drawn plus aged. Resistance to each form of corrosion is also plotted based on material in this typical condition. When materials are used in other conditions (for example as-welded), care must be taken to assure that corrosion and mechanical properties are maintained.

Generally, alloy cost increases as corrosion resistance improves. While there are exceptions to this rule, materials with improved corrosion resistance often contain higher levels of molybdenum, nickel or other more costly alloying elements. Manufacturing costs also affect the final selling price of a material, especially when the alloy is difficult to produce.

COMPARISON OF CARPENTER ALLOYS IN CORROSIVE ENVIRONMENTS

SULFURIC AND NITRIC ACID

Sulfuric acid is an example of an environment that typically causes general corrosion. Figure 8 provides an overall ranking of several alloys in pure sulfuric acid.

The severity of attack in sulfuric acid varies widely with the temperature, concentration and aeration of the acid. Aeration is generally beneficial to higher chromium materials and deleterious to nickel-copper alloys. Increased velocity may be expected to increase attack of all materials.

Some impurities, such as iron, copper or chromium ions, reduce attack of stainless steels in sulfuric acid. While oxidizing impurities are beneficial for stainless steels, they are deleterious for nickel-copper alloys.

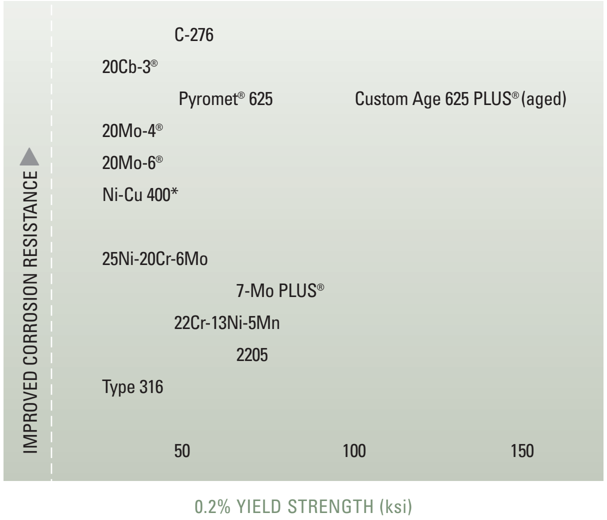
Impurities such as chlorides often result in increased general attack and can cause pitting or stress-corrosion cracking. Materials with insufficient nickel content can also experience cracking in pure sulfuric acid. It is usually wise to confirm that a material chosen for resistance to general corrosion does not exhibit stress-corrosion cracking in the environment of interest.

Generally, Cr-Ni-Mo-Cu alloys with nickel content similar to that of 20Cb-3® stainless or higher are candidates for resisting cracking and general corrosion in a wide variety of sulfuric acid environments.

Several alloys in Figure 8 are useful in specific sulfuric acid environments. Conventional stainless steels such as Type 316 have limited utility, and may be considered for only very dilute or highly concentrated acid at low temperatures. Slightly improved resistance in these concentration ranges may be obtained using higher-chromium materials such as 7-Mo PLUS® or 22Cr-13Ni-5Mn stainless steel. Improved resistance to intermediate concentrations may be obtained with alloys having higher nickel, such as 25Ni-20Cr-6Mo stainless and, particularly, 20Cb-3 stainless steel. Nickel-Copper 400 alloy is a candidate for air-free sulfuric acid environments but is readily attacked in air-saturated solutions.

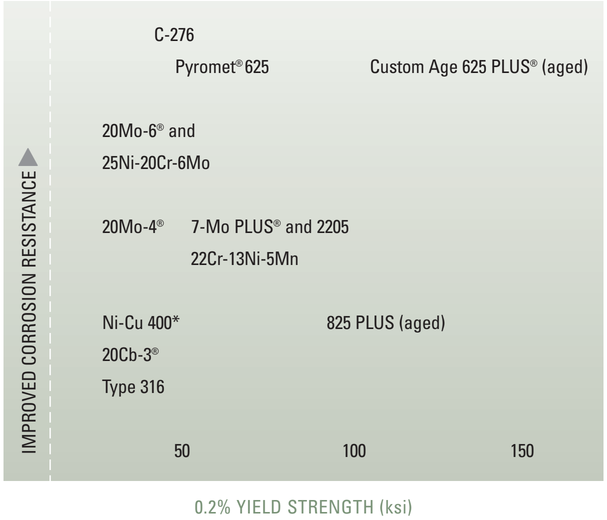
Nitric acid is another example of an environment that can cause general corrosion. Because this acid is oxidizing, alloys with higher chromium are expected to provide improved resistance. Type 316 has useful resistance, 22Cr-13Ni-5Mn stainless is highly resistant, and 7-Mo PLUS stainless is considered for the

Figure 8: Resistance to General Corrosion in Sulfuric Acid



*Resistance varies considerably with aeration or oxidizing impurities.

Figure 9: Resistance to Chloride Pitting/Crevice Corrosion



*Resistance varies considerably with aeration or oxidizing impurities.

most severe service. Materials with lower chromium have very limited utility. Nitric acid can also cause intergranular attack of sensitized materials due to precipitation of carbides or sigma phase at the grain boundaries. Because of this, the Huey test (ASTM A262, boiling 65% nitric acid) is usually employed to screen materials prior to nitric acid service.

PITTING AND CREVICE CORROSION

As seen earlier in this booklet, pitting and crevice corrosion may proceed by essentially the same mechanism. Refer to Figure 9 for an alloy comparison. This figure may be applicable in many environments where chloride pitting rather than general corrosion is expected to occur, such as sea water.

Resistance of stainless steels to pitting and crevice attack is improved by increased chromium and molybdenum, with nitrogen providing benefits in duplex alloys and many austenitic grades. Resistance of austenitic alloys depends upon nickel and sometimes nitrogen to provide stability of the austenite phase and prevent precipitation of sigma or other deleterious phases.

The position of Nickel-Copper 400 in Figure 9 can vary widely with the environment. Nickel-copper alloys have useful resistance to many salt solutions but are not resistant to most oxidizing salts, such as ferric chloride.

CHLORIDE-STRESS-CORROSION CRACKING

Figure 10 summarizes resistance to chloride-stress-corrosion cracking. Resistance to this form of corrosion is strongly affected by nickel content. The resistance decreases as nickel is increased from residual to about 8% and then increases with further nickel additions to about 45%. Materials with about 25% nickel resist cracking in many service environments, and alloys with greater than about 30% nickel are candidates for more severe applications.

Stainless steels with increased molybdenum have provided improved resistance to chloride-stress-corrosion cracking in environments such as aqueous sodium chloride. Service experience has shown that duplex stainless steels have provided resistance superior to that of Type 316 stainless steel. Care must be exercised in welding duplex stainless steels to maintain corrosion resistance and mechanical properties.

APPLICATIONS

MEDICAL

Figure 11 shows candidate alloys for a range of medical applications. For instruments, alloys such as Type 420 and Type 440 have provided edge retention in mild environments, while Custom 455® stainless provided strength and slightly improved corrosion resistance. Further improved corrosion resistance with lower hardness is obtained with 22Cr-13Ni-5Mn stainless and BioDur® 108 alloy. For example, BioDur 108 can be considered a candidate for implantable orthopedic applications such as bone plates, bone screws and spinal fixation components. BioDur Carpenter CCM® alloy and BioDur CCM Plus® alloy may be considered for joint replacement and fracture fixation devices.

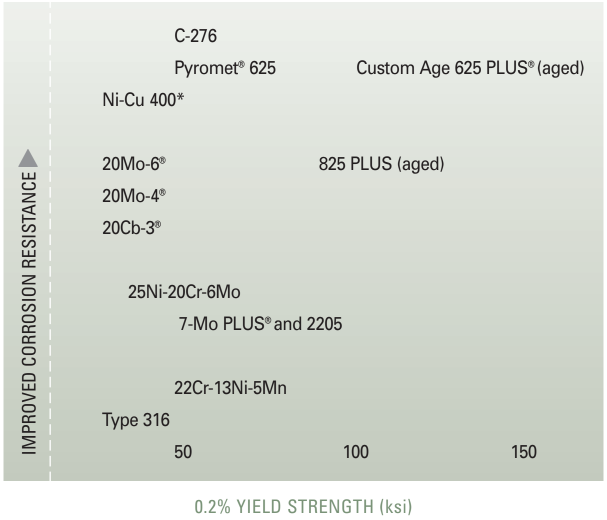
MAGNETIC

Components such as solenoid valves and fuel injectors must operate efficiently using the magnetic field produced by an electric current. Therefore, alloys for magnetic applications must resist corrosion. Figure 12 lists several magnetic alloys that have been used in various corrosive environments.

OIL-FIELD ENVIRONMENTS

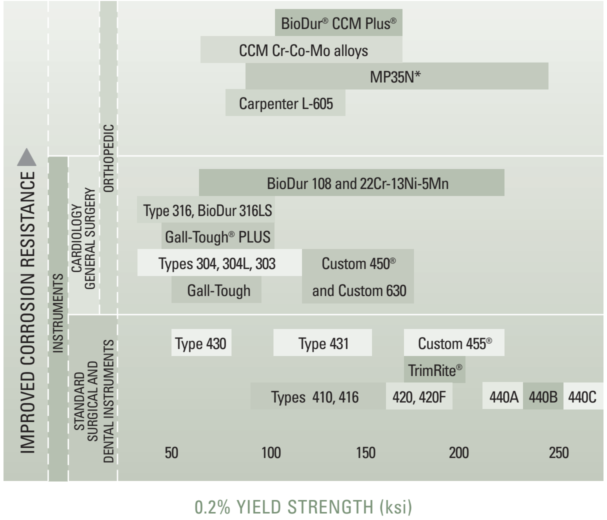
Materials for oil-field production environments frequently must resist sulfide stress cracking, or cracking in the presence of hydrogen sulfide and water in combination with a tensile stress. High-strength, highly alloyed materials (e.g. nickel-base alloys) are susceptible to this form of attack when coupled to iron, indicating that failures are a result of hydrogen entering the metal. This mode of failure can be most severe at temperatures close to ambient.

Figure 10: Resistance to Chloride-Stress-Corrosion Cracking



*Resistance varies considerably with aeration or oxidizing impurities.

Figure 11: Resistance in Medical Applications



*Registered trademark of SPS Technologies, Inc.

Elevated-temperature cracking can also occur in the oil field, in hot down-hole environments. Temperatures can be 350°F (177°C) or above in the presence of brine, carbon dioxide, hydrogen sulfide and possibly elemental sulfur. Also, resistance to pitting or crevice attack can be required because pits may act to concentrate stresses.

Figure 13 describes the relative resistance of several materials to oil field production environments, considering all the above-named forms of corrosion. Figure 13 also shows materials or higher strength levels used for oil field drilling. Both 15-15LC® Modified stainless and 15-15HS stainless have been used when nonmagnetic drill collars, stabilizer bodies and MWD housings are required. The utility of these grades is further enhanced with a proprietary treatment that puts the ID surface into compression to improve resistance to stress-corrosion cracking. Also, Pyromet® Alloy 718 may be used at higher strength levels in some drilling applications where resistance to severe corrosive environments is required.

Figure 12: Corrosion Resistance—Magnetic Applications

Corrosive, high purity environments	Chrome Core® 29 Solenoid Quality
Aqueous, mild chemicals	Chrome Core 18-FM Solenoid Quality
Mild aqueous	Types 430F & 430FR Solenoid Quality
Corrosive fuels, fresh water	Chrome Core 13-FM, Chrome Core 12/Chrome Core 12-FM
Fuels, mild atmospheres	Chrome Core 8/Chrome Core 8-FM

FM = Free Machining grade

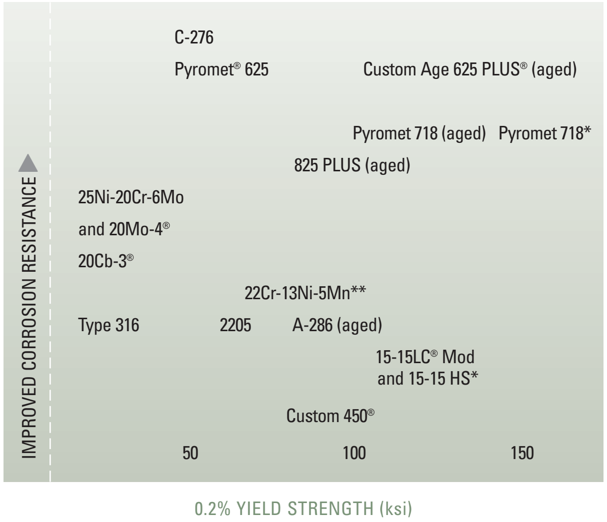
HIGH-STRENGTH WIRE FOR OIL-FIELD AND GENERAL APPLICATIONS

Very high strength can be obtained in wire applications as seen in Figure 14. Material in this chart is in the cold drawn or cold drawn plus aged condition. Example applications include 20Mo-6® HS stainless, which has been used for wireline and armoring wire for oil and gas wells, springs, yacht rigging and cables.

MACHINING GUIDELINES

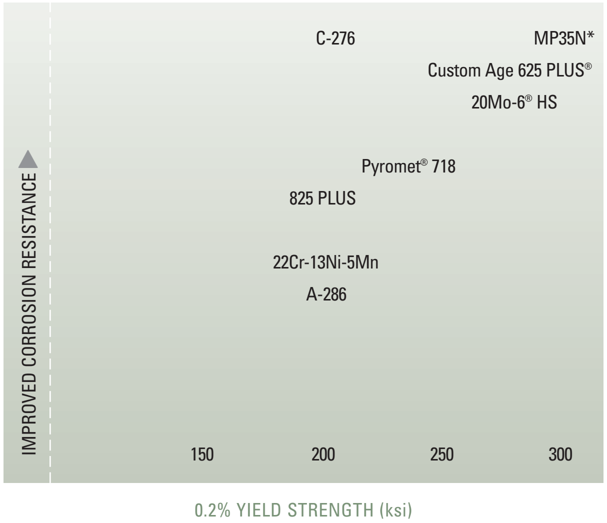
The data in Table 4 represent popular parameters that may be used as a guide for initial machine setup only. The figures used for all metal removal operations covered are starting points. On certain work, the nature of the part may require adjustment of speeds and feeds. Each job should be developed for best production results with optimum tool life. Speeds or feeds should be increased or decreased in small steps.

Figure 13: Resistance to Oil-Field Environments



*Material or strength level for drilling environment. **High strength warm worked condition.

Figure 14: High Strength Wire Applications



*Registered trademark of SPS Technologies, Inc.

TABLE 4–TYPICAL MACHINING SPEEDS USING HIGH-SPEED STEEL TOOLS

				Project 70+® Type 316/316L	15-15LC® Modified, 22Cr-13Ni-5Mn, Gall-Tough® Stainless	7-Mo PLUS® Stainless Carpenter 2205	25Ni-20Cr-6Mo, 20Cb-3® Stainless, 20Mo-4® Stainless, 20Mo-6® Stainless	Nickel-Copper Alloy 400	Pyromet® Alloy 625 Custom Age 625 PLUS® Alloy
TURNING SINGLE POINT AND BOX TOOLS			SFPM	117-143	50-70	50-70	65-75	70-100	15-25
			IPR	.018-.0084	.015-.007	.015-.007	.015-.007	.015-.007	.007
TURNING CUT-OFF AND FORM TOOLS	CUT-OFF TOOL WIDTH	1/16"	SFPM	104	40	40	50	60	15
			IPR	.0018	.001	.001	.001	.002	.002
		1/8"	SFPM	104	40	40	50	60	15
			IPR	.0024	.001	.001	.0015	.0025	.003
		1/4"	SFPM	104	40	40	50	60	15
			IPR	.0024	.0015	.0015	.002	.003	.004
		1/2"	SFPM	104	40	40	50	60	15
			IPR	.0024	.0015	.0015	.001	.003	.004
	FORM TOOL WIDTH	1"	SFPM	104	40	40	50	60	15
			IPR	.0018	.001	.001	.001	.0025	.002
		1 1/2"	SFPM	104	40	40	50	60	15
			IPR	.0012	.0007-.001	.0007-.001	.001	.002	.002
DRILLING	DRILL DIAMETER	1/4"	SFPM	78-98	45-55	45-55	45-55	55	15-20
			IPR	.0048	.004	.004	.004-.006	.005	.003
		3/4"	SFPM	78-98	40-55	40-55	45-55	55	15-20
			IPR	.012	.008-.010	.008-.010	.010-.014	.012	.004
REAMING	REAMER DIAMETER	Under 1/2"	SFPM	104	55-60	55-60	60	55	15
			IPR	.0036	.003	.003	.003	.005	.004
		Over 1/2"	SFPM	104	55-60	55-60	60	55	15
			IPR	.0096	.008	.008	.008	.010	.010
DIE THREADING		3-7 1/2 T.P.I.	SFPM	11-13	4-8	4-8	4-8	10-15	3-6
		8-15 T.P.I.	SFPM	16-29	6-10	6-10	6-10	15-20	3-8
		Over 16 T.P.I.	SFPM	26-39	8-12	8-12	8-12	20-25	6-12
TAPPING			SFPM	19-50	10-25	10-25	12-25	15	7-10
MILLING END PERIPHERAL		Depth of cut .050"	SFPM	117	55-65	55-65	70	65	15
			IPR	.0012-.0048	.001-.004	.001-.004	.001-.004	.002-.004	.001-.002
BROACHING		Chip Load—	SFPM	20	10	10	10	15	6
			IPT	.0036	.002-.003	.002-.003	.003	.002	.002

YOU'LL FIND DETAILED INFORMATION ON HUNDREDS OF CARPENTER ALLOYS INCLUDING THESE CORROSION-RESISTANT ALLOYS:

7-Mo PLUS® stainless
20Cb-3® stainless
20Mo-4® stainless
20Mo-6® stainless
20Mo-6 HS stainless
BioDur® 108 alloy
BioDur CCM Plus® alloy
Carpenter 22Cr-13Ni-5Mn
Carpenter 25Ni-20Cr-6Mo
Carpenter C-276
Carpenter Nickel-Copper 400
Chrome Core® 12-FM
Chrome Core 18-FM
Chrome Core 29
Custom 450® stainless
Custom 455® stainless
Custom 465® stainless
Custom Age 625 PLUS® alloy
Gall-Tough® stainless
Gall-Tough PLUS stainless
Project 70+® Type 316 stainless
Pyromet® Alloy 625
Pyromet Alloy 718
Type 430FR

Free product literature and technical data is available online at **www.cartech.com**.

The comprehensive database includes searchable information on hundreds of alloys including interactive corrosion and Selectaloy® diagrams. In addition, you'll find more than 50 technical articles. Registration is free and fast.

CARPENTER
Specialty Alloys

Carpenter Technology Corporation
Wyomissing, PA 19610 USA

1-800-654-6543 (toll-free within U.S.)
Visit us at www.cartech.com

For on-line purchasing in the U.S.,
visit www.carpenterdirect.com