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DESIGN GUIDELINES FOR THE SELECTION AND USE OF STAINLESS STEEL

NiDI

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INTRODUCTION

Stainless steels are iron-base alloys containing 10.5% or more chromium. They have been used for many industrial, architectural, chemical, and consumer applications for over a half century. Currently there are being marketed a number of stainless steels originally recognized by the American Iron and Steel Institute (AISI) as standard alloys. Also commercially available are proprietary stainless steels with special characteristics. (See Appendix A.)

With so many stainless steels from which to choose, designers should have a ready source of information on the characteristics and capabilities of these useful alloys. To fill this need, the Committee of Stainless Steel Producers initially prepared this booklet. The data was reviewed and updated by the Specialty Steel Industry of North America (SSINA). Written especially for design engineers, it presents an overview of a broad range of stainless steels – both standard and proprietary – their compositions, their properties, their fabrication, and their use. More detailed information on the 60 standard grades, with special emphasis on the manufacture, finish designations and dimensional and weight tolerances of the product forms in which they are marketed, is contained in the Iron and Steel Society of the AIME (the American Institute of Mining, Metallurgical and Petroleum Engineers) "Steel Products Manual–Stainless and Heat Resisting Steels." The AIME undertook the publication, updating and sale of this manual after the AISI discontinued publication in 1986.

IDENTIFICATION

Reference is often made to stainless steel in the singular sense as if it were one material. Actually there are over 50 stainless steel alloys. Three general classifications are used to identify stainless steels. They are: 1. Metallurgical Structure. 2. The AISI numbering system: namely 200, 300, and 400 Series numbers. 3. The Unified Numbering System, which was developed by American Society for Testing and Materials (ASTM) and Society of Automotive Engineers (SAE) to apply to all commercial metals and alloys.

There are also a number of grades known by common names that resemble AISI designations but that are not formally recognized by AISI. These common names, which are neither trademarks nor closely associated with a single producer, are shown and identified in the tables. These common (non-AISI) names do not appear in the ASTM specifications, so it is important to use the UNS designations with these grades.

On the following pages there is a description of these classifications. Tables 1-5 list stainless steels according to metallurgical structure: austenitic, ferritic, martensitic, precipitation hardening, and duplex.

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Austenitic stainless steels (Table 1) containing chromium and nickel are identified as 300 Series types. Alloys containing chromium, nickel and manganese are identified as 200 Series types. The stainless steels in the austenitic group have different compositions and properties, but many common characteristics. They can be hardened by cold working, but not by heat treatment. In the annealed condition, all are essentially nonmagnetic, although some may become slightly magnetic by cold working. They have excellent corrosion resistance, unusually good formability, and increase in strength as a result of cold work.

Type 304 (frequently referred to as 18-8 stainless) is the most widely used alloy of the austenitic group. It has a nominal composition of 18% chromium and 8% nickel.

Table 1
AUSTENITIC STAINLESS STEELS

TYPE	Equivalent UNS	TYPE	Equivalent UNS
201	S20100	310	S31000
202	S20200	310S	S31008
205	S20500	314	S31400
301	S30100	316	S31600
302	S30200	316L	S31603
302B	S30215	316F	S31620
303	S30300	316N	S31651
303Se	S30323	317	S31700
304	S30400	317L	S31703
304L	S30403	317LMN	S31726
302HQ	S30430	321	S32100
304N	S30451	330	N08330
305	S30500	347	S34700
308	S30800	348	S34800
309	S30900	384	S38400
309S	S30908		

Ferritic stainless steels (Table 2) are straight-chromium 400 Series types that cannot be hardened by heat treatment, and only moderately hardened by cold working. They are magnetic, have good ductility and resistance to corrosion and oxidation. Type 430 is the general-purpose stainless of the ferritic group.

Table 2
FERRITIC STAINLESS STEELS

TYPE	Equivalent UNS	TYPE	Equivalent UNS
405	S40500	430FSe	S43023
409	S40900	434	S43400
429	S42900	436	S43600
430	S43000	442	S44200
430F	S43020	446	S44600

Martensitic stainless steels (Table 3) are straight-chromium 400 Series types that are hardenable by heat treatment. They are magnetic. They resist corrosion in mild environments. They have fairly good ductility, and some can be heat treated to tensile strengths exceeding 200,000 psi (1379 MPa).

Type 410 is the general-purpose alloy of the martensitic group.

Table 3
MARTENSITIC STAINLESS STEELS

TYPE	Equivalent UNS	TYPE	Equivalent UNS
403	S40300	420F	S42020
410	S41000	422	S42200
414	S41400	431	S43100
416	S41600	440A	S44002
416Se	S41623	440B	S44003
420	S42000	440C	S44004

Precipitation-hardening stainless steels (Table 4) are chromium-nickel types, some containing other alloying elements, such as copper or aluminum. They can be hardened by solution treating and aging to high strength.

Table 4
PRECIPITATION HARDENING STAINLESS STEELS

UNS	UNS
S13800	S17400
S15500	S17700

Duplex stainless steels (Table 5) have an annealed structure which is typically about equal parts of austenite and ferrite. Although not formally defined, it is generally accepted that the lesser phase will be at least 30% by volume.

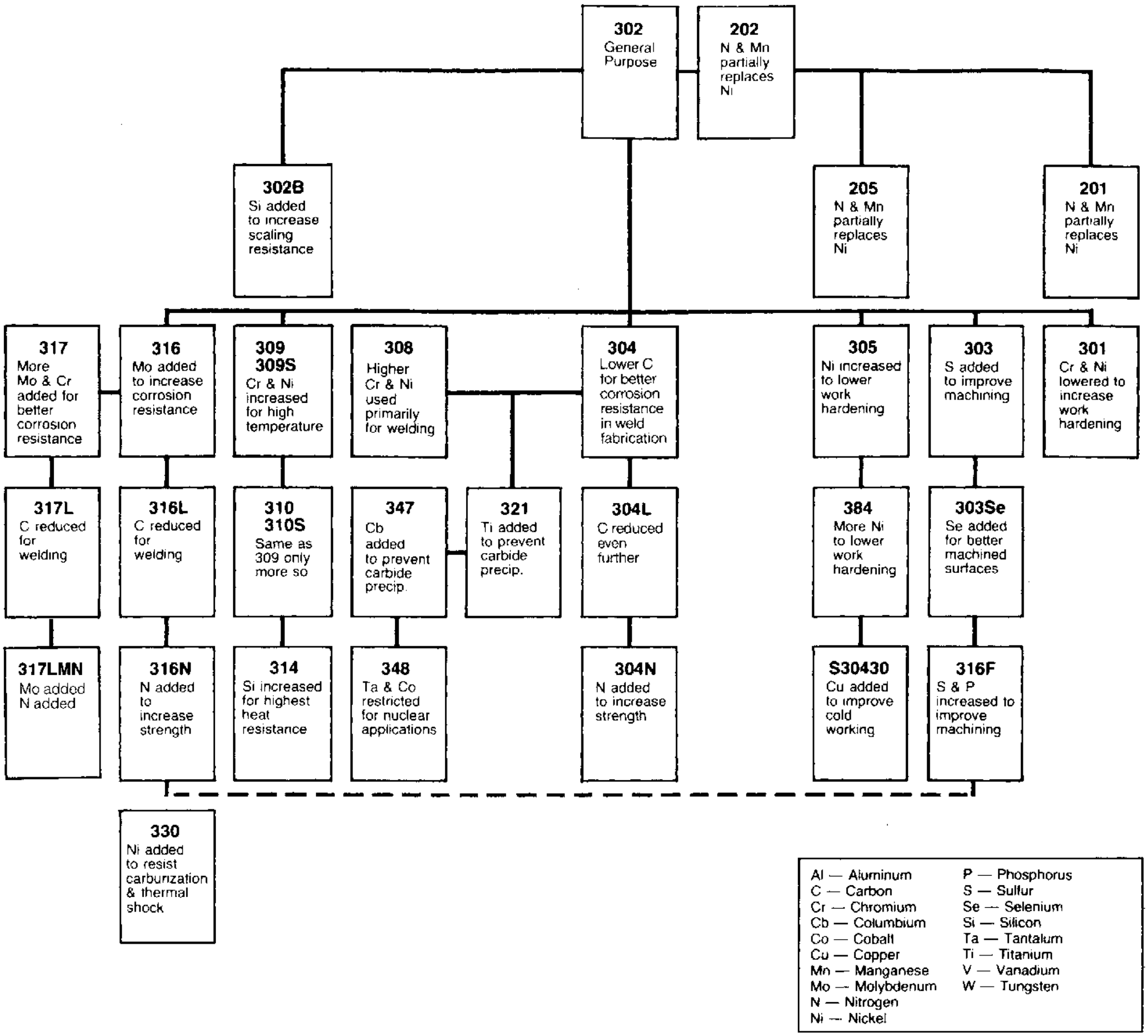
Duplex stainless steels offer several advantages over the common austenitic stainless steels. The duplex grades are highly resistant to chloride stress corrosion cracking, have excellent pitting and crevice corrosion resistance and exhibit about twice the yield stength as conventional grades. Type 329 and 2205 are typical alloys.

With respect to the Unified Numbering System, the UNS designations are shown alongside each AISI type number, in Tables 1-5, except for four stainless steels (see Tables 4 and 5) for which UNS designations only are listed.

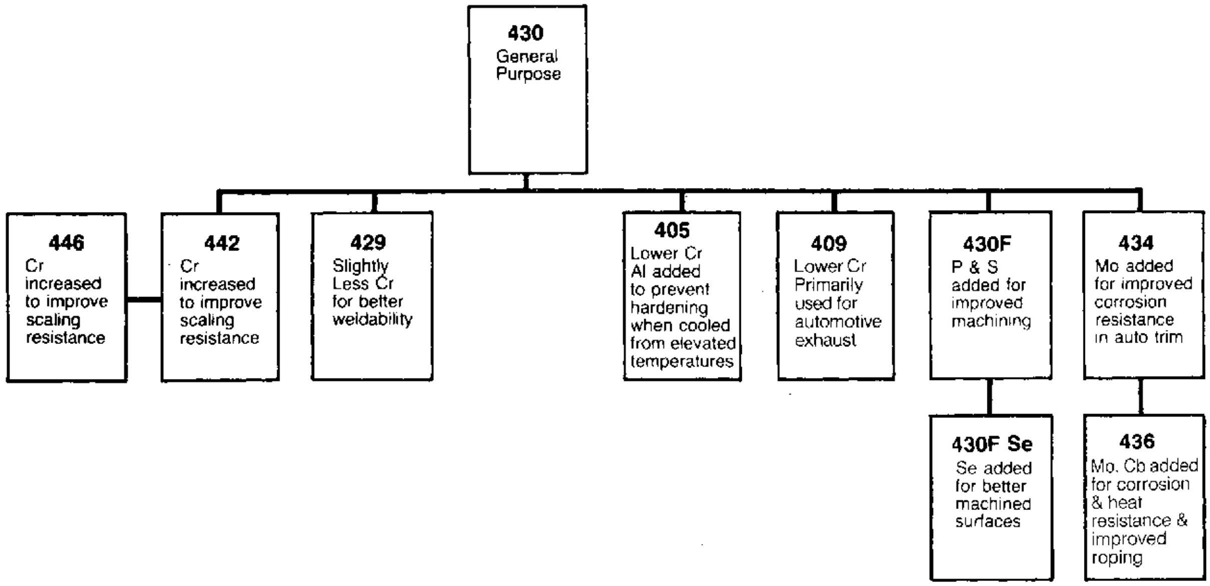
Table 5
DUPLEX

Type	UNS
329	S32900
2205	S31803,S32205

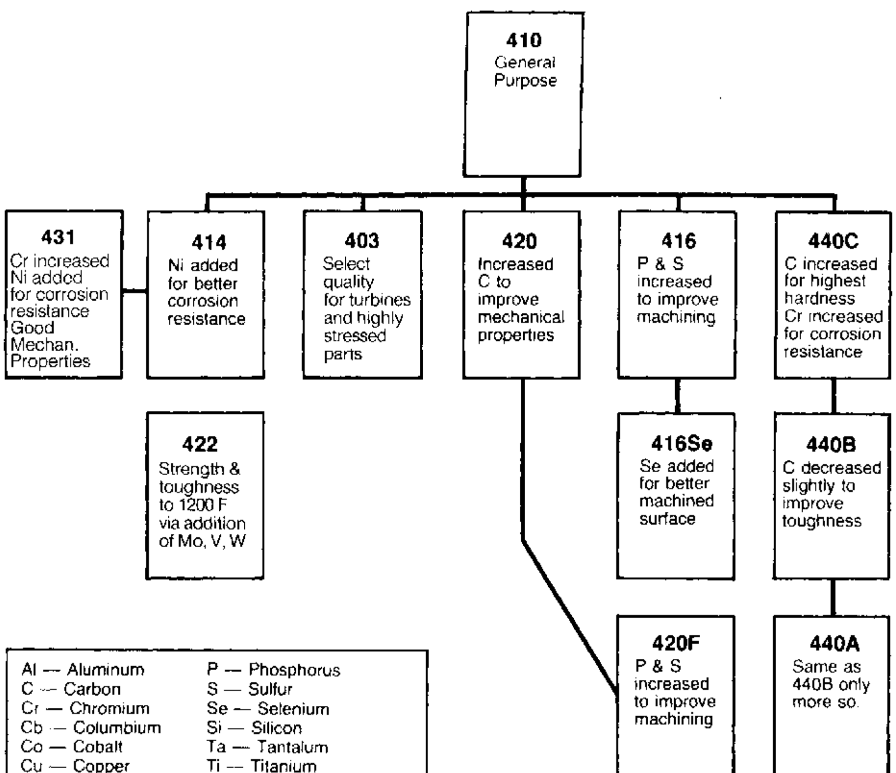
AUSTENITIC


302 General Purpose
202 N & Mn partially replaces Ni
302B Si added to increase scaling resistance
205 N & Mn partially replaces Ni
201 N & Mn partially replaces Ni
317 More Mo & Cr added for better corrosion resistance
316 Mo added to increase corrosion resistance
309 309S Cr & Ni increased for high temperature
308 Higher Cr & Ni used primarily for welding
304 Lower C for better corrosion resistance in weld fabrication
305 Ni increased to lower work hardening
303 S added to improve machining
301 Cr & Ni lowered to increase work hardening
317L C reduced for welding
316L C reduced for welding
310 310S Same as 309 only more so
347 Cb added to prevent carbide precip.
321 Ti added to prevent carbide precip.
304L C reduced even further
384 More Ni to lower work hardening
303Se Se added for better machined surfaces
317LMN Mo added N added
316N N added to increase strength
314 Si increased for highest heat resistance
348 Ta & Co restricted for nuclear applications
304N N added to increase strength
S30430 Cu added to improve cold working
316F S & P increased to improve machining
330 Ni added to resist carburization & thermal shock
Al — Aluminum
C — Carbon
Cr — Chromium
Cb — Columbium
Co — Cobalt
Cu — Copper
Mn — Manganese
Mo — Molybdenum
N — Nitrogen
Ni — Nickel
P — Phosphorus
S — Sulfur
Se — Selenium
Si — Silicon
Ta — Tantalum
Ti — Titanium
V — Vanadium
W — Tungsten

FERRITIC



MARTENSITIC



Al — Aluminum	P — Phosphorus
C — Carbon	S — Sulfur
Cr — Chromium	Se — Selenium
Cb — Columbium	Si — Silicon
Co — Cobalt	Ta — Tantalum
Cu — Copper	Ti — Titanium
Mn — Manganese	V — Vanadium
Mo — Molybdenum	W — Tungsten
N — Nitrogen	
Ni — Nickel	

GUIDELINES FOR SELECTION

Stainless steels are engineering materials with good corrosion resistance, strength, and fabrication characteristics. They can readily meet a wide range of design criteria – load, service life, low maintenance, etc. Selecting the proper stainless steel essentially means weighing four elements. In order of importance, they are:

1. **Corrosion or Heat Resistance –** the primary reason for specifying stainless. The specifier needs to know the nature of the environment and the degree of corrosion or heat resistance required.
2. **Mechanical Properties –** with particular emphasis on strength at room, elevated, or low temperature. Generally speaking, the combination of corrosion resistance and strength is the basis for selection.
3. **Fabrication Operations –** and how the product is to be made is a third-level consideration. This includes forging, machining, forming, welding, etc.
4. **Total Cost –** in considering total cost, it is appropriate to consider not only material and production costs, but the life cycle cost including the cost-saving benefits of a maintenance-free product having a long life expectancy.

CORROSION RESISTANCE

Chromium is the alloying element that imparts to stainless steels their corrosion-resistance qualities by combining with oxygen to form a thin, invisible chromium-oxide protective film on the surface. (Figure 1. Figures are shown in Appendix B.) Because the passive film is such an important factor, there are precautions which must be observed in designing stainless steel equipment, in manufacturing the equipment, and in operation and use of the equipment, to avoid destroying or disturbing the film.

In the event that the protective (passive) film is disturbed or even destroyed, it will, in the presence of oxygen in the environment, reform and continue to give maximum protection.

The protective film is stable and protective in normal atmospheric or mild aqueous environments, but can be improved by higher chromium, and by molybdenum, nickel, and other alloying elements. Chromium improves film stability; molybdenum and chromium increase resistance to chloride penetration; and nickel improves film resistance in some acid environments.

Material Selection

Many variables characterize a corrosive environment – i.e., chemicals and their concentration, atmospheric conditions, temperature, time – so it is difficult to select which alloy to use without knowing the exact nature of the environment. However, there are guidelines:

Type 304 serves a wide range of applications. It withstands ordinary rusting in architecture, it is resistant to food-processing environments (except possibly for high-temperature conditions involving high acid and chloride contents), it resists organic chemicals, dyestuffs, and a wide variety of inorganic chemicals. Type 304 L (low carbon) resists nitric acid well and sulfuric acids at moderate temperature and concentrations. It is used extensively for storage of liquified gases, equipment for use at cryogenic temperatures (304N), appliances and other consumer products, kitchen equipment, hospital equipment, transportation, and waste-water treatment.

Type 316 contains slightly more nickel than Type 304, and 2-3% molybdenum giving it better resistance to corrosion than Type 304, especially in chloride environments that tend to cause pitting. Type 316 was developed for use in sulfite pulp mills because it resists sulfuric acid compounds. Its use has been broadened, however, to handling many chemicals in the process industries.

Type 317 contains 3-4% molybdenum (higher levels are also available in this series) and more chromium than Type 316 for even better resistance to pitting and crevice corrosion.

Type 430 has lower alloy content than Type 304 and is used for highly polished trim applications in mild atmospheres. It is also used in nitric acid and food processing.

Type 410 has the lowest alloy content of the three general-purpose stainless steels and is selected for highly stressed parts needing the combination of strength and corrosion resistance, such as fasteners. Type 410 resists corrosion in mild atmospheres, steam, and many mild chemical environments.

Type 2205 may have advantages over Type 304 and 316 since it is highly resistant to chloride stress corrosion cracking and is about twice as strong.

Table 6 lists the relative corrosion resistance of the AISI standard numbered stainless steels in seven broad categories of corrosive environments. Table 7 details more specific environments in which various grades are used, such as acids, bases, organics, and pharmaceuticals.

The above comments on the suitability of stainless steels in various environments are based on a long history of successful application, but they are intended only as guidelines. Small differences in chemical content and temperature, such as might occur during processing, can affect corrosion rates. The magnitude can be considerable, as suggested by Figures 2 and 3. Figure 2 shows small quantities of hydrofluoric and sulfuric acids having a serious effect on Type 316 stainless steel in an environment of 25% phosphoric acid, and Figure 3 shows effects of temperature on Types 304 and 316 in very concentrated sulfuric acid.

Service tests are most reliable in determining optimum material, and ASTM G4 is a recommended practice for carrying out such tests. Tests should cover conditions both during operation and shutdown. For instance, sulfuric, sulfurous and polythionic acid condensates formed in some processes during shutdowns may be more corrosive than the process stream itself. Tests should be conducted under the worst operating conditions anticipated.

Several standard reference volumes discuss corrosion and corrosion control, including Uhlig's Corrosion Handbook; LaQue and Copsons' Corrosion Resistance Of Metals and Alloys; Fontana and Greens' Corrosion Engineering; A Guide to Corrosion Resistance by Climax Molybdenum Company; the Corrosion Data Survey by the National Association of Corrosion Engineers; and the ASM Metals Handbook. Corrosion data, specifications, and recommended practices relating to stainless steels are also issued by ASTM. Stainless steels resist corrosion in a broad range of conditions, but they are not immune to every environment. For example, stainless steels perform poorly in reducing environments, such as 50% sulfuric and hydrochloric acids at elevated temperatures. The corrosive attack experienced is a breakdown of the protective film over the entire metal surface.

Such misapplications of stainless steels are rare and are usually avoided. The types of attack which are more likely to be of concern are pitting, crevice attack, stress corrosion cracking, and intergranular corrosion, which are discussed in Appendix A.

Table 6

Relative Corrosion Resistance of AISI Stainless Steels (1)

TYPE Number	UNS Number	Mild Atmos-pheric and Fresh Water	Atmospheric		Chemical		
			Industrial	Marine	Mild	Oxidizing	Reducing
201	(S20100)	x	x	x	x	x	
202	(S20200)	x	x	x	x	x	
205	(S20500)	x	x	x	x	x	
301	(S30100)	x	x	x	x	x	
302	(S30200)	x	x	x	x	x	
302B	(S30215)	x	x	x	x	x	
303	(S30300)	x	x		x		
303 Se	(S30323)	x	x		x		
304	(S30400)	x	x	x	x	x	
304L	(S30403)	x	x	x	x	x	
	(S30430)	x	x	x	x	x	
304N	(S30451)	x	x	x	x	x	
305	(S30500)	x	x	x	x	x	
308	(S30800)	x	x	x	x	x	
309	(S30900)	x	x	x	x	x	
309S	(S30908)	x	x	x	x	x	
310	(S31000)	x	x	x	x	x	
310S	(S31008)	x	x	x	x	x	
314	(S31400)	x	x	x	x	x	
316	(S31600)	x	x	x	x	x	x
316F	(S31620)	x	x	x	x	x	x
316L	(S31603)	x	x	x	x	x	x
316N	(S31651)	x	x	x	x	x	x
317	(S31700)	x	x	x	x	x	x
317L	(S31703)	x	x	x	x	x	
321	(S32100)	x	x	x	x	x	
329	(S32900)	x	x	x	x	x	x
330	(N08330)	x	x	x	x	x	x
347	(S34700)	x	x	x	x	x	
348	(S34800)	x	x	x	x	x	
384	(S38400)	x	x	x	x	x	
403	(S40300)	x			x		
405	(S40500)	x			x		
409	(S40900)	x			x		
410	(S41000)	x			x		
414	(S41400)	x			x		
416	(S41600)	x					
416 Se	(S41623)	x					
420	(S42000)	x					
420F	(S42020)	x					
422	(S42200)	x					
429	(S42900)	x	x		x	x	
430	(S43000)	x	x		x	x	
430F	(S43020)	x	x		x		
430F Se	(S43023)	x	x		x		
431	(S43100)	x	x	x	x		
434	(S43400)	x	x	x	x	x	
436	(S43600)	x	x	x	x	x	
440A	(S44002)	x			x		
440B	(S44003)	x					
440C	(S44004)	x					
442	(S44200)	x	x		x	x	
446	(S44600)	x	x	x	x	x	
	(S13800)	x	x		x	x	
	(S15500)	x	x	x	x	x	
	(S17400)	x	x	x	x	x	
	(S17700)	x	x	x	x	x	

- The "X" notations indicate that a specific stainless steel type may be considered as resistant to the corrosive environment categories.

  This list is suggested as a guideline only and does not suggest or imply a warranty on the part of the Specialty Steel Industry of the United States or any of the member companies. When selecting a stainless steel for any corrosive environment, it is always best to consult with a corrosion engineer and, if possible, conduct tests in the environment involved under actual operating conditions.

Table 7

Where Different Grades Are Used (15)

Environment	Grades
Acids	
Hydrochloric acid	Stainless generally is not recommended except when solutions are very dilute and at room temperature.
"Mixed acids"	There is usually no appreciable attack on Type 304 or 316 as long as sufficient nitric acid is present.
Nitric acid	Type 304L or 430 is used.
Phosphoric acid	Type 304 is satisfactory for storing cold phosphoric acid up to 85% and for handling concentrations up to 5% in some unit processes of manufacture. Type 316 is more resistant and is generally used for storing and manufacture if the fluorine content is not too high. Type 317 is somewhat more resistant than Type 316. At concentrations up to 85%, the metal temperature should not exceed 212 ºF (100 ºC) with Type 316 and slightly higher with Type 317. Oxidizing ions inhibit attack and other inhibitors such as arsenic may be added.
Sulfuric acid	Type 304 can be used at room temperature for concentrations over 80%. Type 316 can be used in contact with sulfuric acid up to 10% at temperatures up to 120 ºF (50 ºC) if the solutions are aerated; the attack is greater in airfree solutions. Type 317 may be used at temperatures as high as 150 ºF (65 ºC) with up to 5% concentration. The presence of other materials may markedly change the corrosion rate. As little as 500 to 2000 ppm of cupric ions make it possible to use Type 304 in hot solutions of moderate concentration. Other additives may have the opposite effect.
Sulfurous acid	Type 304 may be subject to pitting, particularly if some sulfuric acid is present. Type 316 is usable at moderate concentrations and temperatures.
Bases	
Ammonium hydroxide, sodium hydroxide, caustic solutions	Steels in the 300 series generally have good corrosion resistance at virtually all concentrations and temperatures in weak bases, such as ammonium hydroxide. In stronger bases, such as sodium hydroxide, there may be some attack, cracking or etching in more concentrated solutions and at higher temperatures. Commercial purity caustic solutions may contain chlorides, which will accentuate any attack and may cause pitting of Type 316 as well as Type 304.
Organics	
Acetic acid	Acetic acid is seldom pure in chemical plants but generally includes numerous and varied minor constituents. Type 304 is used for a wide variety of equipment including stills, base heaters, holding tanks, heat exchangers, pipelines, valves and pumps for concentrations up to 99% at temperatures up to about 120 ºF (50 ºC). Type 304 is also satisfactory for contact with 100% acetic acid vapors, and–if small amounts of turbidity or color pickup can be tolerated–for room temperature storage of glacial acetic acid. Types 316 and 317 have the broadest range of usefulness, especially if formic acid is also present or if solutions are unaerated. Type 316 is used for fractionating equipment, for 30 to 99% concentrations where Type 304 cannot be used, for storage vessels, pumps and process equipment handling glacial acetic acid, which would be discolored by Type 304. Type 316 is likewise applicable for parts having temperatures above 120 ºF (50 ºC), for dilute vapors and high pressures. Type 317 has somewhat greater corrosion resistance than Type 316 under severely corrosive conditions. None of the stainless steels has adequate corrosion resistance to glacial acetic acid at the boiling temperature or at superheated vapor temperatures.
Aldehydes	Type 304 is generally satisfactory.
Amines	Type 316 is usually preferred to Type 304.
Cellulose acetate	Type 304 is satisfactory for low temperatures, but Type 316 or Type 317 is needed for high temperatures.
Citric, formic and tartaric acids	Type 304 is generally acceptable at moderate temperatures, but Type 316 is resistant to all concentrations at temperatures up to boiling.
Esters	From the corrosion standpoint, esters are comparable with organic acids.
Fatty acids	Up to about 300 ºF (150 ºC), Type 304 is resistant to fats and fatty acids, but Type 316 is needed at 300 to 500 ºF (150 to 260 ºC) and Type 317 at higher temperatures.
Paint vehicles	Type 316 may be needed if exact color and lack of contamination are important.
Phthalic anhydride	Type 316 is usually used for reactors, fractionating columns, traps, baffles, caps and piping.
Soaps	Type 304 is used for parts such as spray towers, but Type 316 may be preferred for spray nozzles and flake-drying belts to minimize offcolor product.
Synthetic detergents	Type 316 is used for preheat, piping, pumps and reactors in catalytic hydrogenation of fatty acids to give salts of sulfonated high molecular alcohols.
Tall oil (pulp and paper industry)	Type 304 has only limited usage in tall-oil distillation service. High-rosin-acid streams can be handled by Type 316L with a minimum molybdenum content of 2.75%. Type 316 can also be used in the more corrosive high-fatty-acid streams at temperatures up to 475 ºF (245 ºC), but Type 317 will probably be required at higher temperatures.
Tar	Tar distillation equipment is almost all Type 316 because coal tar has a high chloride content; Type 304 does not have adequate resistance to pitting.
Urea	Type 316L is generally required.
Pharmaceuticals	Type 316 is usually selected for all parts in contact with the product because of its inherent corrosion resistance and greater assurance of product purity.

Table 8
AUSTENITIC STAINLESS STEELS

Type	C	Mn	P	S	Si	Cr	Ni	Mo	Other	Tensile Strength ksi	Tensile Strength MPa	Yield Strength (0.2% offset) ksi	Yield Strength (0.2% offset) MPa	Elongation in 2" (50.80mm) %	Hardness (Rockwell)	Product Form
	Chemical Analysis % (Max. unless noted otherwise)									Nominal Mechanical Properties (Annealed Sheet unless noted otherwise)						
201	0.15	5.50/7.50	0.060	0.030	1.00	16.00/18.00	3.50/5.50		0.25N	95	655	45	310	40	B90	
202	0.15	7.50/10.00	0.060	0.030	1.00	17.00/19.00	4.00/6.00		0.25N	90	612	45	310	40	690	
205	0.12/0.25	14.00/15.50	0.030	0.030	0.50	16.50/18.00	1.00/1.75		0.32/0.40N	120.5	831	69	476	58	B98	(Plate)
301	0.15	2.00	0.045	0.030	1.00	16.00/18.00	6.00/8.00			110	758	40	276	60	B85	
302	0.15	2.00	0.045	0 030	1 00	17.00/19.00	8.00/10.00			90	612	40	276	50	B85	
302B	0.15	2.00	0.045	0.030	2.00/3.00	17.00/19.00	8.00/10.00			95	655	40	276	55	B85	
303	0.15	2.00	0.20	0.15 (min)	1.00	17.00/19.00	8.00/10.00	0.60*		90	621	35	241	50		(Bar)
303Se	0.15	2.00	0.20	0.060	1.00	17.00/19.00	8.00/10.00		0.15Se (min)	90	621	35	241	50		(Bar)
304	0.08	2.00	0.045	0.030	1.00	18.00/20.00	8.00/10.50			84	579	42	290	55	B80	
304L	0.030	2.00	0.045	0.030	1.00	18.00/20.00	8.00/12.00			81	558	39	269	55	B79	
S30430	0.08	2.00	0.045	0.030	1.00	17.00/19.00	8.00/10.00		3.00/4.00Cu	73	503	31	214	70	B70	(Wire)
304N	0.08	2.00	0.045	0.030	1.00	18.00/20.00	8.00/10.50		0.10/0.16N	90	621	48	331	50	B85	
305	0.12	2.00	0.045	0.030	1.00	17.00/19.00	10.50/13.00			85	586	38	262	50	B80	
308	0.08	2.00	0.045	0.030	1.00	19.00/21.00	10.00/12.00			115	793	80	552	40		(Wire)
309	0.20	2.00	0.045	0.030	1.00	22.00/24.00	12.00/15.00			90	621	45	310	45	B85	
309S	0.08	2.00	0.045	0.030	1.00	22.00/24.00	12.00/15.00			90	621	45	310	45	B85	
310	0.25	2.00	0.045	0.030	1.50	24.00/26.00	19.00/22.00			95	655	45	310	45	B85	
310S	0.08	2.00	0.045	0.030	1.50	24.00/26.00	19.00/22.00			95	655	45	310	45	B85	
314	0.25	2.00	0.045	0.030	1.50/3.00	23.00/26.00	19.00/22.00			100	689	50	345	40	B85	
316	0.08	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00		84	579	42	290	50	B79	
316F	0.08	2.00	0.20	0.10min	1.00	16.00/18.00	10.00/14.00	1.75/2.50		85	586	38	262	60	B85	
316L	0.030	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00		81	558	42	290	50	B79	
316N	0.08	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	2.00/3.00	0.10/0.16N	90	621	48	331	48	B85	
317	0.08	2.00	0.045	0.030	1.00	18.00/20.00	11.00/15.00	3.00/4.00		90	621	40	276	45	B85	
317L	0.030	2.00	0.045	0.030	1.00	18.00/20.00	11.00/15.00	3.00/4.00		86	593	38	262	55	B85	
317LMN	0.030	2.00	0.045	0.030	0.75	17.00/20.00	13.50/17.50	4.00/5.00	0.10/0.20N	96	662	54	373	49	B88	
321	0.08	2.00	0.045	0.030	1.00	17.00/19.00	9.00/12.00		5xC Ti (min)	90	621	35	241	45	B80	
330	0.08	2.00	0.040	0.030	0.75/1.50	17.00/20.00	34.00/37.00		0.10Ta 0.20Cb	80	552	38	262	40	B80	
347	0.08	2.00	0.045	0.030	1.00	17.00/19.00	9.00/13.00		10xC Cb (min)	95	655	40	276	45	B85	
348	0.08	2.00	0.045	0.030	1.00	17.00/19.00	9.00/13.00		Cb + Ta 10xC (min) Ta 0.10 max Cc 0.20 max	95	655	40	276	45	B85	
384	0.08	2.00	0.045	0.030	1.00	15.00/17.00	17.00/19.00			75	517	35	241	55	B70	(Wire)

* May be added at manufacturer's option.

MECHANICAL AND PHYSICAL PROPERTIES (Room Temperature)

Austenitic Stainless Steels

The austenitic stainless steels cannot be hardened by heat treatment but can be strengthened by cold work, and thus they exhibit a wide range of mechanical properties. At room temperature, austenitic stainless steels exhibit yield strengths between 30 and 200 ksi (207-1379 MPa), depending on composition and amount of cold work. They also exhibit good ductility and toughness even at high strengths, and this good ductility and toughness is retained at cryogenic temperatures. The chemical compositions and nominal mechanical properties of annealed austenitic stainless steels are given in Table 8.

The difference in effect of cold work of Types 301 and 304 is indicated by the stress strain diagrams in Figure 11.

Carbon and nitrogen contents affect yield strength, as shown by the differences among Types 304, 304L, and 304N. The effect of manganese and nitrogen on strength can be seen by comparing Types 301 and 302 against Types 201 and 202.

Figures 12, 13, 14, and 15 illustrate other effects of small composition changes. For example, at a given amount of cold work, Types 202 and 301 exhibit higher yield and tensile strengths than Types 305 and 310.

Austenitic stainless steels which can be cold worked to high tensile and yield strengths, while retaining good ductility and toughness, meet a wide range of design criteria. For example, sheet and strip of austenitic steels – usually Types 301 and 201 – are produced in the following tempers:

Temper	Tensile Strength Minimum		Yield Strength Minimum	
	ksi	MPa	ksi	MPa
¼-Hard	125	862	75	517
½-Hard	150	1034	110	758
¾-Hard	175	1207	135	931
Full-Hard	185	1276	140	965

In structural applications, the toughness and fatigue strength of these steels are important. At room temperature in the annealed condition, the austenitic steels exhibit Charpy V-notch energy absorption values in excess of 100 ft.-lb. The effect of cold rolling Type 301 on toughness is illustrated in Figure 16. This shows Type 301 to have good toughness even after cold rolling to high tensile strengths.

Fatigue or endurance limits (in bending) of austenitic stainless steels in the annealed condition shown in Table 9 are about one-half the tensile strength.

New Design Specification

Until recently, design engineers wanting to use austenitic stainless steels structurally had to improvise due to the lack of an appropriate design specification. The familiar American Institute for Steel Construction and AISI design specifications for carbon steel design do not apply to the design of stainless steel members because of differences in strength properties, modulus of elasticity, and the shape of the stress strain curve. Figure 17 shows that there is no well-defined yield point for stainless steel.

Table 9
TYPICAL ENDURANCE LIMITS OF ANNEALED CHROMIUM-NICKEL STAINLESS STEEL SHEET (2)

AISI Type	Endurance limit, ksi	MPa
301	35	241
302	34	234
303	35	241
304	35	241
316	39	269
321	38	262
347	39	269

Now the American Society of Civil Engineers (ASCE), in conjunction with the SSINA, has prepared a standard (ANSI/ASCE-8-90) "Specification for the Design of Cold-Formed Stainless Steel Structural Members." This standard covers four types of austenitic stainless steel, specificially Types 201, 301, 304 and 316, and three types of ferritic stainless steels (See Ferritic section below). This standard requires the use of structural quality stainless steel as defined in general by the provisions of the American Society for Testing and Materials (ASTM) specifications.

Some of the physical properties of austenitic stainless steels are similar to those of the martensitic and ferritic stainless steels. The modulus of elasticity, for example, is 28 x 10^6 psi (193 GPa) and density is 0.29 lb. per cu. in. (8060 Kg/m^3). The physical properties of annealed Type 304 are shown in Table 10.

Ferritic Stainless Steels

Ferritic stainless steels contain approximately 12% chromium (and up). The chemical composition of the standard grades are shown in Table 11 along with nominal mechanical properties. Also several proprietary grades (see Appendix A) have achieved relatively wide commercial acceptance.

Three ferritic stainless steels, namely Types 409, 430 and 439 are included in the ASCE "Specification for the Design of Cold-Formed Stainless Steel Structural Members." Designers should be aware of two notations in this specification:

(1) The maximum thickness for Type 409 ferritic stainless used in the standard is limited to 0.15 inches.

(2) The maximum thickness for Type 430 and 439 ferritic stainless steels is limited to 0.125 inches.

This is in recognition of concerns for the ductile to brittle transition temperature of the ferritic stainless steels in structural application. It should be noted that these alloys have been used in plate thickness for other applications.

Generally, toughness in the annealed condition decreases as the chromium content increases. Molybdenum tends to increase ductility, whereas carbon tends to decrease ductility. Ferritic stainless steels can be used for structural applications (as noted above), as well as such traditional applications as kitchen sinks, and automotive, appliance, and luggage trim, which require good resistance to corrosion and bright, highly polished finishes.

When compared to low-carbon steels, such as SAE 1010, the standard numbered AISI ferritic stainless steels, (such as Type 430) exhibit somewhat higher yield and tensile strengths, and low elongations. Thus, they are not as formable as the low-carbon steels. The proprietary ferritic stainless steels, on the other hand, with lower carbon levels have improved ductility and formability comparable with that of low-carbon steels. Because of the higher strength levels, the ferritic stainless steels require slightly more power to form.

Micro cleanliness is important to good formability of the ferritic types because inclusions can act as initiation sites for cracks during forming.

Type 405 stainless is used where the annealed mechanical properties and corrosion resistance of Type 410 are satisfactory but when better weldability is desired. Type 430 is used for formed products, such as sinks and decorative trim. Physical properties of Type 430 are shown in Table 10. Types 434 and 436 are used when better corrosion resistance is required and for relatively severe stretching.

For fasteners and other machined parts, Types 430F and 430F Se are often used, the latter being specified when forming is required in addition to machining.

Types 442 and 446 are heat resisting grades.

Type 409, which has the lowest chromium content of the stainless steels, is widely used for automotive exhaust systems.

Table 10 PHYSICAL PROPERTIES OF GENERAL-PURPOSE STAINLESS STEELS (ANNEALED) (1)	Type 304	Type 430	Type 410	S13800
Modulus of Elasticity in Tension psi x 10^6 (GPa)	28.0 (193)	29.0 (200)	29.0 (200)	29.4 (203)
Modulus of Elasticity in Torsion psi x 10^6 (GPa)	12.5 (86.2)	– –	– –	– –
Density, lbs/in^3 (kg/m^3)	0.29 (8060)	0.28 (7780)	0.28 (7780)	0.28 (7780)
Specific Heat, Btu/lb/F (J/kg•K) 32-212F (0-100ºC)	0.12 (503)	0.11 (460)	0.11 (460)	0.11 (460)
Thermal Conductivity, Btu/hr/ft/F (W/m•K)				
212ºF (100ºC)	9.4 (0.113)	15.1 (0.182)	14.4 (0.174)	8.1 (0.097)
932ºF (500ºC)	12.4 (0.149)	15.2 (0.183)	16.6 (0.201)	12.7 (0.152)
Mean Coefficient of Thermal Expansion x10^{-6}/F (x10^{-6}/ºC)				
32-212ºF (0-100ºC)	9.6 (17.3)	5.8 (10.4)	5.5 (9.9)	5.9 (10.6)
32-600ºF (0-315ºC)	9.9 (17.9)	6.1 (11.0)	6.3 (11.4)	6.2 (11.2)
32-1000ºF (0-538ºC)	10.2 (18.4)	6.3 (11.4)	6.4 (11.6)	6.6 (11.9)
32-1200ºF (0-648ºC)	10.4 (18.8)	6.6 (11.9)	6.5 (11.7)	– –
32-1800ºF (0.982ºC)	– –	6.9 (12.4) (32-1500ºF)	– –	– –
Melting Point Range ºF	2550 to 2650	2600 to 2750	2700 to 2790	2560 to 2625
(ºC)	(1398 to 1454)	(1427 to 1510)	(1483 to 1532)	(1404 to 1440)

Table 11 FERRITIC STAINLESS STEELS (1)

Chemical Analysis % (Max. unless noted otherwise)

Type	C	Mn	P	S	Si	Cr	Ni	Mo	Other
405	0.08	1.00	0.040	0.030	1.00	11.50/14.50	0.60		0.10/0.30 Al
409	0.08	1.00	0.045	0.045	1.00	10.50/11.75	0.50		6xC/0.75 Ti
429	0.12	1.00	0.040	0.030	1.00	14.00/16.00	0.75		
430	0.12	1.00	0.040	0.030	1.00	16.00/18.00	0.75		
430F	0.12	1.25	0.060	0.15 (min)	1.00	16.00/18.00		0.60*	
430F Se	0.12	1.25	0.060	0.060	1.00	16.00/18.00			0.15 Se (min.)
434	0.12	1.00	0.040	0.030	1.00	16.00/18.00		0.75/1.25	
436	0.12	1.00	0.040	0.030	1.00	16.00/18.00		0.75/1.25	5xC/0.70Cb+Ta
442	0.20	1.00	0.040	0.030	1.00	18.00/23.00	0.60		
446	0.20	1.50	0.040	0.030	1.00	23.00/27.00	0.75		0.25N

* May be added at manufacturer's option.

Nominal Mechanical Properties

(Annealed sheet unless noted otherwise)

Type	Tensile Strength		Yield Strength (to .2% offset)		Elongation in 2" (50.80 mm) %	Hardness (Rockwell)	Product Form
	ksi	MPa	ksi	MPa			
405	65	448	40	276	25	B75	
409	65	448	35	241	25	B75	
429	70	483	40	276	30	B80	(Plate)
430	75	517	50	345	25	B85	
430F	95	655	85	586	10	B92	
430F Se	95	655	85	586	10	B92	(Wire)
434	77	531	53	365	23	B83	
436	77	531	53	365	23	B83	
442	80	552	45	310	20	B90	(Bar)
446	80	552	50	345	20	B83	

Martensitic Stainless Steels

The martensitic grades are so named because when heated above their critical temperature (1600ºF or 870ºC) and cooled rapidly, a metallurgical structure known as martensite is obtained. In the hardened condition the steel has very high strength and hardness, but to obtain optimum corrosion resistance, ductility, and impact strength, the steel is given a stress-relieving or tempering treatment (usually in the range 300-700ºF (149-371ºC)).

Tables 12, 13 and 14 give the chemical compositions and mechanical properties of martensitic grades in the annealed and hardened conditions.

The martensitic stainless steels fall into two main groups that are associated with two ranges of mechanical properties: low-carbon compositions with a maximum hardness of about Rockwell C45 and the higher-carbon compositions, which can be hardened up to Rockwell C60. (The maximum hardness of both groups in the annealed condition is about Rockwell C24.) The dividing line between the two groups is a carbon content of approximately 0.15%.

In the low-carbon class are Types 410, 416 (a free-machining grade) and 403 (a "turbine-quality" grade). The properties, performance, heat treatment, and fabrication of these three stainless steels are similar except for the better machinability of Type 416.

On the high-carbon side are Types 440A, B, and C.

Types 420, 414, and 431, however, do not fit into either category. Type 420 has a minimum carbon content of 0.15% and is usually produced to a carbon specification of 0.3-0.4%. While it will not harden to such high values as the 440 types, it can be tempered without substantial loss in corrosion resistance. Hence, a combination of hardness and adequate ductility (suitable for cutlery or plastic molds) is attained.

Types 414 and 431 contain 1.25–2.50% nickel, which is enough to increase hardenability, but not enough to make them austenitic at ambient temperature. The addition of nickel serves two purposes: (1) it improves corrosion resistance because it permits a higher chromium content, and (2) it enhances toughness.

Martensitic stainless steels are subject to temper embrittlement and should not be heat treated or used in the range of 800 to 1050ºF (427-566ºC) if toughness is important. The effect of tempering in this range is shown by the graph in Figure 18. Tempering is usually performed above this temperature range.

Impact tests on martensitic grades show that toughness tends to decrease with increasing hardness. High-strength (high-carbon) Type 440A exhibits lower toughness than Type 410. Nickel increases toughness, and Type 414 has a higher level of toughness than Type 410 at the same strength level.

Martensitic grades exhibit a ductile-brittle transition temperature at which notch ductility drops very suddenly. The transition temperature is near room temperature, and at low temperature about -300ºF (-184ºC) they become very brittle, as shown by the data in Figure 19. This effect depends on composition, heat treatment, and other variables.

Clearly, if notch ductility is critical at room temperature or below, and the steel is to be used in the hardened condition, careful evaluation is required. If the material is to be used much below room temperature, the chances are that quenched-and-tempered Type 410 will not be satisfactory. While its notch ductility is better in the annealed condition down to -100ºF (-73ºC), another type of stainless steel is probably more appropriate.

The fatigue properties of the martensitic stainless steels depend on heat treatment and design. A notch in a structure or the effect of a corrosive environment can do more to reduce fatigue limit than alloy content or heat treatment.

Figure 20 gives fatigue data for Type 403 turbine quality stainless at three test temperatures. The samples were smooth and polished, and the atmosphere was air.

Another important property is abrasion or wear resistance. Generally, the harder the material, the more resistance to abrasion it exhibits. In applications where corrosion occurs, however, such as in coal handling operations, this general rule may not hold, because the oxide film is continuously removed, resulting in a high apparent abrasion/corrosion rate.

Other mechanical properties of martensitic stainless steels, such as compressive yield shear strength, are generally similar to those of carbon and alloy steels at the same strength level.

Room-temperature physical properties of Type 410 are shown in Table 10. The property of most interest is modulus of elasticity. The moduli of the martensitic stainless steels (29 x 10^6 psi) (200 GPa) are slightly less than the modulus of carbon steel (30 x 10^6 psi) (207 GPa) but are markedly higher than the moduli of other engineering materials, such as aluminum (10 x 10^6 psi) (67 GPa).

The densities of the martensitic stainless steels (about 0.28 lb. per cu. in.) (7780 Kg/m^3) are slightly lower than those of the carbon and alloy steels. As a result, they have excellent vibration damping capacity.

The martensitic stainless steels are generally selected for moderate resistance to corrosion, relatively high strength, and good fatigue properties after suitable heat treatment. Type 410 is used for fasteners, machinery parts and press plates. If greater hardenability or higher toughness is required, Type 414 may be used, and for better machinability, Types 416 or 416 Se are used. Springs, flatware, knife blades, and hand tools are often made from Type 420, while Type 431 is frequently used for aircraft parts requiring high yield strength and resistance to shock. Cutlery consumes most of Types 440A and B, whereas Type 440C is frequently used for valve parts requiring good wear resistance.

High-carbon martensitic stainless steels are generally not recommended for welded applications, although Type 410 can be welded with relative ease. Hardening heat treatments should follow forming operations because of the poor forming qualities of the hardened steels.

Table 12 MARTENSITIC STAINLESS STEELS (1)
Chemical Analysis % (Max. unless noted otherwise)

Type	C	Mn	P	S	Si	Cr	Ni	Mo	Other
403	0.15	1.00	0.040	0.030	0.50	11.50/13.00			
410	0.15	1.00	0.040	0.030	1.00	11.50/13.50			
414	0.15	1.00	0.040	0.030	1.00	11.50/13.50	1.25/2.50		
416	0.15	1.25	0.060	0.15 (Min)	1.00	12.00/14.00		0.60*	
416 Se	0.15	1.25	0.060	0.060	1.00	12.00/14.00			0.15 Se (Min.)
420	0.15 (Min.)	1.00	0.040	0.030	1.00	12.00/14.00			
420 F	0.15 (Min.)	1.25	0.060	0.15 (Min.)	1.00	12.00/14.00		0.60*	
422	0.20/0.25	1.00	0.025	0.025	0.75	11.00/13.00	0.50/1.00	0.75/1.25	0.15/0.30 V 0.75/1.25 W
431	0.20	1.00	0.040	0.030	1.00	15.00/17.00	1.25/2.50		
440A	0.60/0.75	1.00	0.040	0.030	1.00	16.00/18.00		0.75	
440B	0.75/0.95	1.00	0.040	0.030	1.00	16.00/18.00		0.75	
440C	0.95/1.20	1.00	0.040	0.030	1.00	16.00/18.00		0.75	

*May be added at manufacturer's option

Table 13 Nominal Mechanical Properties
(Annealed sheet unless noted otherwise)

Type	Tensile Strength		Yield Strength (0.2% offset)		Elongation in 2" (50.80 mm)	Hardness (Rockwell)	Product Form
	ksi	MPa	ksi	MPa	%		
403	70	483	45	310	25	B80	
410	70	483	45	310	25	B80	
414	120	827	105	724	15	B98	
416	75	517	40	276	30	B82	(Bar)
416Se	75	517	40	276	30	B82	(Bar)
420	95	655	50	345	25	B92	(Bar)
420F	95	655	55	379	22	220 (Brinell)	(Bar)
422*	145	1000	125	862	18	320 (Brinell)	(Bar)
431	125	862	95	655	20	C24	(Bar)
440A	105	724	60	414	20	B95	(Bar)
440B	107	738	62	427	18	B96	(Bar)
440C	110	758	65	448	14	B97	(Bar)

*Hardened and Tempered

Precipitation Hardening Stainless Steels

The principle of precipitation hardening is that a supercooled solid solution (solution annealed material) changes its metallurgical structure on aging. The principal advantage is that products can be fabricated in the annealed condition and then strengthened by a relatively low-temperature 900-1150ºF (482-620ºC) treatment, minimizing the problems associated with high-temperature treatments. Strength levels of up to 260 ksi (1793 MPa) (tensile) can be achieved – exceeding even those of the martensitic stainless steels – while corrosion resistance is usually superior – nearly equal to that of Type 304 stainless. Ductility is similar to corresponding martensitic grades at the same strength level. Table 15 shows the chemical composition and the nominal mechanical properties of four AISI standard precipitation hardening stainless steels in solution treated and age hardened conditions.

Precipitation hardening stainless steels have high strength, relatively good ductility, and good corrosion resistance at moderate temperatures. They are utilized for aerospace structural components, fuel tanks, landing gear covers, pump parts, shafting, bolts, saws, knives, and flexible bellows-type expansion joints.

Physical properties of UNS S13800 are shown in Table 10.

Table 14

NOMINAL MECHANICAL PROPERTIES

As Quenched Hardness and Properties After Hardening and Tempering 1 in. (25.4 mm) Diameter Bars

Type	UNS	Hardening Temp. °F (°C)	As Quenched Hardness HB	As Quenched Hardness HR	Tempering Temp. °F (°C)	Tensile Strength, ksi (MPa)	Yield Str. 0.2% Offset ksi (MPa)	Elon. in. 2 in. (50.80 mm) %	Red. of Area %	Izod Impact V-Notch Ft. Lbs. (J)	Tempered Hardness HB	Tempered Hardness HR
403 and	S40300	1800 (981)	410	C43	400 (204)	190 (1310)	145 (1000)	15	55	35 (47)	390	C41
410	S41000				600 (315)	180 (1241)	140 (965)	15	55	35 (47)	375	C39
					800* (426)	195 (1344)	150 (1034)	17	55		390	C41
					1000* (538)	145 (1000)	115 (793)	20	65		300	C31
					1200 (648)	110 (758)	85 (586)	23	65	75 (102)	225	B97
					1400 (760)	90 (621)	60 (414)	30	70	100 (136)	180	B89
416 and	S41600	1800 (981)	410	C43	400 (204)	190 (1310)	145 (1000)	12	45	20 (27)	390	C41
416 Se	S41623				600 (315)	180 (1241)	140 (965)	13	45	20 (27)	375	C39
					800* (426)	195 (1344)	150 (1034)	13	50		390	C41
					1000* (538)	145 (1000)	115 (793)	15	50		300	C31
					1200 (648)	110 (758)	85 (586)	18	55	30 (41)	225	B97
					1400 (760)	90 (621)	60 (414)	25	60	60 (81)	180	B89
414	S41400	1800 (981)	425	C44	400 (204)	100 (1379)	150 (1034)	15	55	45 (61)	410	C43
					600 (315)	190 (1310)	145 (1000)	15	55	45 (61)	400	C41
					800 (426)	200 (1379)	150 (1034)	16	58		415	C43
					1000* (538)	145 (1000)	120 (827)	20	60		290	C30
					1200 (760)	120 (827)	105 (724)	20	65	50 (68)	250	C22
431	S43100	1900 (1036)	440	C45	400 (204)	205 (1413)	155 (1069)	15	55	30 (41)	415	C43
					600 (315)	195 (1344)	150 (1034)	15	55	45 (61)	400	C41
					800* (426)	205 (1413)	155 (1069)	15	60		415	C43
					1000* (538)	150 (1034)	130 (896)	18	60		325	C34
					1200 (760)	125 (862)	95 (655)	20	60	50 (68)	260	C24
420	S42000	1900 (1036)	540	C54	600 (315)	230 (1586)	195 (1344)	8	25	10 (14)	500	C50
440A	S44002	1900 (1036)	570	C56	600 (315)	260 (1793)	240 (1655)	5	20	4 (5)	510	C51
440B	S44003	1900 (1036)	590	C58	600 (315)	280 (1931)	270 (1862)	3	15	3 (4)	555	C55
440C	S44004	1900 (1036)	610	C60	600 (315)	285 (1965)	275 (1896)	2	10	2 (3)	580	C57

*Tempering within the range of 750 to 1050 ºF (399 to 565 ºC) is not recommended because such treatment will result in low and erratic impact properties and loss of corrosion resistance. Note. Variations in chemical composition within the individual type ranges may affect the mechanical properties.

Table 15

PRECIPITATION HARDENING STAINLESS STEELS (1)

Chemical Analysis % (Max. unless noted otherwise)

Type	C	Mn	P	S	Si	Cr	Ni	Mo	Other
S13800	0.05	0.10	0.010	0.008	0.10	12.25/13.25	7.50/8.50	2.00/2.50	0.90/1.35 Al 0.010 N
S15500	0.07	1.00	0.040	0.030	1.00	14.00/15.50	3.50/5.50		2.50/4.50 Cu 0.15/0.45 Cb + Ta
S17400	0.07	1.00	0.040	0.030	1.00	15.50/17.50	3.00/5.00		3.00/5.00 Cu 0.15/0.45 Cb + Ta
S17700	0.09	1.00	0.040	0.040	0.040	16.00/18.00	6.50/7.75		0.75/1.50 Al

Nominal Mechanical Properties

(Solution Treated Bar)

Type	Tensile Strength ksi	Tensile Strength MPa	Yield Strength (0.2%offset) ksi	Yield Strength (0.2%offset) MPa	Elongation in 2" (50.80 mm) %	Hardness (Rockwell)
S13800	160	1103	120	827	17	C33
S15500	160	1103	145	1000	15	C35
S17400	160	1103	145	1000	15	C35
S17700	130	896	40	276	10	B90

HIGH TEMPERATURE MECHANICAL PROPERTIES

Stainless steels are used at temperatures up to about 2000ºF (1093ºC) because they have good strength at elevated temperature and good resistance to corrosion and oxidation.

In steam power generation, for example, high allowable design stresses permit the use of thin sections and high operating temperatures. In aircraft and spacecraft design, the AISI numbered stainless steels are used for parts in which hot strength is crucial. Stainless steels are used extensively in heat exchangers in which there is need for both corrosion resistance and hot strength, especially for pressure service. The nuclear power industry represents many high-temperature applications for stainless steels, such as superheaters, boilers, feed-water heaters, valves, and main steam lines.

At steam temperatures over 1050ºF (566ºC), the austenitic stainless steels are preferred. This is illustrated by Table 16, which shows allowable stresses for Type 304 seamless pipe in unfired vessels, as compared with a low-alloy chromium-molybdenum steel.

In analyzing high-temperature properties, hot strength and thermal stability (from the standpoint of softening or embrittlement) are important. Physical properties are also significant.

Figure 21 gives a broad concept of the hot-strength advantages of stainless steels in comparison to low-carbon unalloyed steel. Precipitation hardening stainless steels also have excellent hot strength at moderate temperatures, but their strength declines sharply as they overage at high temperature.

Figure 22 compares the effect of temperature on the strength and ductility of annealed vs. cold worked Type 301. Above 1000ºF (537ºC), design will be based on creep or rupture strength.

Figure 23 shows short-time tensile and yield strengths of various stainless steels.

Table 17 shows creep and rupture strengths of annealed 400 Series stainless steels exposed to temperatures up to 1500ºF (816ºC), while Table 18 shows data for five stainless steels at 1600-2000ºF (871-1093ºC). Figures 24, 25, and 26 show comparative 100,000 hour stress-rupture data for Types 304, 321, and 347, respectively.

These data generally apply to stainless steels normally furnished by mills, but it should be recognized that processing variables can occur. To minimize such variables in materials for high-temperature service, ASTM has established an "H" modification of some AISI numbered stainless steels. This modification establishes a minimum carbon level in grades such as 304H and 321H when the intended application requires good high temperature properties.

Welding can affect high-temperature rupture and creep strength characteristics. Nevertheless, good welding practices result in reliable values.

Pressure vessels and other elevated-temperature equipment are designed to American Society of Mechanical Engineers Boiler and Pressure Vessel Codes. These represent an excellent compendium of minimum requirements for design, fabrication, inspection and construction. Designers should refer to the latest applicable revisions that reflect current technology.

THERMAL STABILITY

With time and temperature, changes in metallurgical structure can be expected for almost any steel or alloy. In stainless steels, the changes can be softening, carbide precipitation, or embrittlement.

Softening occurs in the martensitic stainless steels when exposed to temperatures approaching or exceeding the original tempering temperature. Type 440C, for example, can be held at 900ºF (482ºC) for only short periods if the high hardness is to be retained. Cold-worked austenitic stainless steels, as shown previously in Figure 22, may also soften at elevated temperature.

Embrittlement usually means the loss of room-temperature toughness. Embrittled equipment must be handled carefully to avoid impact when it is cooled down for maintenance. Table 19 shows how prolonged holding at temperatures of 900 to 1200ºF (482-649ºC) can affect room-temperature toughness of various stainless steels, while Figure 27 puts embrittlement in better perspective with respect to the three "general-purpose" types. Note that the transition temperature for Types 410 and 430 is near room temperature, while there is only minor loss of toughness in Type 304. Embrittlement is rarely of concern with austenitic stainless steels.

Ferritic and duplex stainless steels are subject to embrittlement when exposed to temperatures of 700-950ºF over an extended period of time. Martensitic grades with greater than 12% chromium also have been known to display brittle tendencies after extended periods in the same temperature range. This phenomenon is called 885F embrittlement because of the temperature at which embrittlement is most pronounced.

885F embrittlement results in low ductility and increased hardness and tensile strengths at room temperature, and the metal may fracture catastrophically if not handled carefully. The metal, however, retains its desirable mechanical properties at operating temperature (500ºF and higher). The effect of 885F embrittlement can be removed by heat treatment at 1100ºF (593ºC).

Ferritic and duplex grades are subject to sigma-phase embrittlement when exposed to temperatures of 1000-1800ºF (538-987ºC) over extended periods, which also results in loss of room-temperature ductility and corrosion resistance. Sigmaphase can be removed by heat treatment for ferritic grades at 1650ºF (899ºC) followed by air cooling, and at 1900ºF (1038ºC), and higher for duplex grades.

Carbide precipitation occurs (see section on corrosion) in austenitic stainless steels in the temperature range of 800-1600ºF (427-871ºC). This causes a loss of toughness and may make the steel subject to intergranular corrosion in certain environments. It can be removed by heat treatment above 1900ºF (1038ºC).

Brittle failure under load is of concern, especially in welded fabrications. This type of embrittlement is largely a problem at temperatures of 1000-1500ºF (538-816ºC), since strength and not ductility is the limiting factor at higher temperatures. Because of difficulty in evaluating data, and the variable conditions involved, designers are encouraged to seek technical assistance from stainless steel producers.

Physical properties such as linear expansion and thermal conductivity are of interest. Figure 28 shows austenitic stainless steels to have greater thermal expansion than martensitic or ferritic grades. This should be considered when joining dissimilar metals.

Thermal conductivity is also different among different stainless steels. However, in heat exchange applications, film resistance, fouling, and other surface factors have a far greater effect on heat transfer than the alloy itself.

Fluctuating thermal stresses, resulting from periodic changes in temperature, can lead to fatigue problems. A rule of thumb has been used with apparent success: For a 20-year life, a figure of 7000 cycles – corresponding to one cycle a day – has been used in piping design, while 40,000 is the number of temperature swings for process equipment over the same period. The 300 Series stainless steels are more sensitive to thermal fatigue than the 400 Series types.

Table 16
ALLOWABLE STRESS AT MAXIMUM METAL TEMPERATURE (2)

ºF	900		950		1000		1050		1100		1150		1200	
ºC	482		510		538		566		593		621		649	
Type	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
304	10.0	68.9	9.8	67.2	9.5	65.2	9.0	62.1	8.3	56.9	6.9	47.6	5.5	37.9
2¼Cr-1 Mo	13.1	90.3	11.0	75.8	7.8	53.8	5.8	40.0	4.2	29.0	3.0	20.7	2.0	13.8

Table 17
RUPTURE AND CREEP CHARACTERISTICS OF CHROMIUM STAINLESS STEELS IN ANNEALED CONDITION (2)

ºF	800		900		1000		1100		1200		1300		1400		1500	
ºC	427		482		538		593		649		704		760		861	
Type	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
					Stress for rupture in 1000 hours											
405	–	–	25.0	172	16.0	110	6.8	47	3.8	27	2.2	15	1.2	8	0.8	6
410	54.0	372	34.0	234	19.0	131	10.0	69	4.9	34	2.5	18	1.2	8	–	–
430	–	–	30.0	207	17.5	120	9.1	63	5.0	34	2.8	2.0	1.7	12	0.9	6
446	–	–	–	–	17.9	123	5.6	39	4.0	28	2.7	19	1.8	13	1.2	8
					Stress for rupture in 10,000 hours											
405	–	–	22.0	152	12.0	83	4.7	33	2.5	18	1.4	10	0.7	5	0.4	3
410	42.5	294	26.0	179	13.0	90	6.9	47	3.5	24	1.5	10	0.6	4	–	–
430	–	–	24.0	165	13.5	94	6.5	43	3.4	23	2.2	15	0.7	5	0.5	3
446	–	–	–	–	13.5	94	3.0	21	2.2	15	1.6	11	1.1	8	0.8	6
					Stress for creep rate of 0.0001 % per hour											
405	–	–	43.0	296	8.0	55	2.0	14	–	–	–	–	–	–	–	–
410	43.0	296	29.0	200	9.2	63	4.2	29	2.0	14	1.0	7	0.8	6	–	–
430	23.0	159	15.4	106	8.6	59	4.3	30	1.2	8	1.4	10	0.9	6	0.6	4
446	31.0	214	16.4	113	6.1	42	2.8	20	1.4	10	0.7	5	0.3	2	0.1	1
					Stress for creep rate of 0.00001 % per hour											
405	–	–	14.0	97	4.5	32	0.5	3	–	–	–	–	–	–	–	–
410	19.5	135	13.8	96	7.2	49	3.4	24	1.2	8	0.6	4	0.4	3	–	–
430	17.5	120	12.0	83	6.7	46	3.4	24	1.5	10	0.9	6	0.6	4	0.3	2
446	27.0	186	13.0	90	4.5	32	1.8	13	0.8	6	0.3	2	0.1	1	0.05	0.3

Table 18
RUPTURE AND CREEP CHARACTERISTICS OF CHROMIUM-NICKEL STAINLESS STEELS (17)

	Testing temperature		Stress								Extrapolated elogation at rupture in 10,000 hr, %
			Rupture Time						Creep Rate		
			100 hr		1000 hr		10,000 hr		0.01 % hr.		
Type	°F	°C	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	
302	1600	871	4.70	33	2.80	19	1.75	12	2.50	17	150
	1800	982	2.45	17	1.55	11	0.96	7	1.30	9	30
	2000	1093	1.30	9	0.76	5	0.46	3	.62	4	18
309S	1600	871	5.80	40	3.20	22	–	–	3.50	24	–
	1800	982	2.60	18	1.65	11	1.00	7	1.00	7	105
	2000	1093	1.40	10	0.83	6	0.48	3	.76	5	42
310S	1600	871	6.60	45	4.00	28	2.50	17	4.00	28	30
	1800	982	3.20	22	2.10	15	1.35	9	1.75	12	60
	2000	1093	1.50	10	1.10	7	0.76	5	.80	6	60
314	1600	871	4.70	32	3.00	21	1.95	13	2.30	16	110
	1800	982	2.60	18	1.70	12	1.10	8	1.00	7	120
	2000	1093	1.50	10	1.12	7	0.85	6	.90	6	82
316	1600	871	5.00	34	2.70	19	1.40	10	2.60	18	30
	1800	982	2.65	18	1.25	9	0.60	4	1.20	8	35
	2000	1093	1.12	8	0.36	2	–	–	4.00	28	–

Table 19 **EFFECT OF PROLONGED HOLDING AT 900-1200 ºF (482-649ºC) ON ROOM-TEMPERATURE TOUGHNESS AND HARDNESS (2)**																					
	Room-Temperature Charpy keyhole impact strength														Room-temperature Brinell hardness						
			after 1000 hr at						after 10,000 hr at							after 1000 hr at			after 10,000 hr at		
	Unexposed		900(482)		1050(566)		1200ºF(649ºC)		900(428)		1050(566)		1200ºF(649ºC)		Unex-	900	1050	1200ºF	900	1050	1200ºF
Type	ft-lb	J	ft-lb	J	ft-lb	J	ft-lb	J	ft-lb	J	ft-lb	J	ft-lb	J	posed	(482)	(566)	(649ºC)	(482)	(566)	(649ºC)
304	91	123	87	118	75	102	60	81	79	107	62	84	47	64	141	145	142	143	143	132	143
304L	82	111	93	126	76	103	72	98	85	115	71	96	63	85	137	140	134	134	143	143	143
309	95	129	120	163	85	115	43	58	120	163	51	69	44	60	109	114	109	130	140	153	159
310	75	102	–	–	48	65	29	39	62	84	29	39	2	3	124	119	119	130	152	174	269
316	80	108	86	117	72	98	44	60	87	118	49	66	21	28	143	151	148	170	145	163	177
321	107	145	101	137	90	122	69	94	88	119	72	98	62	84	168	143	149	166	156	151	148
347	56	76	60	81	55	75	49	66	63	85	51	69	32	43	169	156	167	169	156	169	123
405	35	47	–	–	36	49	26	35	–	–	39	53	34	46	165	–	143	137	–	143	143
410	33	45	–	–	41	56	27	37	39	53	3	4	21	28	143	–	114	154	124	143	128
430	46	62	–	–	32	43	34	46	1	1	3	4	4	5	184	–	186	182	277	178	156
446	1	1	–	–	1	1	1	1	1	1	1	1	1	1	201	–	211	199	369	255	239

LOW TEMPERATURE MECHANICAL PROPERTIES

Alloys for low-temperature service must have suitable engineering properties, such as yield and tensile strengths and ductility. Experience with brittle fracture of steel ships during World War II demonstrated that many metals may have satisfactory "room-temperature" characteristics but not perform adequately at low temperatures. Low temperature brittle fracture can occur, sometimes with catastrophic failure, without any warning by stretching, sagging, bulging or other indication of plastic failure. Alloys that are ordinarily ductile may suddenly fail at very low levels of stress.

In the handling and storage of liquid gases at cryogenic temperatures, few steels can be used, Austenitic stainless steels are among these few because they exhibit good ductility and toughness at the most severe of cryogenic temperatures – minus 423ºF (253ºC) and lower.

Table 20 shows tensile properties of several stainless steels at cryogenic temperatures. Austenitic grades show not only good ductility down to -423ºF (253ºC), but they also show an increase in tensile and yield strengths.

Toughness is also excellent as indicated by the impact strength values – although there is some decrease as temperature decreases. Table 21 shows results of impact tests on four austenitic grades in different plate thicknesses, indicating that toughness is not markedly affected by section size. Impact tests show that Type 304 is very stable over long periods of exposure and does not exhibit any marked degradation of toughness. Properly made welds also have excellent low temperature properties.

Austenitic grades cold worked to high strength levels are also suitable for low temperature service. Type 310 can be cold worked as much as 85% and still exhibit a good notched-to-unnotched tensile ratio down to -423ºF (-253ºC). Tests indicate that toughness levels at cryogenic temperatures are higher in cold worked Type 310 than in cold worked Type 301.

Table 20 **TYPICAL MECHANICAL PROPERTIES OF STAINLESS STEELS AT CRYOGENIC TEMPERATURES (2)**									
Type	Test Temperature		Yield Strength 0.2% Offset		Tensile Strength		Elongation in 2"	Izod Impact	
	ºF	ºC	ksi	MPa	ksi	MPa	%	ft. lbs.	J
304	– 40	– 40	34	234	155	1,069	47	110	149
	– 80	– 62	34	234	170	1,172	39	110	149
	–320	–196	39	269	221	1,524	40	110	149
	–423	–252	50	344	243	1,675	40	110	149
310	– 40	– 40	39	269	95	655	57	110	149
	– 80	– 62	40	276	100	689	55	110	149
	–320	–196	74	510	152	1,048	54	85	115
	–423	–252	108	745	176	1,213	56		
316	– 40	– 40	41	283	104	717	59	110	149
	– 80	– 62	44	303	118	814	57	110	149
	–320	–196	75	517	185	1,276	59		
	–423	–252	84	579	210	1,448	52		
347	– 40	– 40	44	303	117	807	63	110	149
	– 80	– 62	45	310	130	896	57	110	149
	–320	–196	47	324	200	1,379	43	95	129
	–423	–252	55	379	228	1,572	39	60	81
410	– 40	– 40	90	621	122	841	23	25	34
	– 80	– 62	94	648	128	883	22	25	34
	–320	–196	148	1,020	158	1,089	10	5	7
430	– 40	– 40	41	283	76	524	36	10	14
	– 80	– 62	44	303	81	558	36	8	11
	–320	–196	87	607	92	634	2	2	3

HEAT TRANSFER PROPERTIES

Stainless steels are used extensively for heat exchangers because their ability to remain clean enhances heat transfer efficiency. For example, Figure 29 illustrates that films and scale on exchanger surfaces impair heat transfer to a far greater extent than the metal wall, which accounts for only 2% of the total resistance to heat flow. Table 22 supports this contention by showing that thermal conductivity of a metal has only a minor effect on the "U" valve, or the overall heat-transfer coefficient.

The degree to which other factors affect heat transfer are dependent on the type of fluid involved, its velocity, and the nature of scale or fouling buildup on the surface. Since corrosion and scale accumulation is minimal with stainless steels, there would be less difference in service performance among various metals than would be indicated by thermal conductivity data. The power generation industry, for instance, has very carefully analyzed transfer characteristics of heat exchanger materials and has conclusively demonstrated that stainless steels behave in a manner far superior to other materials.

Figure 30 compares two condenser tubing materials exposed simultaneously to identical operating conditions. In the early stages of the test the relative performance of both materials corresponded to published thermal conductivity figures. However, in only 240 days, the overall heat transfer rate of the stainless steel was found to surpass that of the Admiralty brass. The heat transfer rate for both materials decreased with time, but that of the Admiralty brass was more rapid due to fouling and corrosion, while the stainless steel was affected only by fouling. Similar results were observed in desalination tests conducted in Freeport, Texas. Two booklets on heat exchangers are available from the Nickel Development Institute. One is “A Discussion of Stainless Steels for Surface Condenser and Feedwater Heater Tubing,” and the other, “The Role of Stainless Steels in Industrial Heat Exchangers.”

Table 21
LOW-TEMPERATURE IMPACT STRENGTH OF SEVERAL ANNEALED AUSTENITIC STAINLESS STEELS (2)

AISI Type	Testing Temp ºF	Testing Temp ºC	Specimen orientation	Type of notch	Product size	Energy absorbed, ft-lb	Energy absorbed, J
304	– 320	– 196	Longitudinal	Keyhole	3-in. plate	80	108
304	– 320	– 196	Transverse	Keyhole	3-in. plate	80	108
304	– 320	– 196	Transverse	Keyhole	2½-in. plate	70	95
304	– 423	– 252	Longitudinal	Keyhole	½-in. plate	80	108
304	– 423	– 252	Longitudinal	V-notch	3½-in. plate	91.5	124
304	– 423	– 252	Transverse	V-notch	3½-in. plate	85	115
304L	– 320	– 196	Longitudinal	Keyhole	½-in. plate	73	99
304L	– 320	– 196	Transverse	Keyhole	½-in. plate	43	58
304L	– 320	– 196	Longitudinal	V-notch	3½-in. plate	67	91
304L	– 423	– 252	Longitudinal	V-notch	3½-in. plate	66	90
310	– 320	– 196	Longitudinal	V-notch	3½-in. plate	90	122
310	– 320	– 196	Transverse	V-notch	3½-in, plate	87	118
310	– 423	– 252	Longitudinal	V-notch	3½-in. plate	86.5	117
310	– 423	– 252	Transverse	V-notch	3½-in. plate	85	115
347	– 320	– 196	Longitudinal	Keyhole	½-in. plate	60	81
347	– 320	– 196	Transverse	Keyhole	½-in. plate	47	64
347	– 423	– 252	Longitudinal	V-notch	3½-in. plate	59	80
347	– 423	– 252	Transverse	V-notch	3½-in. plate	53	72
347	– 300	– 184	Longitudinal	V-notch	6½-in. plate	77	104
347	– 300	– 184	Transverse	V-notch	6½-in. plate	58	79

Table 22
EFFECT OF METAL CONDUCTIVITY ON "U" VALUES (18)

Application	Material	Film Coefficients Btu/hr/ft²/°F (W/m²•K) h_o	Film Coefficients h_i	Thermal Conductivity of Metal Btu/hr/ft²/°F/in. (W/m•K)	"U" Value Btu/hr/ft²/°F (W/m²•K)
Heating water with saturated steam	Copper	300 (1704)	1000 (5678)	2680 (387)	229 (1300)
	Aluminum	300 (1704)	1000 (5678)	1570 (226)	228 (1295)
	Carbon Steel	300 (1704)	1000 (5678)	460 (66)	223 (1266)
	Stainless Steel	300 (1704)	1000 (5678)	105 (15)	198 (1124)
Heating air with saturated steam	Copper	5 (28)	1000 (5678)	2680 (387)	4.98 (28)
	Aluminum	5 (28)	1000 (5678)	570 (226)	4.97 (28)
	Carbon Steel	5 (28)	1000 (5678)	460 (66)	4.97 (28)
	Stainless Steel	5 (28)	1000 (5678)	105 (15)	4.96 (28)

Where h_o=outside fluid film heat-transfer coefficient
h_i=inside fluid film heat-transfer coefficient
Stainless steel is 300 Series Type

$$\text{“U”} = \frac{1}{\frac{1}{h_o} + \frac{\text{thickness of metal wall}}{\text{thermal conductivity}} + \frac{1}{h_i}}$$

SHAPES, SIZES, AND FINISHES

Exhibit 1 illustrates mill processes for making various stainless steel products. Because alloy composition must be very carefully controlled, various refining steps are used in conjunction with electric furnace (or vacuum furnace) melting and at the Argon Oxygen Decarburization (AOD) vessel. Other refining steps are vacuum arc, partial pressure inert gas arc, electron beam, and electroslag consumable arc remelting practices. During these remelting steps, certain impurities are reduced to minimum levels, and inclusion levels are lowered.

During the final stages of producing basic mill forms – sheet, strip, plate, and bar – and bringing these forms to specific sizes and tolerances, the materials are subjected to hot reduction with or without subsequent cold rolling operations, annealing, and cleaning. Further steps are required to produce other mill forms, such as wire and tubing.

Table 23 shows how the mill forms are classified by size, and Tables 24, 25, and 26 identify finishes and conditions in which sheet, bar, and plate are available.

Finishes are produced by three basic methods. These are (1) rolling between polished or textured rolls, (2) polishing and/or buffing with abrasive wheels, belts, or pads, and (3) blasting with abrasive grit or glass beads. The resulting surface textures vary from the "natural" appearance produced by hot or cold rolling (or by extrusion) to mirror-bright surfaces.

Rolled finishes result from the initial forming of the metal at the mill. These are the simplest and usually the lowest in cost, and they include a wide range of appearance depending on the character of the rolls themselves, which can be highly polished or etched to produce a dull matte finish.

Patterned finishes are also made by rolling, and they are available in a wide variety of sculptural designs and textures, all of which are proprietary in nature and not included in AISI numbered finish designations. These are produced either by passing mill-rolled finished sheet between two mating rolls of specific design or by impressing different patterns on each side of the sheet. These finishes usually have the added advantage of stiffness. They are supplied by some mills and by specialty processors.

Polished finishes are produced by mechanical polishing, and sometimes by buffing, and are characterized by fine parallel grit lines – the fineness being determined by the grit size used in the final step. These grit lines can impart a directional character to the finish, which when present should be considered in final product design. Some polished and buffed finishes are produced by some mill and specialty processors.

Blast finishes are applied by conventional blasting techniques using glass beads.

While finishes are usually selected for appearance, selection cannot be made independently of fabrication considerations. For example, if evidence of exposed welds is to be removed, rolled nondirectional finishes are generally not specified because they cannot be blended or refinished. A polished finish such as No. 4, on the other hand, can be blended by matching grit size to that used for the original polish. It is also important to consider the effects of various fabrication methods used in the manufacture of the stainless steel products. Severe forming, for example, can distort or locally remove grit lines, so it may be necessary to refinish the surface after fabrication, such as in the manufacture of pots and pans.

It should also be recognized that each finish can have variations in appearance depending upon composition, thickness, method of application, and supplier. In rolled finishes, the thinner the sheet, the smoother the surface. The 200 and 300 Series stainless steels have a characteristically different appearance than 400 Series types. Color variations may occur among the different types within the same metallurgical category. The practicability of describing any of the finishes in terms of measurable limits, such as for smoothness or reflectance, has not been established, so designers are encouraged to provide samples showing the final finish desired.

Tables 24, 25, and 26, as mentioned previously, show AISI numbered finishes and conditions for sheet, bar and plate. While there are no specific designations for polished finishes on bar or plate, the sheet finish designations are often used to describe the desired effect. This also applies to finishes on ornamental tubing.

There are three standard finishes for strip, which are broadly described by the finishing operations employed:

No. 1 Strip Finish is approximately the same as No. 2D Sheet Finish. It varies in appearance from dull gray matte to a fairly reflective surface, depending largely on alloy composition and amount of cold reduction.

No. 2 Strip Finish is approximately the same as a No. 2B sheet finish. It is smoother, more reflective than No. 1, and likewise varies with alloy composition.

Bright Annealed Finish is a highly reflective finish that is retained by final annealing in a controlled atmosphere furnace.

Mill-Buffed Finish is a bright cold rolled, highly reflective finish obtained on either No. 2 or on bright annealed strip by continuously buffing in coil form. The purpose of mill-buffing is to provide a uniform finish with regard to color and reflectivity. It can also provide a surface receptive to chromium plating. The finish has wide use in automotive trim, household trim, tableware, utensils, fire extinguishers, plumbing fixtures, etc.

Because of the wide variety of standard and nonstandard finishes, designers are encouraged to examine samples before selecting a finish.

FABRICATION

Stainless steels are generally selected, first on the basis of corrosion resistance and, second, do the basis of strength or other mechanical properties. A third-level consideration is fabrication. While the three general-purpose stainless types predominate, namely Types 304, 430, and 410, there are variations of these types that are better suited to certain manufacturing operators. (Service requirements may preclude the use of these variations, so it is well to know that all stainless steels can be readily fabricated by conventional manufacturing methods.)

The handbook "Stainless Steel Fabrication" is available from the SSINA and describes these alloys and various fabrication methods.

HOT FORMING

Stainless steels are readily formed by hot operations such as rolling, extrusion, and forging – methods that result in finished or semifinished parts.

Hot rolling is generally a steel mill operation for producing standard mill forms and special shapes. Exhibit 2 illustrates the variety of hot-rolled, cold-rolled, and cold-drawn shapes available in stainless steel bar.

Exhibit 3 provides some design guidelines for extrusion.

Forging is used extensively for stainless steels of all types (Exhibit 4).

Exhibit 1
The Making of Stainless Steel

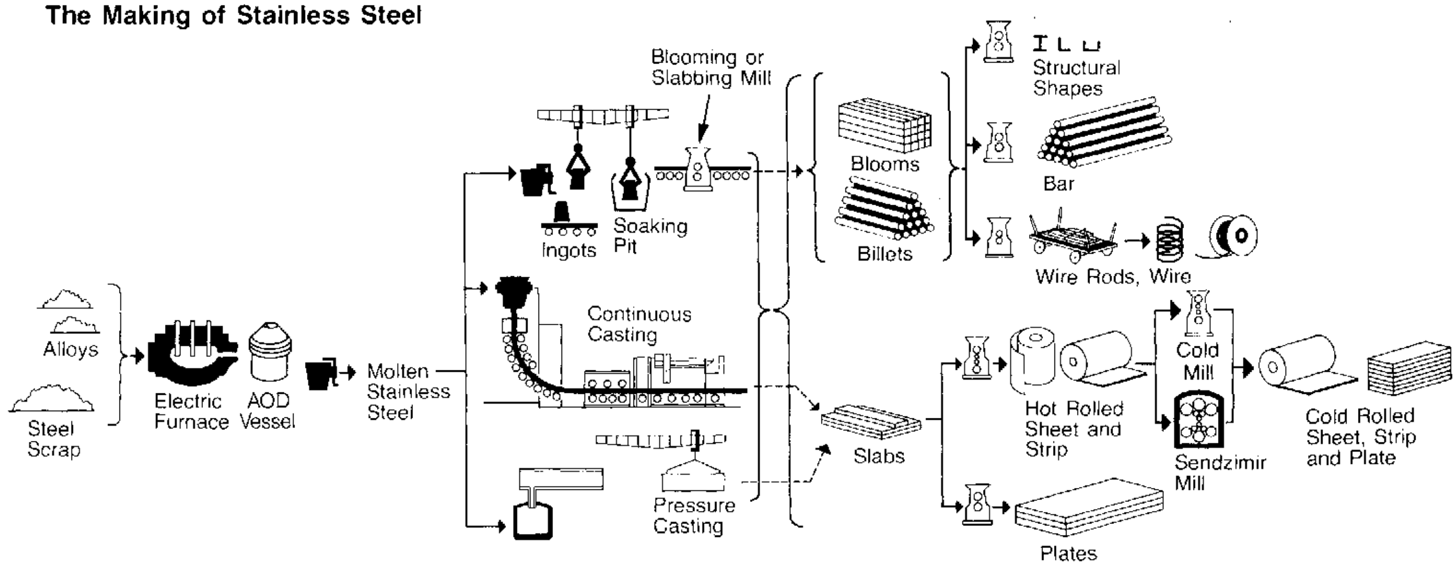


Table 23
CLASSIFICATION OF STAINLESS STEEL PRODUCT FORMS (2)

Item	Description	Dimensions		
		Thickness	**Width**	**Diameter or Size**
Sheet	Coils and cut lengths: Mill finishes Nos. 1, 2D & 2B Pol. finishes Nos. 3, 4, 6, 7 & 8	under 3/16" (4.76 mm) " " "	24" (609.6 mm) & over all widths	-
Strip	Cold finished, coils or cut lengths Pol. finishes Nos. 3, 4, 6, 7 & 8	under 3/16" (4.76 mm) " " "	under 24" (609.6 mm) all widths	-
Plate	Flat rolled or forged	3/16" (4.76 mm) & over	over 10" (254 mm)	-
Bar	Hot finished rounds, squares, octagons and hexagons Hot finished flats Cold finished rounds, squares, octagons and hexagons Cold finished flats	- 1/8" (3.18 mm) to 8"(203 mm) incl. - 1/8" (3.18 mm) to 4½" (114 mm)	- ¼" (6.35 mm) to 10" (254 mm) incl. - 3/8" (9.53 mm) to 4½" (114 mm)	¼" (6.35 mm) & over - over 1/8" (3.18 mm) -
Wire	Cold finishes only: (in coil) Round, square, octagon, hexagon, and flat wire	under 3/16" (4.76 mm)	under 3/8" (9.53 mm)	-
Pipe & Tubing	Several different classifications, with differing specifications, are available, For information on standard sizes consult your local Steel Service Center or the SSINA.			
Extrusions	Not considered "standard" shapes, but of potentially wide interest. Currently limited in size to approximately 6½" (165.1 mm) diameter, or structurals.			

Table 24
STANDARD MECHANICAL SHEET FINISHES (2)

Unpolished or Rolled Finishes:

No. 1 A rough, dull surface which results from hot rolling to the specified thickness followed by annealing and descaling.

No. 2D A dull finish which results from cold rolling followed by annealing and descaling, and may perhaps get a final light roll pass through unpolished rolls. A 2D finish is used where appearance is of no concern.

No. 2B A bright, cold-rolled finish resulting in the same manner as No. 2D finish, except that the annealed and descaled sheet receives a final light roll pass through polished rolls. This is the general-purpose cold-rolled finish that can be used as is, or as a preliminary step to polishing.

Polished Finishes;

No. 3 An intermediate polish surface obtained by finishing with a 100-grit abrasive. Generally used where a semifinished polished surface is required. A No. 3 finish usually receives additional polishing during fabrication.

No. 4 A polished surface obtained by finishing with a 120-150 mesh abrasive, following initial grinding with coarser abrasives. This is a general-purpose bright finish with a visible "grain" which prevents mirror reflection.

No. 6 A dull satin finish having lower reflectivity than No. 4 finish. It is produced by Tampico brushing the No. 4 finish in a medium of abrasive and oil. It is used for architectural applications and ornamentation where a high luster is undesirable, and to contrast with brighter finishes.

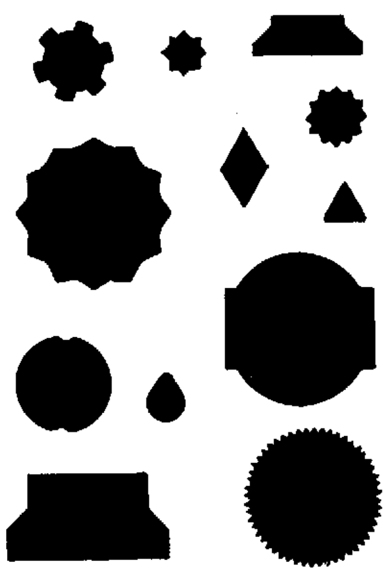
No. 7 A highly reflective finish that is obtained by buffing finely ground surfaces but not to the extent of completely removing the "grit" lines. It is used chiefly for architectural and ornamental purposes.

No. 8 The most reflective surface; which is obtained by polishing with successively finer abrasives and buffing extensively until all grit lines from preliminary grinding operations are removed. It is used for applications such as mirrors and reflectors.

Exhibit 2

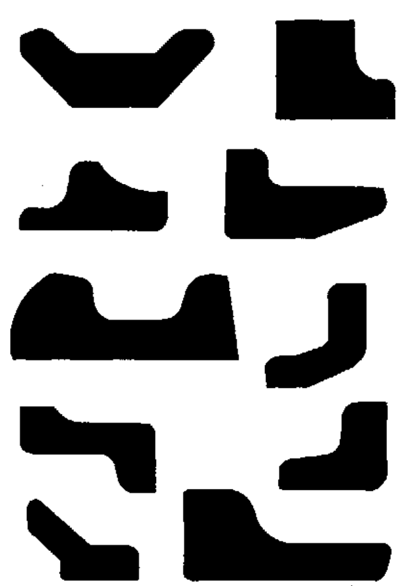
COLD-DRAWN SHAPES . . .

For achieving superior mechanical properties, lower machining costs, faster production and reduced scrap loss.



HOT-ROLLED SHAPES . . .

For applications where parts are made from straight lengths, curved pieces; or are to be formed into rings, welded and finish-machined.



COLD-ROLLED SHAPES . . .

For applications where parts require close tolerance, fine surface finishes, superior mechanical properties.

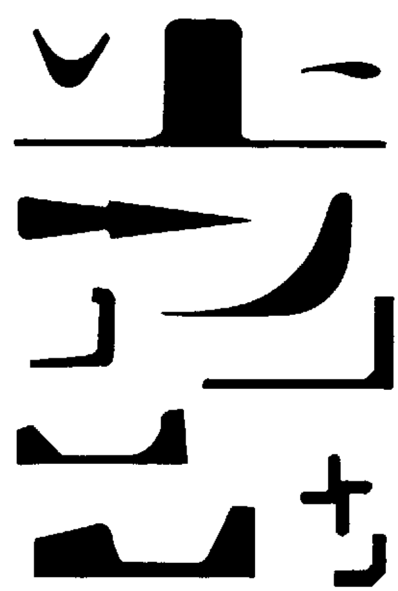


Exhibit 3
Extrusion Guidelines

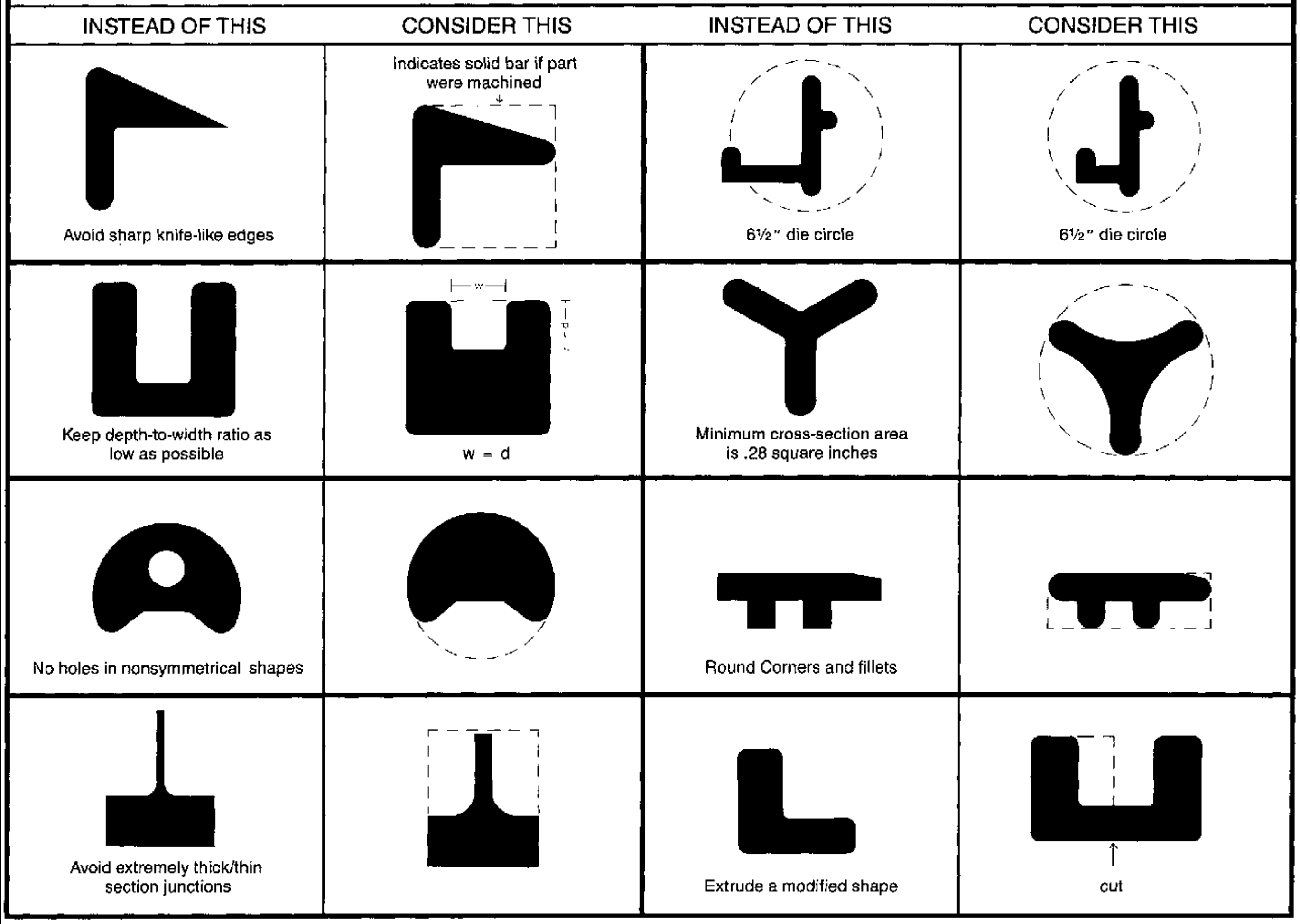


Exhibit 4

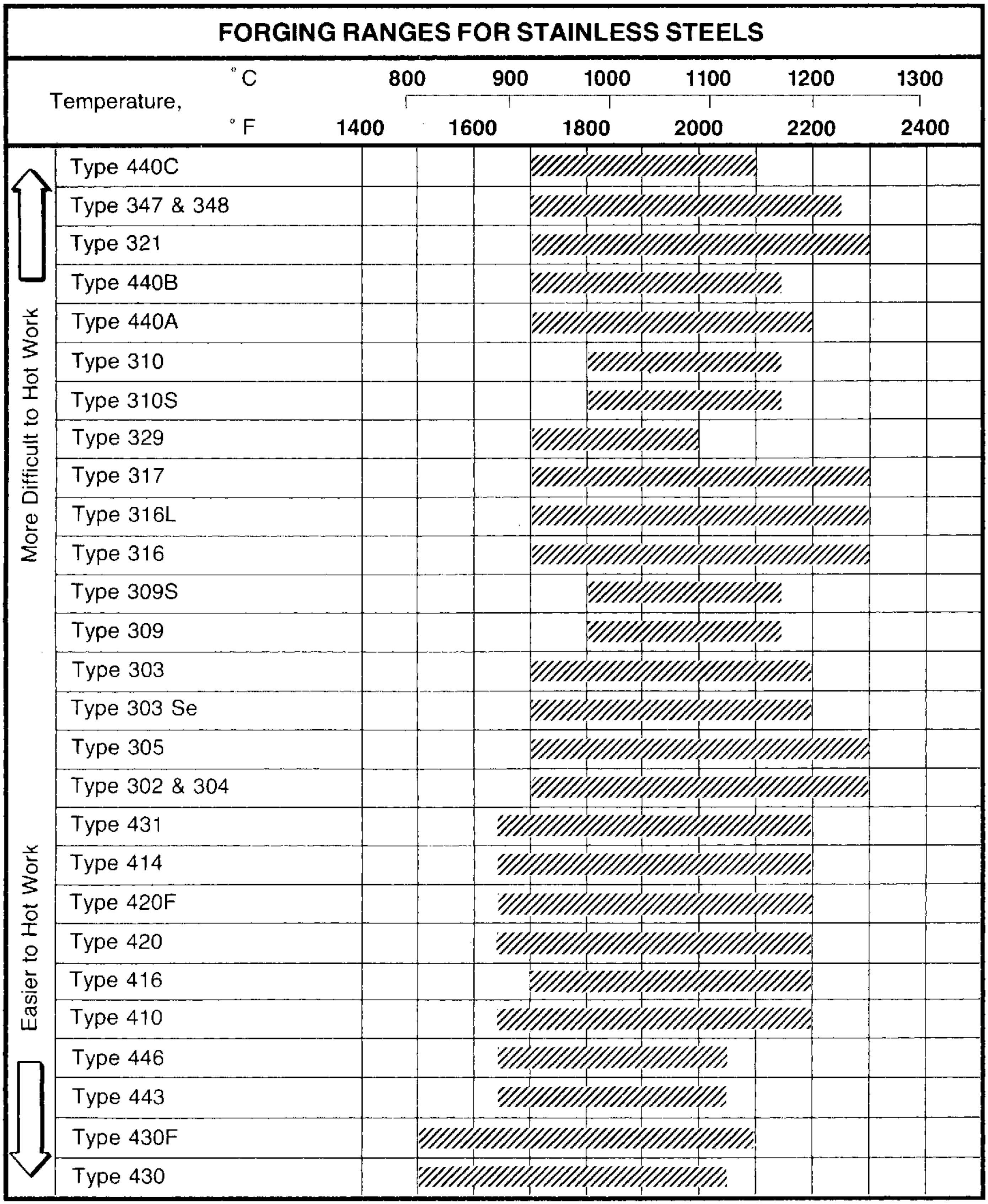

FORGING RANGES FOR STAINLESS STEELS
Temperature, °C
800
900
1000
1100
1200
1300
°F
1400
1600
1800
2000
2200
2400
More Difficult to Hot Work
Easier to Hot Work
Type 440C
Type 347 & 348
Type 321
Type 440B
Type 440A
Type 310
Type 310S
Type 329
Type 317
Type 316L
Type 316
Type 309S
Type 309
Type 303
Type 303 Se
Type 305
Type 302 & 304
Type 431
Type 414
Type 420F
Type 420
Type 416
Type 410
Type 446
Type 443
Type 430F
Type 430

Table 25

CONDITIONS & FINISHES FOR BAR (2)

Conditions		Surface Finishes*
1. Hot worked only	(a)	Scale not removed (excluding spot condition ing)
	(b)	Rough turned**
	(c)	Pickled or blast cleaned and pickled
2. Annealed or otherwise heat treated	(a)	Scale not removed (excluding spot condition ing)
	(b)	Rough turned
	(c)	Pickled or blast cleaned and pickled
	(d)	Cold drawn or cold rolled
	(e)	Centerless ground
	(f)	Polished
3. Annealed and cold worked to high tensile strength***	(d)	Cold drawn or cold rolled
	(e)	Centerless ground
	(f)	Polished

* Surface finishes (b), (e) and (f) are applicable to round bars only.

** Bars of the 4xx series stainless steels which are highly hardenable, such as Types 414, 420, 420F, 431, 440A, 440B and 440C, are annealed before rough turning. Other hardenable grades, such as Types 403, 410, 416 and 416Se, may also require annealing depending on their composition and size.

*** Produced in Types 302, 303Se, 304 and 316.

Table 26

CONDITIONS & FINISHES FOR PLATE (2)

Condition and Finish	Description and Remarks
Hot rolled	Scale not removed. Not heat treated. Plates not recommended for final use in this condition.*
Hot rolled, annealed or heat treated	Scale not removed. Use of plates in this condition is generally confined to heat resisting applications. Scale impairs corrosion resistance.*
Hot rolled, annealed or heat treated, blast cleaned or pickled	Condition and finish commonly preferred for corrosion resisting and most heat resisting applications.
Hot rolled, annealed, descaled and temper passed	Smoother finish for specialized applications.
Hot rolled, annealed, descaled cold rolled, annealed, descaled, optionally temper passed	Smooth finish with greater freedom from surface imperfections than the above.
Hot rolled, annealed or heat treated, surface cleaned and polished	Polished finishes: refer to Table 24.

*Surface inspection is not practicable on plates which have not been pickled or otherwise descaled.

Table 27
RELATIVE FORMING CHARACTERISTICS OF AISI 200 AND 300 SERIES (2)
(Not Hardenable by Heat Treatment)

Forming Method	201	202	301	302	302B	303, 303Se	304	304L	305	308	309	309S	310	310S	314	316	316L	317	321	347, 348	384
Blanking	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Brake forming	B	A	B	A	B	D	A	A	A	B	A	A	A	A	A	A	A	A	A	A	B
Coining	B-C	B	B-C	B	C	C-D	B	B	A-B	D	B	B	B	B	B	B	B	B	B	B	A
Deep drawing	A-B	A	A-B	A	B-C	D	A	A	B	D	B	B	B	B	B-C	B	B	B	B	B	B
Embossing	B-C	B	B-C	B	B-C	C	B	B	A-B	D	B	B	B	B	B-C	B	B	B	B	B	A-B
Forging, cold	C	B	C	B	B	D	B	B	A-B	D	B-C	B-C	B	B	B-C	B	B	B	B	B	A
Forging, hot	B	B	B	B	B	B-C	B	B	B	B	B-C	B-C	B-C	B-C	B-C	B	B	B-C	B	B	B
Heading, cold	C-D	C	C-D	C	D	D-C	C	C	B-A	D	C	C	C	C	C-D	C	C	C	C	C	A
Heading, hot	B	B	B	B	B	C	B	B	B	B	C	C	C	C	C	B	B	B-C	C-B	C-B	B
Punching	C	B	C	B	B	B	B	B	B	–	B	B	B	B	B	B	B	B	B	B	B
Roll forming	B	A	B	A	–	D	A	A	A	–	B	B	A	A	B	A	A	B	B	B	A
Sawing	C	C	C	C	C	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Spinning	C-D	B-C	C-D	B-C	C	D	B	B	A	D	C	C	B	B	C	B	B	B-C	B-C	B-C	A

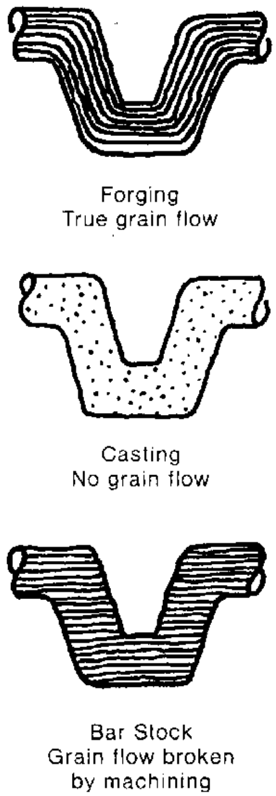
A = Excellent B = Good C = Fair D = Not generally recommended
Note: Ratings are for making comparisons of alloys within their own metallurgical group. They should not be used to compare 300 Series with 400 Series types.

Table 28
RELATIVE FORMING CHARACTERISTICS OF AISI 400 SERIES (2)

Forming Method	FERRITIC (Not Hardenable by Heat Treatment) 430	430F, 430FSe	405	429	434	436	442	446	MARTENSITIC (Hardenable by Heat Treatment) 410	403	414	416, 416Se	420	420F	431	440A	440B	440C
Blanking	A	B	A	A	A	A	A	A	A	A	A	B	B	B	C-D	B-C	–	–
Brake forming	A*	B-C*	A*	A*	A*	A*	A"	A*	A*	A*	A*	C*	C*	C*	C*	C*	–	–
Coining	A	C-D	A	A	A	A	B	B	A	A	B	D	C-D	C-D	C-D	D	D	D
Deep drawing	A-B	D	A	A-B	B	B	B	B-C	A	A	B	D	C-D	C-D	C-D	C-D	–	–
Embossing	A	C	A	A	A	A	B	B	A	A	C	C	C	C	C-D	C	D	D
Forging, cold	B	D	B	B	B	B	B-C	C	B	B	C	D	C-D	C-D	C-D	C-D	D	D
Forging, hot	B	C	B	B	B	B	B-C	B-C	B	B	B	C	B	B	B	B	B	B
Hardening by cold work, typical tensile strength (1000 psi)																		
Annealed	73	75	–	–	–	–	–	–	90	90	–	70	–	–	–	–	–	–
25% reduction	96	95	–	–	–	–	–	–	120	120	–	90	–	–	–	–	–	–
50% reduction	115	110	–	–	–	–	–	–	130	130	–	105	–	–	–	–	–	–
Hardening by heat treatment	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Heading, cold	A	D	A	A	A	A	B	C	A	A	D	D	C	C	C-D	C	C-D	C-D
Heading, hot	B	C	B	B	B	B	B-C	B-C	B	B	B	C	B	B	B	B	B	B
Punching	A-B	A-B	A-B	A-B	A-B	A	A-B	B	A-B	A-B	B	A-B	B-C	B-C	C-D	–	–	–
Roll forming	A	D	A	A	A	A	A	B	A	A	C	D	C-D	C-D	C-D	C-D	–	–
Sawing	B	A-B	B	B	B	B	B-C	B-C	B	B	C	B	C	C	C	C	C	C
Spinning	A	D	A	A	A-B	A-B	B-C	C	A	A	C	D	D	D	D	D	D	D

A = Excellent B = Good C = Fair D = Not generally recommended *Severe sharp bends should be avoided

Exhibit 5



A unique feature of forgings is that the continuous grain flow follows the contour of the part, as illustrated by the top drawing in Exhibit 5. In comparison is the random grain structure of a cast part (center) and the straight-line orientation of grain in a machined part (bottom). From this difference stem secondary advantages inherent in forged stainless steels as follows:

Strength where needed. Through grain refinement and flow, forging puts the strength where it's needed most.

Lighter weight. Higher strength-to-weight ratio permits the use of thinner, light weight sections without sacrificing safety.

Improved mechanical properties. Forging develops the full impact resistance, fatigue resistance, ductility, creep-rupture life, and other mechanical properties of stainless steels.

Repeatable dimensions. Tolerances of a few thousandths are routinely maintained from part to part, simplifying final fixturing and machining requirements.

Structural uniformity. Forgings are sound, nonporous, and uniform in metallurgical structure. The booklet, "Stainless Steel Forgings," available from NiDI discusses in greater detail the forgability of stainless steels, and it provides guidelines for designing stainless forgings.

COLD FORMING

The mechanical properties of stainless steels serve as an indication of their relative formability at ambient or room temperature. Annealed austenitic grades are typified as having low yield strengths, high tensile strengths, and high elongations. Some of these alloys work harden to a high degree, which further increases their strength properties. The ferritic alloys have much lower ductility than the austenitic types and are closer to carbon steel with respect to mechanical properties; and they do not work harden significantly during cold forming.

Because of their excellent mechanical properties, stainless steels have excellent cold-forming characteristics. Table 27 shows the relative fabrication characteristics of the austenitic stainless steels and Table 28 shows the relative fabrication characteristics of the martensitic and ferritic grades.

Sheet, Strip and Plate

The bending characteristics of annealed austenitic stainless steels, as indicated by Table 29, are considered excellent. Many types will withstand a free bend of 180 degrees with a radius equal to one-half the material thickness or less. In a controlled V-block, the bend angle limit is 135 degrees. As the hardness of the stainless increases, bending becomes more restrictive. This is indicated by the data in Table 30 which show, for example, the free-bend characteristics of Type 301 in the ¼, ½, ¾, and full-hard temper. The bend characteristics of the 400 Series types, shown in Table 31 are also good. However, they tend to be somewhat less ductile than the 300 Series types, so the minimum bend radius is equal to the material thickness.

Table 29
BENDING CHARACTERISTICS: Annealed Stainless Steel Sheet & Strip (2)

Type	Free Bend	V-Block
301, 302, 304, 305, 309, 310, 316, 321, 347	180° R=½T	135° R=½T

NOTE: R=radius of bend; T=thickness of material. All bends are parallel to direction of rolling.

Table 30
BENDING CHARACTERISTICS: Temper Rolled Stainless Steel Sheet & Strip (2)

Type	Temper	Gage 0.050 in. (1.27 mm) and under	Gage 0.051 in.-0.187 in. (1.30-4.75 mm)
		Free Bend	
301	¼ hard	180° R=½T	90° R=T
301	½ hard	180° R=T	90° R=T
301	¾ hard	180° R=1½T	–
301	full hard	180° R=2T	–
302	¼ hard	180° R=½T	90° R=T
316	¼ hard	180° R=T	90° R=T
		V-Block	
301	¼ hard	135° R=T	135° R=1½T
301	½ hard	135° R=2T	135° R=2T
301	¾ hard	135° R=3T	–
301	full hard	135° R=3T	–
302	¼ hard	135° R=2T	135° R=2T
316	¼ hard	135° R=2½T	135° R=3T

NOTE: R=radius of bend; T=thickness of material. All bends are parallel to direction of rolling.

Table 31 Typical Bending Characteristics of Annealed Stainless Steel Sheet, Strip and Plate (2)				
AISI Type	Gage to 0.374" (9.50 mm)		Gage 0.375" to 0.500" (9.53-12.7 mm)	
	Free Bend	V-Block	Free Bend	V-Block
405	180° R=T	135° R=T	180°R=T	135° R=2T
410	180° R=T	135° R=T	180°R=T	135° R=2T
430	180° R=T	135° R=T	180°R=T	135° R=2T
442	180° R=T	135° R=T	180°R=2T	135° R=2T
446	180° R=T	135° R=T	180°R=2T	135° R=2T

NOTE: R=radius of bend; T=thickness of material. All bends are parallel to direction of rolling.

In simple bending operations, there is little need to consider variations of the general-purpose alloys, since all stainless steels within a metallurgical group tend to behave in a similar manner. However, in the more complex forming operations in which the metal is pressed, drawn, or stretched, considerable latitude exists for alloy selection. This can be visualized somewhat when one considers the need for extensive work hardening when a part is made essentially by stretching.

All of the 300 Series alloys work harden considerably and can be stretched severely, but this property is exemplified by Type 301. During stretching, holddown pressures are applied to the flange areas to prevent metal from flowing into the die. During this stretch, severe metal thinning occurs. However, as the metal thins it work-hardens sufficiently to exceed the strength in the thicker (less strong) sections, thus preventing cracking or tearing. A good example of stretching and the need for Type 301 is the manufacture of automobile wheel-covers.

At the other extreme is Type 305 with a low work-hardening rate that prevents excessive strengthening. It has good ductility and is an excellent choice for deep drawing in which little hold-down pressure is used. The use of this material can minimize annealing for multiple draws.

Between Types 301 and 305 is Type 304, which is the preferred choice when the forming operation combines both drawing and stretching.

The ferritic stainless steels do not exhibit nearly as high ductility as the austenitic types, nor do they have significant work-hardening traits. Their formability is thus more like that of carbon steel in that they cannot be stretched without thinning and fracturing – and formability usually decreases with increasing chromium content. In addition, these grades can show brittle tendencies that become more pronounced with increasing chromium content. To offset this factor, moderate warming of the higher chromium types is often recommended prior to drawing.

Bar and Wire

Many components of stainless steel are made from bar or wire with cold heading being the most widely used forming method. Many types of stainless are available as cold heading wire.

However, for multiple-blow operations in which a number of forming steps are performed in rapid sequence, it is desirable to use a material with good ductility but with a low work-hardening rate. Three stainless steels predominate in this respect; Types 305, 384, and (UNS) S30430. These three are similar to Type 304 in terms of corrosion resistance and mechanical properties.

With a chromium-nickel ratio less than that of Type 304, Type 305 has less tendency to work harden. Accordingly, a greater amount of deformation is possible before annealing is necessary. It is also readily available as bar and wire for cold heading, cold extrusion, and other cold-forming processes. In terms of corrosion resistance, it is freely interchangeable with Type 304. Type 305 resists attack by nitric acid and is used in a wide range of organic and inorganic chemicals, foodstuffs, and sterilizing solutions. It also has good high-temperature scaling resistance, and is utilized for continuous service at 1600ºF (871ºC). Unlike Type 304, however, Type 305 remains nonmagnetic even after severe cold work.

Type 384 is widely used for fasteners, cold-headed bolts, screws, upset nuts, and instrument parts, also for severe coining, extrusion, and swaging. It is also ideally suited for thread rolling. Because Type 384 is similar in chromium content to Type 304, it generally can be used anywhere that Type 304 is used. Exhibit 6 truss square shoulder bolt warm-headed in Type 384.

Both Types 305 and 384 are subject to carbide precipitation if heated or cooled slowly in the range of 800-1650ºF (427-899ºC). This can lead to intergranular corrosion in aggressive environments. This condition can be corrected, however, by annealing and water quenching from at least 1900ºF (1038ºC).

Type (UNS) S30430 is one of the most widely used cold-heading stainless steels that is often identified by a popular trade name 304 HQ. Its composition is similar to that of Type 304 except that it contains 3.00-4.00% copper. This eliminates cracking, especially in recessed heads, and results in improved tool performance. It becomes mildly magnetic after severe cold working.

The three types just described are the principal stainless steels used for cold-heading operations. However, many other stainless steel types are available as coldheading wire. They include Types 410, 430, 440C, (UNS) S17400 (a precipitation hardening type) and several proprietary stainless alloys.

It is well to keep in mind that the inherent high strength of stainless steels requires more power in forming than that for forming carbon steel. And since many of the alloys work harden rapidly in cold-forming operations, there is need for added power after the start of initial deformation. The booklet, "Cold Forming Stainless Steel Bar and Wire," which is available from NiDI, describes in greater depth the selection of materials and the design of products to be fabricated by cold forming methods.

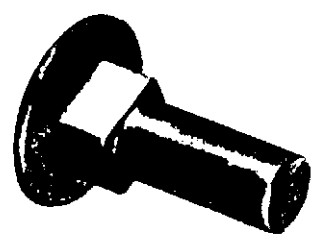
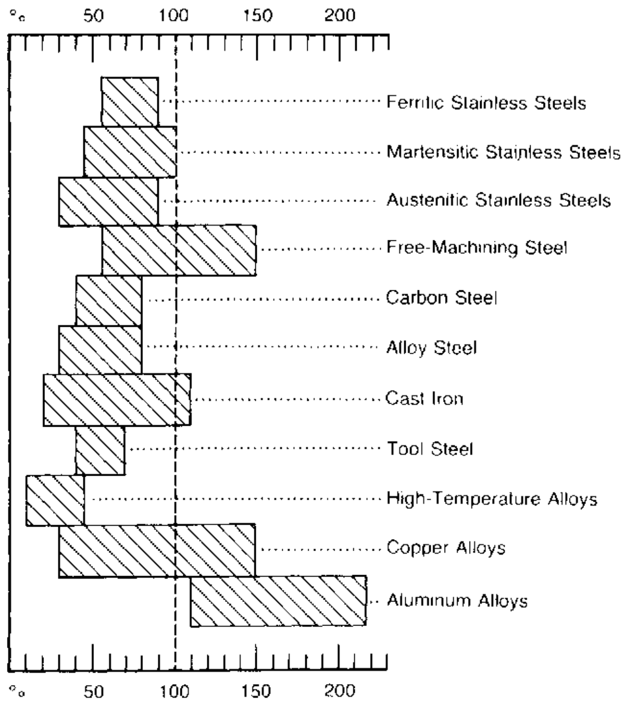


Exhibit 6

A warm-headed truss square shoulder bolt of Type 384 stainless. By using warm heading, less forming pressure was required on the die resulting in increased tool life.

Exhibit 7

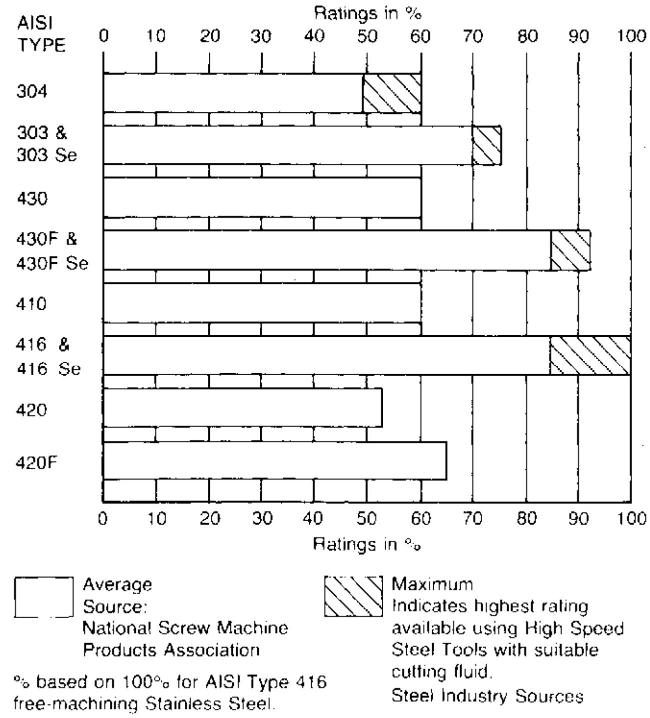
Comparative Machinability of Common Metals



100% Type 416 Stainless Steel

Exhibit 8

Comparative Machinability of Frequently Used Stainless Steels and Their Free-Machining Counterparts



It has been traditional in machining literature to compare the machinability of various metals to AISIB-1112 which is a free-machining carbon steel. However, since Type 416 stainless steel has a machining rating equal to that of B-1112, and since B-1112 is no longer on the market, comparisons in this booklet will be made with Type 416 as the base at 100%.

MACHINING

The machining characteristics of stainless steels are substantially different from those of carbon or alloy steels and other metals, as illustrated in Exhibit 7, "Comparative Machinability of Common Metals." In varying degree, most stainless steels without composition modification are tough, rather gummy, and they tend to seize and gall.

While the 400 Series stainless steels are the easiest to machine, a stringy chip produced during the machining, can slow productivity. The 200 and 300 Series, on the other hand, have the most difficult machining characteristics, primarily because of their propensity to work harden at a very rapid rate.

An experienced machine shop production engineer can work around these conditions and achieve good productivity with any of the stainless steels. However, wherever conditions permit, the design engineer can help minimize problems and get maximum machining productivity. Here are three suggestions: (1) specify a free-machining stainless steel, (2) suggest to the production engineer that he use a special analysis stainless steel that is "more suited for machining," or (3) specify stainless steel bar for machining that is in a slightly hardened condition.

Free-Machining Stainless Steels

Some stainless steel compositions contain sulfur, selenium, lead, copper, aluminum, or phosphorus – either separately or in combination – in sufficient quantity to improve the machining characteristics of the metal. These alloying elements reduce the friction between the workpiece and the tool, thereby minimizing the tendency of the chip to weld to the tool. Also, sulfur and selenium form inclusions that reduce the friction forces and transverse ductility of the chips, causing them to break off more readily. The improvement in machinability in the free-machining stainless steels – namely Types 303, 303 Se, 430F, 430F Se, 416, 416 Se, and 420F – is clearly evident in Exhibit 8, "Comparative Machinability of Frequently Used Stainless Steels." (Also, excellent are several proprietary free-machining alloys.)

Suppose, for example, that Type 304 is being considered on the basis of corrosion resistance and strength, but the machine shop needs the best possible machining rate. Type 303 could be specified as an alternate, provided its properties meet end-use requirements and 304 is not specifically requested. The chromium, nickel, and sulfur contents of Type 303 are slightly different than those of Type 304, and as a result Type 303 can be machined at speeds about 25-30% faster than Type 304.

Type 303 Se is another free-machining stainless steel similar to Type 303 except that it contains selenium as the ingredient to enhance the machining characteristics. It is used for better surface finishes or when cold working may be involved, such as staking, swaging, spinning, or severe thread rolling, in addition to machining.

If end-use conditions call for Type 430 stainless, the designer can specify free-machining Types 430F or 430F Se, which have similar properties although less corrosion resistance. Type 430F contains more sulfur, while 430F Se contains selenium instead of a high sulfur content.

The free-machining choices in lieu of Type 410 are Types 416 (higher sulfur) or 416 Se (selenium). And for Type 420, the shop might consider Type 420F.

It should be understood that the alloying elements used to improve the free-machining characteristics of stainless steels can adversely affect corrosion resistance, transverse ductility, and other qualities, such as weldability. These grades should be used only after careful consideration, but when used, they will machine at significantly higher production rates.

Special Analysis Stainless Steels

If, for example, end-use conditions are too restrictive to permit the use of Type 303 instead of Type 304, designers might suggest using Type 304 with a special analysis that has somewhat better machining qualities but with very little difference in corrosion resistance. In melting of special analysis stainless steels, minor modifications are made in the composition to enhance certain characteristics of the metal. A stainless steel producer should be consulted.

Hardened Stainless Steel Bar

When conditions require maximum resistance to corrosion in the alloy selected, and there is no room for compromise in the composition of the stainless steel, the machine shop can order bar stock in a slightly hardened condition that may result in a small improvement in machinability. Under any circumstances, and especially when corrosive environments are involved, it is always good practice to consult with a stainless steel producer.

Screw Machining Operations

Automatic screw machining is a fast and efficient method for machining that benefits greatly from the use of the free-machining stainless steels. In many typical screw machine applications, parts are turned out at rates as high as 300 to 400 pieces per hour. However, one should not have any misgivings about screw machining any of the stainless steels. With appropriate design and good shop practices, even the non free-machining types can be handled at relatively high rates. The machinability of stainless steels in general has improved significantly in the past few years, primarily through melting and refining practices that permit tighter analysis control.

JOINING

Welding

Nearly all of the stainless steels can be welded by most methods employed by industry today. Because of differences between these alloys and carbon or low-alloy steels, however, there are variations in welding techniques. First, it is important that procedures be followed to preserve corrosion resistance in the weld and in the area immediately adjacent to the weld, referred to as the heat-affected-zone (HAZ). Second, it is desirable to maintain optimum mechanical properties in the joint, and, third, certain steps are necessary to minimize problems of heat distortion. The principal difference between stainless and other steel types is alloy content, which provides corrosion resistance. In welding, it is necessary to select a weld rod that provides weld filler metal having corrosion resistant properties as nearly identical to the base metal as possible or better. This is not always as obvious as some might expect. For instance, a Type 308 weld rod is specified for welding Type 304, and a 300 Series rod is often used for joining 400 Series types. The best suggestion is to follow American Welding Society (AWS) practices for weld rod selection (and weld procedures as well) or to consult weld rod manufacturers. The latter have up-to-date tables for rod selection. Proper weld rod selection not only insures preservation of the corrosion resistant properties, but it is also important in achieving optimum mechanical properties.

Another principal difference between austenitic stainless and carbon or low-alloy steels is thermal conductivity, with stainless about half that of other steels. Hence, heat is not dissipated as rapidly.

There are four methods to accommodate this situation: lower weld current settings, skip-weld techniques to minimize heat concentration, use of back-up chill bars or other cooling techniques to dissipate heat, and proper joint design. The first three methods fall in the realm of welding shop procedures that are often adequately covered by AWS recommended practices and welding shop standard practices. It is always good policy, however, for designers to double check to see that the welding shop follows proper procedures. Also, it is often desirable to provide specimen welds for establishing quality. These precautions are important because corrosion problems often begin in weld areas. One problem, discussed earlier, is carbide precipitation (sensitization) that can lead to intergranular corrosion in corrosive environments. The lack of proper heat dissipation can also lead to heat distortion of the finished product that can be unacceptable for aesthetic reasons.

From the designer's viewpoint, joint configuration can also encourage heat dissipation. For this reason, the use of beveled joints is common in thinner gages, which in carbon steel might be welded as a square-edge butt. Beveling permits the use of several light passes, thus avoiding the high temperature that would be reached in a single, heavy pass.

Cleaning of the edges to be welded is also important. Contamination from grease and oil can lead to carburization in the weld area with subsequent reduction of corrosion resistance. Post weld clean-up is also important and should not be done with carbon steel files and brushes. Carbon steel cleaning tools, as well as grinding wheels that are used on carbon steel, can leave fine particles imbedded in the stainless steel surface that will later rust and stain if not removed by chemical cleaning.

Martensitic Stainless Steels

There is always the possibility of metallurgical change during cooling, which can lead to cracking. This can be offset by preheating and postheating to reduce the cooling rate. Filler metal for welds can be identical to the base metal or it can be an austenitic stainless steel composition.

Ferritic Stainless Steels

The three major difficulties associated with welding ferritic stainless steels are (1) excessive grain growth, (2) sensitization, and (3) lack of ductility. Heat treating after welding can minimize some of these problems, or one of the proprietary ferritic alloys with lower carbon and nitrogen contents can be specified. Filler metal can be of either a similar composition or an austenitic composition (Types 308, 309, 316L, or 310), which is helpful in improving ductility and toughness.

Austenitic Stainless Steels

The 200 and 300 Series are the most weldable of the stainless steels. The problems that arise relate mainly to sensitization in the heat-affected-zone, which can be minimized by using the low-carbon or stabilized grades.

Preheating is not required; postheating is necessary only to redissolve precipitated carbides and to stress relieve components that are to be used in environments that may cause stress corrosion cracking.

The coefficient of expansion of austenitic types is higher than that of carbon steels; hence thermal contraction is greater. Precautions are necessary to avoid bead cracking and minimize distortion, such as sound fixtures, tack welding, skip welding, copper chill bars, minimum heat input, and small weld passes.

Precipitation Hardening Stainless Steels

The precipitation hardening grades are suited to welding with little need for pre- or post-heat treatment except to restore or improve mechanical properties.

Free-Machining Stainless Steels

Problems of porosity and segregation arise when free-machining types are welded. However, special filler rods (Type 312) are available that, with careful exclusion of hydrogen from the weld, will assist welding.

Soldering

Stainless steels are readily soldered with relatively few problems arising from temperature. Aggressive fluxes, however, are necessary to prepare the surface for soldering. Phosphoric acid type fluxes are preferred because they are not corrosive at room temperature.

Brazing

All stainless steels can be brazed, but because the brazing alloys are usually composed of copper, silver, and zinc, high temperatures are required. Care must be taken that the brazing cycle does not cause such high-temperature problems as carbide precipitation and a lessening of corrosion resistance.

Fastening

Although fasteners are available in many materials, stainless fasteners are a good first choice, especially if the materials being joined are stainless. Stainless fasteners are easy to make, in both standard and special designs, and they are readily available.

Since corrosion resistance is an important aspect of product reliability, inherent in any attempt to prevent corrosion is the careful selection of fastener materials. A common practice in industry is to use fasteners made of metals or alloys that are equal to or more corrosion resistant than the materials they join. This practice is justified because the fasteners may have to withstand higher loads with greater unit stress than the parts being held together, and they are usually considerably smaller in surface area than the material being joined. Also, corrosion-weakened fasteners may lead to a more immediate failure with more serious consequences than the same amount of corrosive attack elsewhere in the assembly.

Corrosion protection for a fastened joint encompasses much more than a consideration of the corrosion resistance of the fastener itself. Required is an analysis of the entire assembled joint as a system. This system includes structural design, material stresses, product life expectancy and environmental conditions.

Where two dissimilar metals are in contact in the presence of an electrolyte, a battery effect is created, current flows, and one of the metals corrodes. In considering a bimetallic couple, it is important to know which of the two metals is more anodic (less noble). A guide to this is the arrangement of metals in the galvanic series chart shown in Exhibit 9. Any metal in this series will tend to have corrosion accelerated when it is coupled, in the presence of an electrolyte, with a metal in a lower position on the chart. The corrosion of this lower metal will tend to be reduced, or even avoided.

A very important factor to consider in evaluating the potential for galvanic corrosion is the relative surface area of the two different metals in contact. For example, carbon steel is located above stainless steel in the galvanic series and is accordingly subject to accelerated corrosion when a galvanic couple is established. But the extent of this galvanic action depends on the relative surface area of each material. For instance, if small steel fasteners, such as rivets, are used to join stainless steel plates, and the assembly is exposed to water, the steel rivets will corrode quickly. If, on the other hand, stainless rivets are used to join steel plates in water, both rivets and plates will suffer negligible galvanic attack, even in the immediate vicinity of the rivets. Aircraft designers, for instance, who specify stainless steel fasteners in aluminum structures depend upon this area-relationship principle.

When the designer has determined candidate fastener materials on the basis of their corrosion-resistant properties, his next concern probably will be the mechanical and physical properties of these materials. Once again, the group of stainless steels covers a wide choice. The choice need not be difficult if the designer uses the guidelines available to him, such as the specifications published by the Industrial Fasteners Institute (IFI).

Data on stainless steel fasteners are available from NiDI in the booklet, "Stainless Steel Fasteners, A Systematic Approach to Their Selection."

Exhibit 9

Galvanic Series of Metals and Alloys in Sea Water (14)

Magnesium	Anodic ↑
Zinc	More Likely to Be
Alclad 3003	Attacked
Aluminum 3003	
Aluminum 6061	
Aluminum 6063	
Aluminum 5052	
Mild Steel	
Low Alloy Steel	
Cast Iron	
Stainless Steels (Active)	
Muntz Metal	
Yellow Brass	
Red Brass	
Copper	
Aluminum Bronze	
Silver	
Stainless Type 430 (Passive)	
Stainless Type 304 (Passive)	
Stainless Type 316 (Passive)	
Monel	More Noble
Gold	Cathodic ↓

SURFACE PROTECTION AND CLEANING

Stainless steels must have clean surfaces to offer optimum corrosion resistance. Design engineers should take steps to see that fabricators either protect the metal surface from contamination during forming or other manufacturing steps or restore the surface by mechanical or chemical cleaning.

Metal particles from steel dies can become imbedded in the surface of the stainless at pressure points. This pickup will rust and stain the surface when exposed to moisture. Chromium plated dies, or a paper or plastic protective covering on the stainless steel being formed, can prevent such problems during many fabrication steps, except for the more severe operations, such as forging, machining, heading, coining, drawing, welding, or spinning.

In the case of protective coverings, a number of materials are available. Such coverings should be selected on the basis of their ability to remain intact during layout and fabrication, and on the basis of their ability to be removed readily.

When stainless cannot be protected by covering, procedures should be employed to keep the material clean. Rusty water drips, dirt from overhead cranes, unclean handling equipment, even dust from open doors, can be sources of staining. Perhaps the most severe problems arise in shops that work on carbon steel as well as stainless. Using grinding tools on stainless that were previously used on carbon steel can leave particles on the stainless surface that will later rust and stain. In such cases, the best procedure is to chemically clean the stainless after fabrication, in solutions that will dissolve the carbon steel particles, such as solutions of nitric acid and water.

From a practical standpoint, the composition of the cleaning bath is not important as long as it serves the function of chemically cleaning the surface without harm or discoloration. Procedures and makeup of solutions are widely published or are available from companies listed on the back cover of this booklet.

It is also important to see that stainless components are thoroughly clean prior to heat treatment. Lubricants, grease, or foreign particles can burn into the steel surface during heating, which can increase the cost of final cleaning or, in extreme cases, render the parts unusable, if appearance is a vital factor.

When stainless steels are heated for forging, annealing, or hardening, an oxidized scale forms on the surface. If not removed, the scale lowers corrosion resistance and can interfere with subsequent operations. Scale can be removed mechanically by glass bead blasting or tumbling, or by chemical pickling. The type or degree of scaling determines the method of cleaning. Frequently, both glass bead blasting and chemical clearing are used. Composition of pickling baths vary widely so fabricators are encouraged to seek advice from stainless steel producers.

Note: ASTM A380 is a good reference on cleaning procedures and surface treatments for stainless steel.

APPENDIX A
CORROSION CHARACTERISTICS

Pitting occurs when the protective film breaks down in small isolated spots, such as when halide salts contact the surface. Once started, the attack may accelerate because of differences in electric potential between the large area of passive surface vs. the active pit.

Pitting is avoided in many environments by using Types 316 and 317, which contain molybdenum. The four alloys in Table I, plus Type 317, performed well in desalination environments during a three-year test conducted by the Committee of Stainless Steel Producers in Freeport, Texas.

Table I	
ALLOY	**UNS**
Alloy 6X (20Cr-23Ni-6Mo)	N08366
Alloy 216 (19.75Cr-6Ni-8.25Mn - 2.5Mo-0.37N)	S21600
Nitronic 50® (22Cr-13Ni-5Mn-2.25Mo)	S20910
®Registered Trademark of Armco Steel Corporation	
Alloy 20Cb-3® (20Cr-33Ni-2.5Mo-3.5Cu)	N08020
®Registered Trademark of Carpenter Technology	

Crevice Corrosion results from local differences in oxygen concentration associated with deposits on the metal surface, gaskets, lap joints, or crevices under bolt or rivet heads where small amounts of liquid can collect and become stagnant. The material responsible for the formation of a crevice need not be metallic. Wood, plastics, rubber, glass, concrete, asbestos, wax, and living organisms have all been reported to cause crevice corrosion. Once attack begins within the crevice, its progress is very rapid, especially in chloride environments. For this reason, the stainless steels containing molybdenum are often used to minimize the problem. Notwithstanding, the best solution to crevice corrosion is a design that eliminates crevices.

Stress Corrosion Cracking is caused by the combined effects of tensile stress and corrosion. Many alloys systems have been known to experience stress corrosion cracking – brass in ammonia, carbon steel in nitrate solutions, titanium in methanol, aluminum in sea water, and gold in acetic acid. Stainless steels are susceptible to stress corrosion cracking in chloride environments. It is necessary for tensile stress, chlorides and elevated temperature all to be present for stress corrosion cracking to occur. Wet-dry or heat transfer conditions, which promote the concentration of chlorides, are particularly aggressive with respect to initiating stress corrosion cracking. While the mechanism of stress corrosion cracking is not fully understood, laboratory tests and service experience have resulted in methods to minimize the problem. For instance, alloy 2205 (a duplex stainless containing 21-23% chromium, 4.5-6.5% nickel, and 2.5-3.5% molybdenum plus nitrogen) exhibits superior resistance to chloride stress corrosion cracking; plus it has a general corrosion and pitting resistance similar to Type 317. Studies by Climax Molybdenum Company indicate that Type 317 with 3.5% (minimum) molybdenum has excellent resistance, and it has been shown to perform well in a flue-gas desulfurization environment. Several proprietary austenitic stainless steels also have shown resistance to stress cracking in hot chloride environments.

The ferritic stainless steels, such as Types 405 and 430, should also be considered when the potential exists for stress-corrosion cracking.

The corrosion resistance of ferritic stainless steels is improved by increased chromium and molybdenum contents, while ductility, toughness, and weldability are improved by reducing carbon and nitrogen contents. The commercialization of new melting and refining processes has resulted in several new ferritic stainless steels with improved characteristics, which can be classified as follows; those with about 18% chromium having corrosion resistance similar to Type 304, and those with more than 18% chromium with resistance to corrosion comparable or superior to Type 316 in many media. With two exceptions (439, 444), these ferritic stainless steels are not AISI numbered grades. Some of these stainless steels are listed in Table II.

The high-chromium ferritic types have resistance to chlorides previously obtainable only in high-nickel and titanium alloys.

Table II		
ALLOY	**ASTM**	**UNS**
18 Cr and Ti	439	S43035
18 Cr - 2 Mo	444	S44400
18 Cr - 2 Mo + S	XM-34	S18200
26 Cr - 1 Mo	XM-27	S44625
26 Cr - 1 Mo - Ti	XM-33	S44626
29 Cr - 4 Mo		S44700
29 Cr - 4 Mo - Ti/Cb		S44735
29 Cr - 4 Mo - 2 Ni		S44800

Other Corrosion Types should be considered when using stainless steels, such as corrosion fatigue, delayed brittle fracture and hydrogen stress cracking. Corrosion fatigue is encountered in cyclic loading in a corrosive environment. Brittle fracture is caused by hydrogen impregnation of an alloy during processing, which leads to brittle failure when subsequently loaded. Hydrogen stress cracking results from a cathodic reaction in service.

The austenitic stainless steels resist hydrogen effects, but martensitic and precipitation-hardening alloys may be susceptible to both hydrogen stress cracking and chloride stress-corrosion cracking.

Sulfide ions, selenium, phosphorus and arsenic compounds increase the propensity for hydrogen to enter hardenable stainless steels and cause hydrogen stress cracking. Their presence should warn of a failure possibility. Cathodic protection can also cause hydrogen stress cracking of high-strength alloys in service, if "overprotected." Therefore, cathodic protection, or coupling hardenable stainless steels to less-noble materials in corrosive environments should be used with caution.

Excessive exposure of duplex stainless steels to 1300 to 1750ºF (700 to 955ºC) tends to form intermetallic compounds such as sigma phase or chi phase. These compounds of iron, chromium, and molybdenum are highly detrimental to corrosion resistance and toughness.

Intergranular Corrosion

When austenitic stainless steels are heated or cooled through the temperature range of about 800-1650ºF (427-899ºC), the chromium along grain boundaries tends to combine with carbon to form chromium carbides. Called carbide precipitation, or sensitization, the effect is a depletion of chromium and the lowering of corrosion resistance in areas adjacent to the grain boundary. This is a time temperature dependent phenomenon, as indicated in Figure 4 (See Appendix B).

Sensitization may result from slow cooling from annealing temperatures, stress-relieving in the sensitization range, or welding. Due to the longer time at temperature of annealing or stress-relieving, it is possible that the entire piece of material will be sensitized, whereas the shorter time at temperature characteristic of welding can result in sensitization of a band, usually 1/8 to ¼ inch wide, adjacent to but slightly removed from the weld. This region is known as the Heat-Affected-Zone or HAZ.

Intergranular corrosion depends upon the magnitude of the sensitization and the aggressiveness of the environment to which the sensitized material is exposed. Many environments do not cause intergranular corrosion in sensitized austenitic stainless steel. For example, glacial acetic acid at room temperature or fresh clean water do not; strong nitric acids do. Carbide precipitation and subsequent intergranular corrosion in austenitic stainless steels have been thoroughly investigated; the causes are understood and methods of prevention have been devised. These methods include:

1. Use of stainless steel in the annealed condition.
2. Selection of the low-carbon (0.030% maximum) stainless steels for weld fabrication. Low-carbon grades are Types 304L, 316L, and 317L. The less carbon available to combine with the chromium, the less likely is carbide precipitation to occur. However, the low-carbon grades may become sensitized at extremely long exposures to temperatures in the sensitization range.
3. Selection of a stabilized grade, such as Type 321 (titanium stabilized) or Type 347 (columbium stabilized), for service in the 800-1650ºF (427-899ºC) range. The protection obtained with these grades is based upon the greater affinity of titanium and columbium for carbon as compared to chromium.

   Columbium stabilization is preferred because its carbides are more readily retained in welds and it is easier to add in the steelmaking process. However, the use of columbium stabilized steel requires additional care in welding.
4. Redissolving carbides by annealing parts after fabrication, although this is not always practical.

It should be understood that the above steps are necessary only if the service environment is known to be capable of causing intergranular corrosion.

Although sensitization can also occur in the ferritic stainless steels (heated to 1700ºF (927ºC) and water quenched or air cooled) it is far less likely to occur than with austenitic grades, and intergranular corrosion has not been a problem in these steels–except for a narrow band in the heat-affected-zone close to welds. (Most of the proprietary ferritic stainless steels mentioned earlier are stabilized to prevent sensitization during welding.) Galvanic corrosion is discussed briefly in the section on fasteners, page 29.

HIGH TEMPERATURE CORROSION RESISTANCE

Stainless steels have been widely used for elevated-temperature service, so fundamental and practical data concerning their resistance to corrosion are available.

When stainless steels are exposed at elevated temperatures, changes can occur in the nature of the surface film. For example, at mildly elevated temperatures in an oxidizing gas, a protective oxide film is formed.

In more aggressive environments, with temperatures above 1600ºF (871ºC), the surface film may break down with sudden increase in scaling. Depending on alloy content and environment, the film may be self healing for a period of time followed by another breakdown.

Under extreme conditions of high temperature and corrosion, the surface film may not be protective at all.

For these reasons, the following data should serve only as a starting point for material selection, not as a substitute for service tests.

Oxidation

In nonfluctuating-temperature service, the oxidation resistance (or scaling resistance) of stainless steels depends on chromium content, as indicated by the curve in Figure 5. Steels with less than 18% chromium (ferritic grades primarily) are limited to temperatures below 1500ºF (816ºC). Those containing 18-20% chromium are useful to temperatures of 1800ºF (982ºC), while adequate resistance to scaling at temperatures up to 2000ºF (1093ºC) requires a chromium content of at least 22%, such as Types 309, 310 or 446.

The maximum service temperature based on a rate of oxidation of 10 mg. per sq. cm. in 1000 hours is given for several stainless steels in Table III for nonfluctuating-temperature. The corrosion resistance of several stainless steels in steam and oxidizing flue gases, compared with their corrosion resistance in air, is shown in Figure 6.

In many processes, isothermal (constant temperature) conditions are not maintained and process temperatures vary. The temperature limits under variable conditions are shown in Table III in the column "Intermittent Service." Expansion and contraction differences between the base metal and the protective film (or scale) during heating and cooling cause cracking and spalling of the protective scale. This allows the oxidizing media to attack the exposed metal surface.

The spalling resistance of the austenitic stainless steels is greatly improved at higher nickel levels, as illustrated in Figure 7. Nickel reduces the thermal expansion differential between alloy and oxide film and thereby reducing stresses at the alloy-oxide interface during cooling. Also, Type 446 and the proprietary ferritic chromium-molybdenum stainless steels have a fairly low coefficient of thermal expansion, which tends to enhance spalling resistance.

A number of proprietary austenitic stainless steels that rely on silicon, aluminum, or cerium additions for improved oxidation resistance are listed in ASTM A240 and other product specifications.

Effect of Atmosphere

Much attention has been given to the compatibility of stainless steels with air or oxygen. However, trends in the design of steam and other forms of power generation have resulted in a growing interest in oxidation in such environments as carbon monoxide, carbon dioxide, and water vapor. Exposure to mild conditions in these environments leads to the formation of the protective oxide film described earlier, but when conditions become too severe, film breakdown can occur. The onset of this transition is unpredictable and sensitive to alloy composition.

Although the reaction mechanisms are probably similar in air, oxygen, water vapor, and carbon dioxide, reaction rates may vary considerably. For example, similar scaling behavior has been observed in air and oxygen except that scale breakdown occurs more rapidly in oxygen. For this reason, results obtained in air should be applied with care when considering service in pure oxygen.

An increase in corrosion rates can be expected in the presence of water vapor. Figure 8 illustrates the effect of moist air on the oxidation of Types 302 and 330. Type 302 undergoes rapid corrosion in wet air at 2000ºF (1093ºC), whereas a protective film is formed in dry air. The higher nickel Type 330 is less sensitive to the effects of moisture, so it is assumed that increased chromium and nickel permits higher operating temperatures in moist air. Types 309 and 310 are superior at temperatures greater than 1800ºF (982ºC), and Type 446 is usable at temperatures approaching 2000ºF (1093ºC). The addition of moisture to oxygen significantly increases the corrosion rates of Types 304, 321, 316 and 347, and for the other grades listed in Table III, the temperature limits should be adjusted downwards.

Table III
Suggested Maximum Service Temperatures in Air

AISI Type	Intermittent Service		Continuous Service	
	ºC	ºF	ºC	ºF
201	815	1500	845	1550
202	815	1500	845	1550
301	840	1550	900	1650
302	870	1600	925	1700
304	870	1600	925	1700
308	925	1700	980	1800
309	980	1800	1095	2000
310	1035	1900	1150	2100
316	870	1600	925	1700
317	870	1600	925	1700
321	870	1600	925	1700
330	1035	1900	1150	2100
347	870	1600	925	1700
410	815	1500	705	1300
416	760	1400	675	1250
420	735	1350	620	1150
440	815	1500	760	1400
405	815	1500	705	1300
430	870	1600	815	1500
442	1035	1900	980	1800
446	1175	2150	1095	2000

It is difficult to indicate maximum service temperatures for steam service, one reason being the sensitivity of corrosion rate to surface condition. (Cold worked surfaces tend to reduce corrosion effects in steam service.) Most austenitic stainless steels can be used at temperatures up to 1600ºF (871ºC), and Types 309, 310, and 446 at higher temperatures. Types 304, 321, and 347 are being used in low-pressure steam systems at temperatures approaching 1400ºF (760ºC). Scale on Types 304, 347, and 316 tends to exfoliate at higher temperatures.

The oxidation of stainless steels in carbon dioxide and carbon dioxide-carbon monoxide atmospheres at 1100-1800ºF (593-982ºC) is of interest because of their use in gas-cooled nuclear reactors. Type 304 is serviceable in this environment, although some proprietary stainless steels offer better resistance.

A note of caution about stainless steels at high temperatures in stagnant oxidizing environments: The protective film breaks down in the presence of certain metal oxides, causing accelerated attack. For instance, austenitic types are susceptible to attack in the presence of lead oxide at temperatures as low as 1300ºF (704ºC). Vanadium oxide, found in fuel ash, may cause failure of Types 309 and 310 at 1900ºF (1038ºC) when water vapor is present. Molybdenum oxide behaves in a similar manner.

Sulfidation

Sulfur in various forms and even in relatively small quantities accelerates corrosion in many environments. Sulfur dioxide, hydrogen sulfide, and sulfur vapor are among the most corrosive forms. Sulfur vapor and hydrogen sulfide are considerably more aggressive than sulfur dioxide.

Sulfur attack, although closely related to oxidation, is more severe. Metal sulfides melt at lower temperatures than comparable oxides, and they may fuse to metal surfaces. Also, sulfides are less likely to form tenacious, continuous, protective films. Fusion and lack of adherence result in accelerated corrosion.

The resistance of stainless steels to sulfidation depends on chromium content.

Sulfur Dioxide

Type 316, in a series of 24-hour laboratory tests, was subjected to mixtures of oxygen and sulfur dioxide (varying from 100% oxygen to 100% sulfur dioxide) at temperatures between 1100 and 1600ºF (593 and 871ºC). Results indicated that the rate of attack was largely independent of the gas composition, and no scale developed– only a heavy tarnish.

Hydrogen Sulfide

Low chromium steels are adequate to resist attack in relatively low hydrogen sulfide levels, but hydrogen sulfide under high pressure results in rapid corrosion. Then a minimum of about 17% chromium is required to obtain satisfactory resistance. Type 304 has been used extensively for this service. The iso-corrosion curves shown in Figure 9 show the effects of hydrogen sulfide and temperature on the austenitic stainless steels.

Sulfur Vapor

Sulfur vapor readily attacks the austenitic grades. In tests, relatively high corrosion rates were encountered in flowing sulfur vapor at 1060ºF (571ºC), although it has been reported that Type 310 has been successfully used for a sulfur vapor line at 900ºF (482ºC).

In liquid sulfur, most austenitic grades are resistant up to 400ºF (204ºC), with the stabilized Types 321 and 347 showing satisfactory service to 832ºF (444ºC).

Flue Gas

The corrosivity of flue gas containing sulfur dioxide or hydrogen sulfide is similar to that of most sulfur-bearing gases. Accordingly, the corrosion resistance of stainless steels in flue gas environments is improved by increased chromium content, as shown in Figure 10. Table IV indicates the effect of chromium content on corrosion in various fuel sources. Corrosion rates of 1 to 2 mils per year have been reported for Types 304, 321, 347 and 316 in the temperature range 1200-1400ºF (649-760ºC).

For reducing flue-gas environments, satisfactory material selection requires service tests.

Other High-Temperature Environments

Data are available on the corrosion resistance of stainless steels in other high-temperature environments, such as their use for liquid-metal environments. Designers are referred to the following publications for additional data on high-temperature applications: Selection of Stainless Steels, ASM Engineering Bookshelf and Corrosion Resistance of the Austenitic Stainless Steels in High-Temperature Environments, by The Nickel Development Institute.

Table IV
CORROSION RATES OF STAINLESS STEELS IN FLUE GASES
(EXPOSURE 3 MONTHS) (16)

Material AISI Type	Corrosion Rate					
	Coke Oven Gas (1500 ºF) (816 ºC)		Coke Oven Gas (1800 ºF) (982 ºC)		Natural Gas (1500 ºF) (816 ºC)	
	mpy	mmpy	mpy	mmpy	mpy	mmpy
430	91	2.31	236†	6.00	12	0.30
446(26 Cr)	30	0.76	40	1.02	4	0.10
446(28 Cr)	27	0.69	14	0.36	3	0.08
302B	104	2.64	225†	6.00	–	–
309S	37*	0.94	45	1.14	3	0.08
310S	38*	0.97	25	0.64	3	0.08
314	23*	0.58	94	2.39	3	0.08

*Pitted specimens–average pit depth. † Specimens destroyed.

APPENDIX B

Figure 1

Effect of Chromium Content on Corrosion Rate (2)

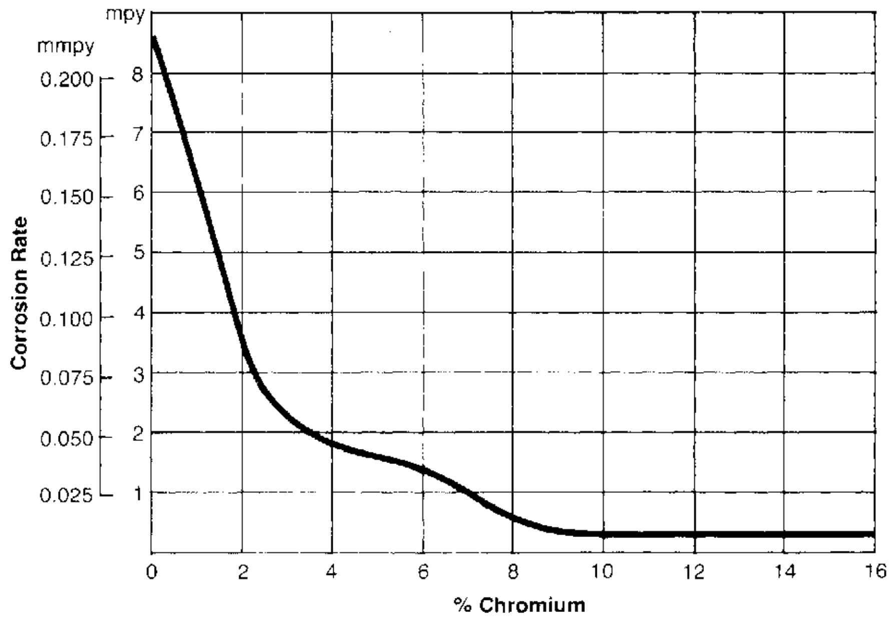
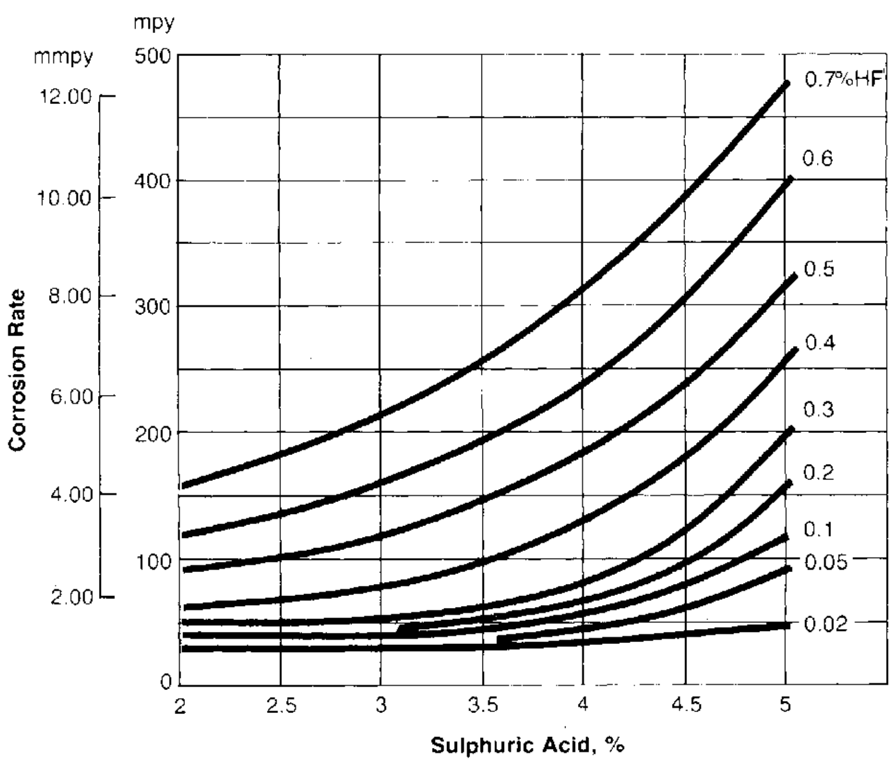


Figure 2

Effect of Chemical Content on Corrosion Rate (3)



Small quantities of hydrofluoric and sulfuric acids can have a serious effect on Type 316 stainless in 25% P_2O_5 phosphoric acid with 1.5% F as H_2SiF_6 at 190°F (90°C).

Figure 3
Effect of Temperature on Corrosion Rate (4)

93% H_2SO_4 with Velocity of 0.1 foot/second

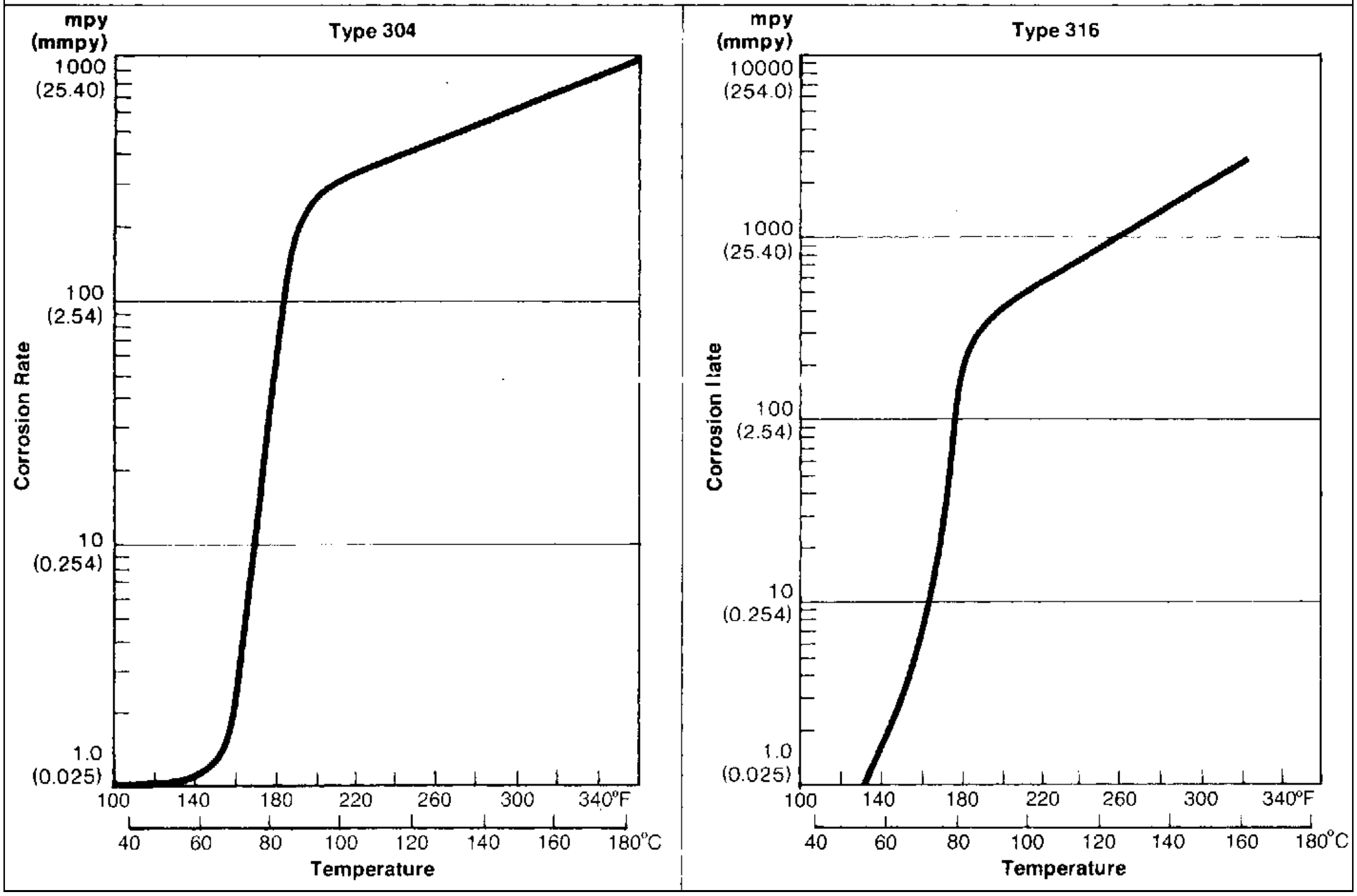
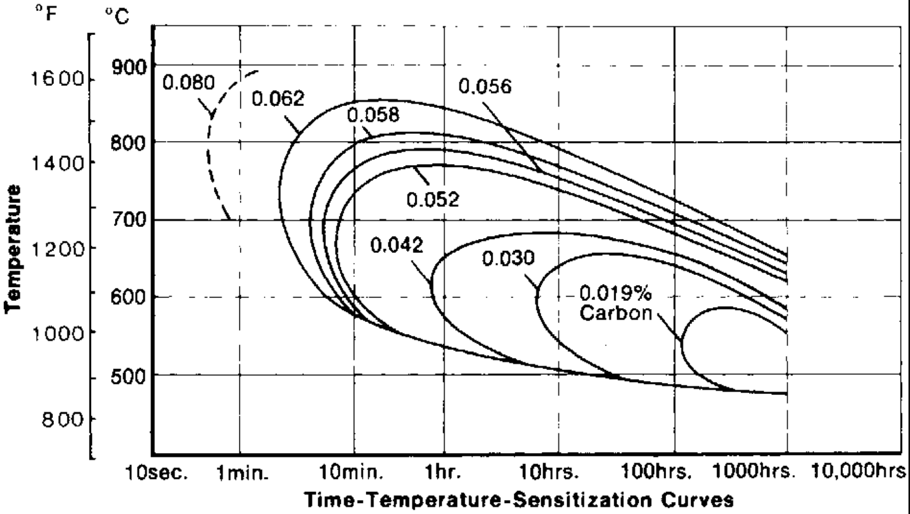


Figure 4

Effect of Carbon Content on Carbide Precipitation (5)



Time required for formation of carbide precipitation in stainless steels with various carbon contents. Carbide precipitation forms in the areas to the right of the various carbon-content curves. Within time-periods applicable to welding, chromium-nickel stainless steels with 0.05% carbon would be quite free from grain boundary precipitation. (7)

Figure 5

Effect of Chromium Content on Scaling Resistance (At 1800°F or 982°C) (2)

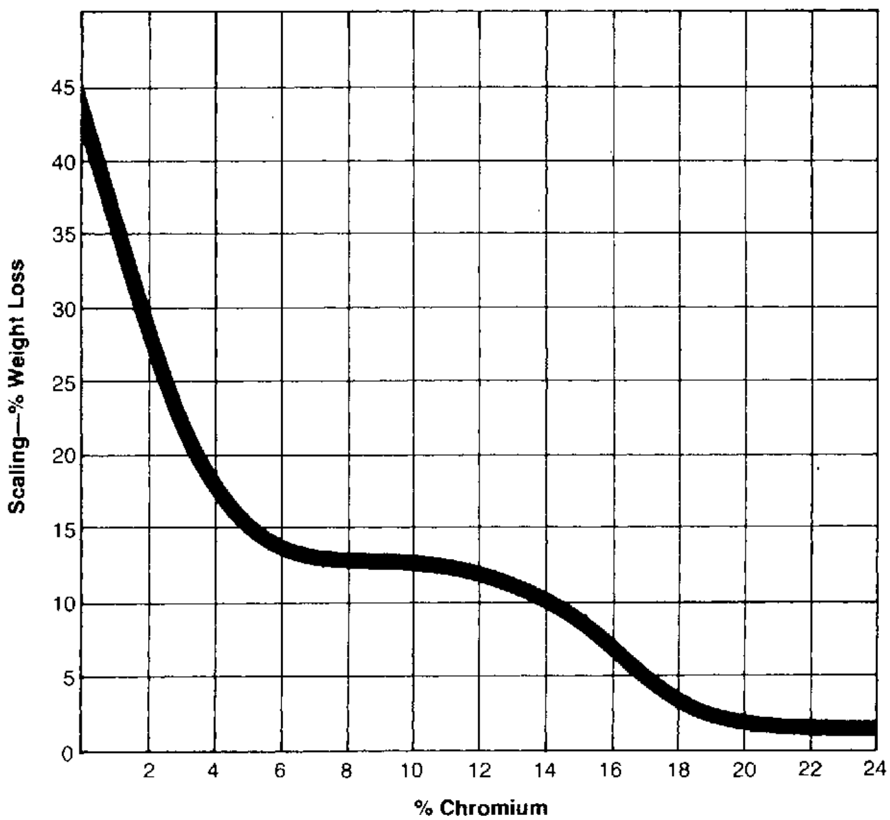
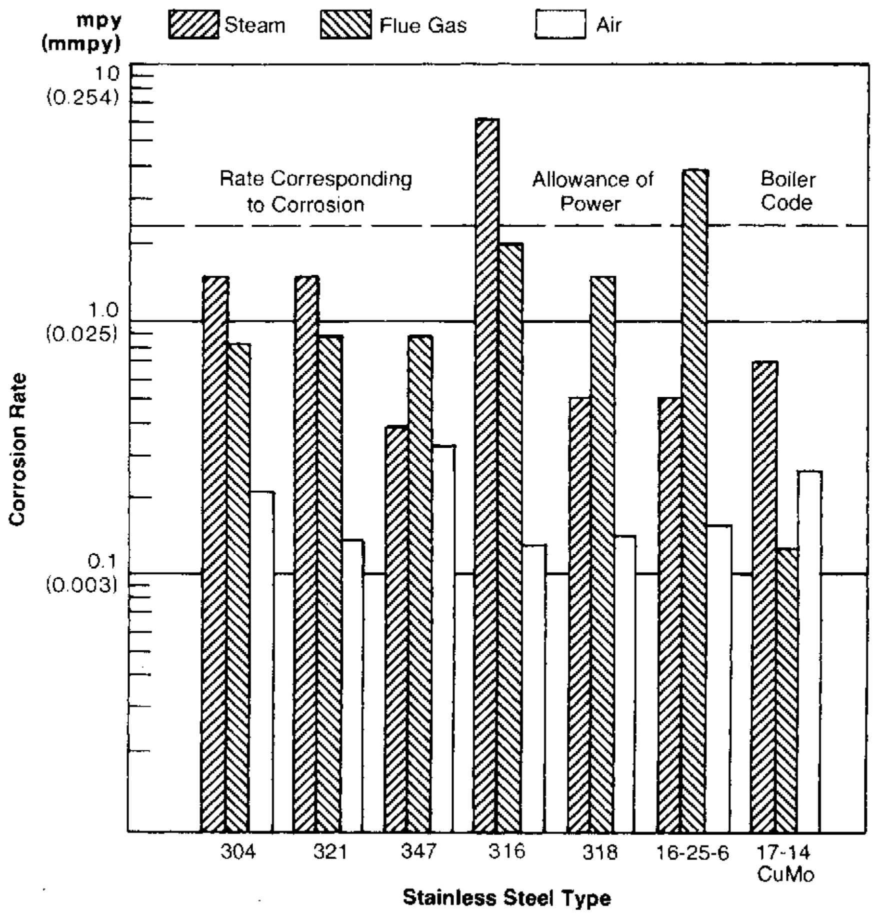


Figure 6

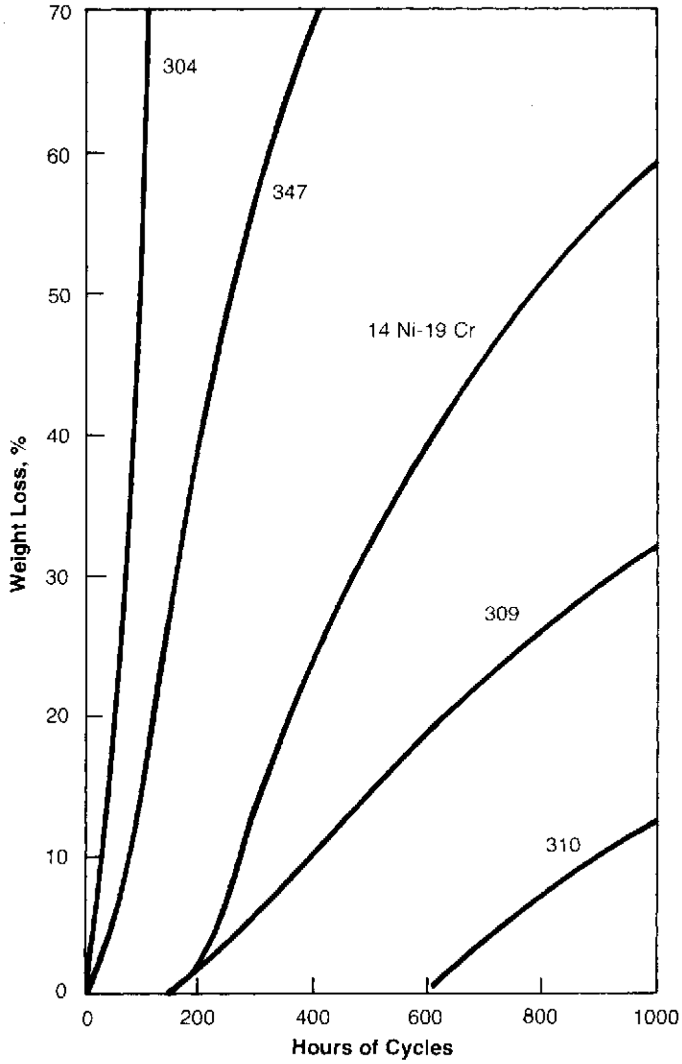
Corrosion Rates in Various Gases (7)



Comparative corrosion rates of stainless steels in steam at 1250°F (677°C), flue gas at 1200 to 1400°F (649 to 760°C), and air at 1400°F (760°C). (Exposure time was 6950 hours for steam and flue gas, 1260 hours for air.)

Figure 7

Effect of Nickel (Cr, Cb) on Scaling Resistance (2)



Scaling resistance of some iron-chromium-nickel alloys in cycling-temperature conditions at 1800°F (982°C). Cycle consisted of 15 min. in the furnace and 5 min. in air. Sheet specimens 0.031 in. (0.787 mm) thick were exposed on both sides.

Figure 8

Oxidation of Types 302 and 330 in Wet and Dry Air (8)

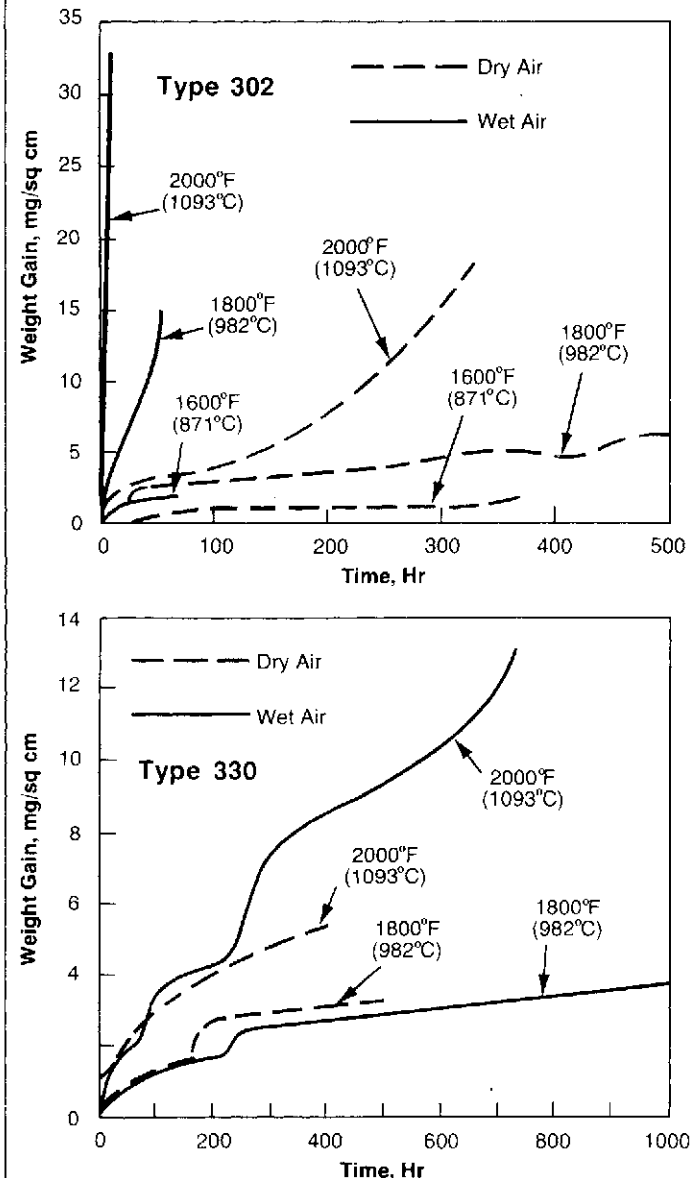
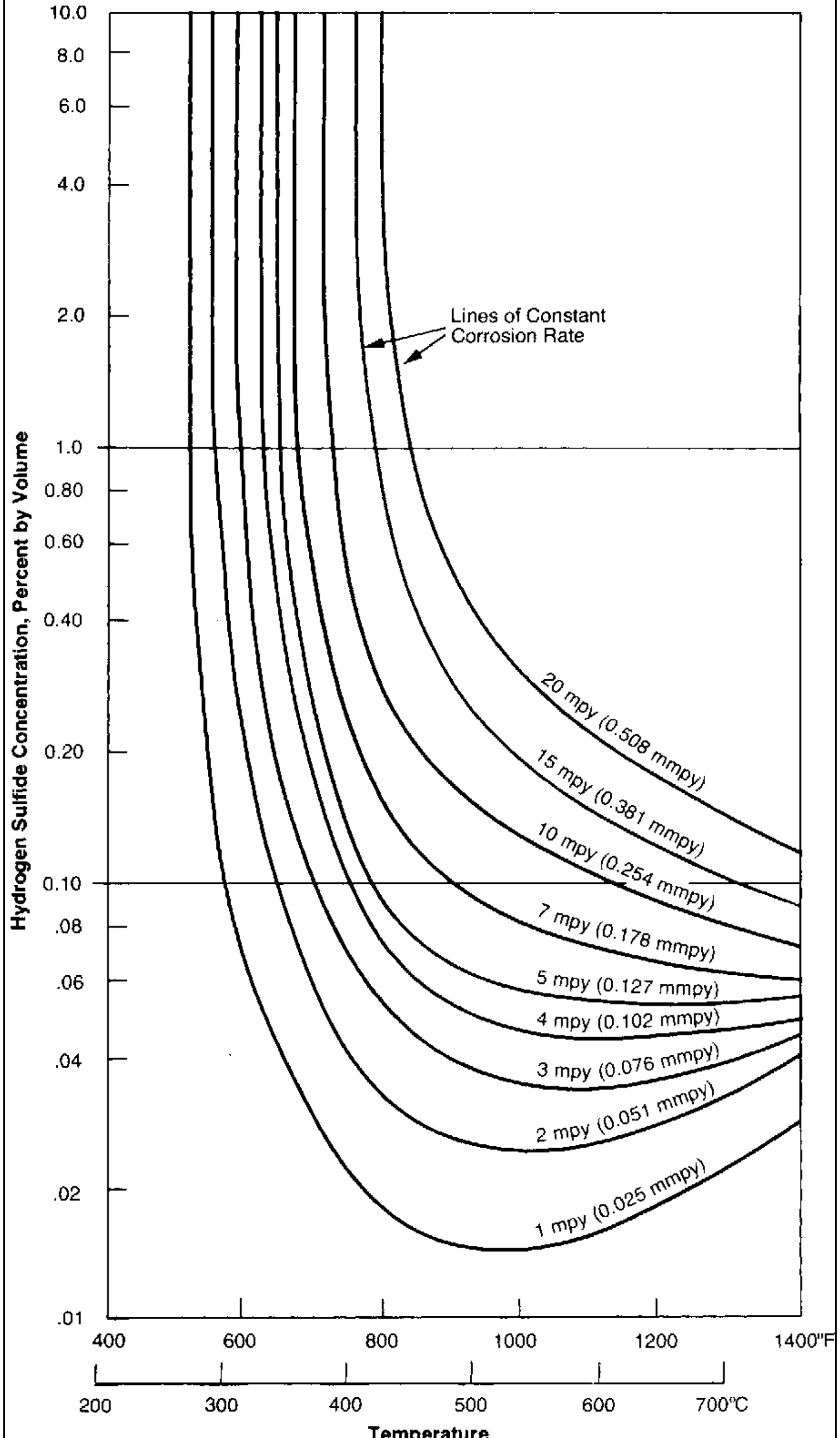


Figure 9

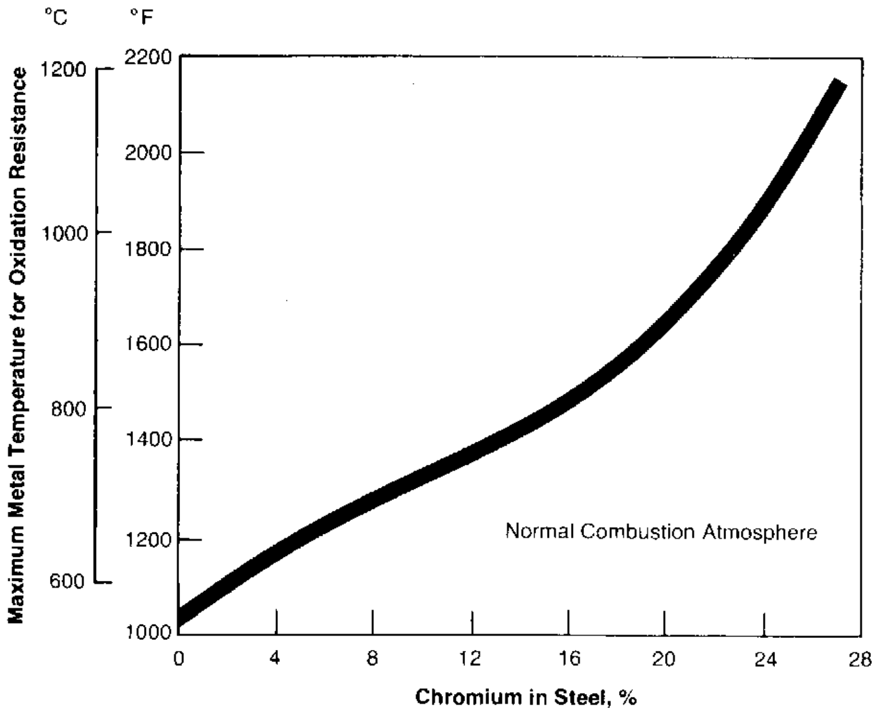
Effect of Temperature and H_2S on Corrosion Rate (9)



Effect of temperature and hydrogen sulfide concentration on corrosion rate of chromium-nickel austenitic stainless steels in hydrogen atmospheres at 175 to 500 psig (1.21-3.45 MPa). (Exposure time greater than 150 hr.)

Figure 10

Effect of Chromium in Normal Combustion Atmosphere (10)



Effect of chromium on the oxidation resistance of steel in a normal combustion atmosphere

Figure 11

Stress Strain Curves for Type 304 and Type 301 (2)

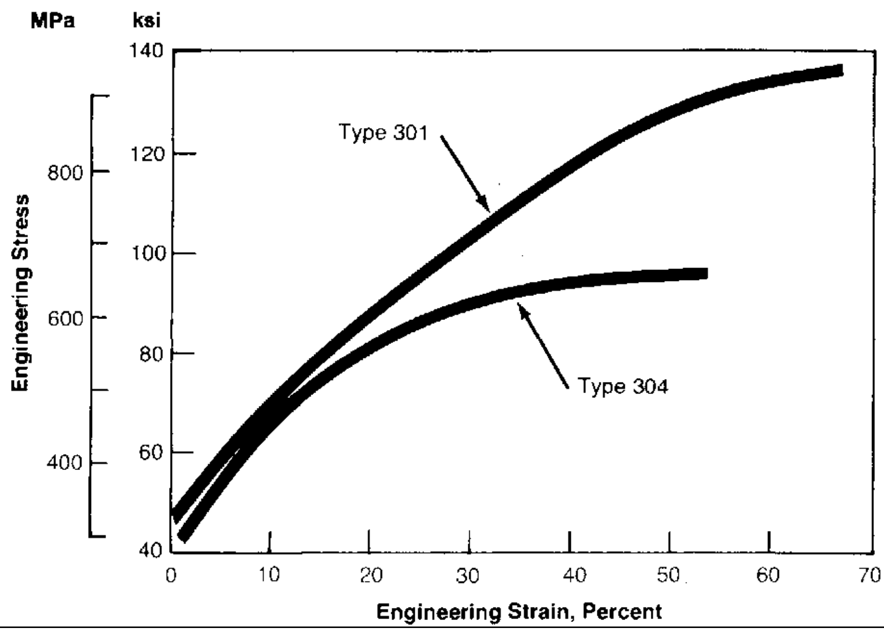


Figure 12
Effect of Cold Work on Mechanical Properties of Type 202 (2)

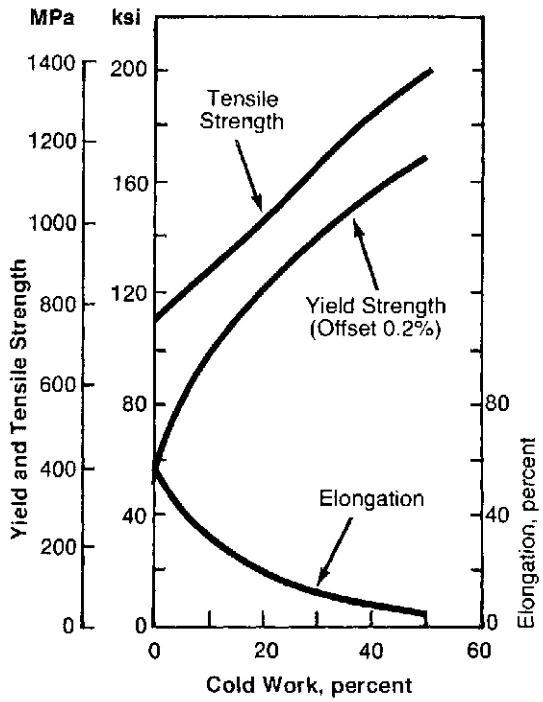


Figure 14
Effect of Cold Work on Mechanical Properties of Type 305 (2)

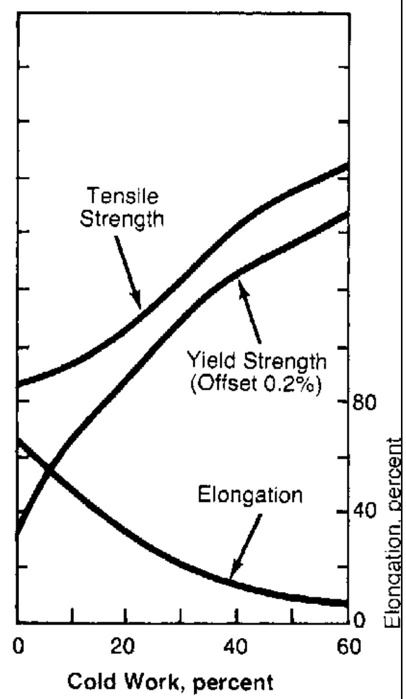


Figure 13
Effect of Cold Work on Mechanical Properties of Type 301 (2)

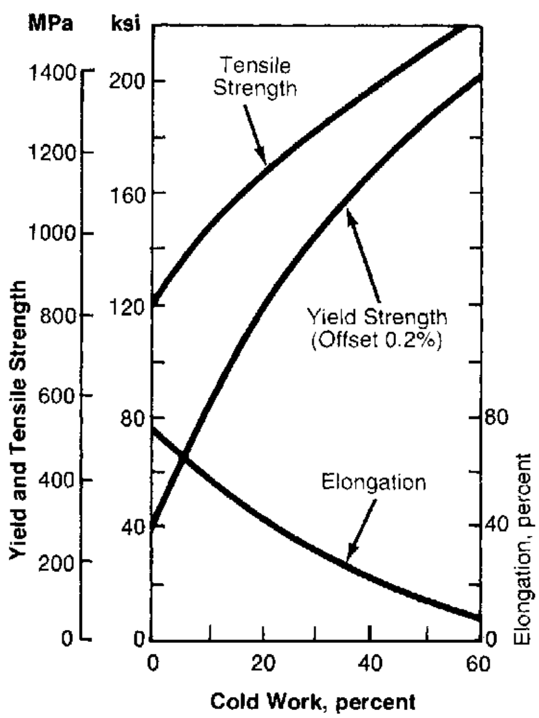


Figure 15
Effect of Cold Work on Mechanical Properties of Type 310 (2)

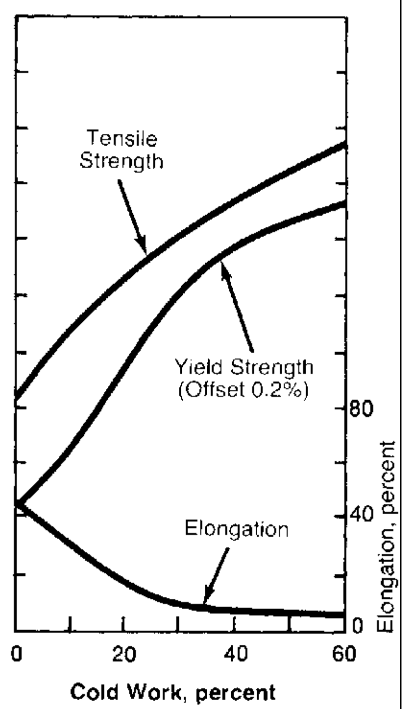


Figure 16
Effect of Cold Rolling and Test Direction on Notch Strength of Type 301 Sheet (2)

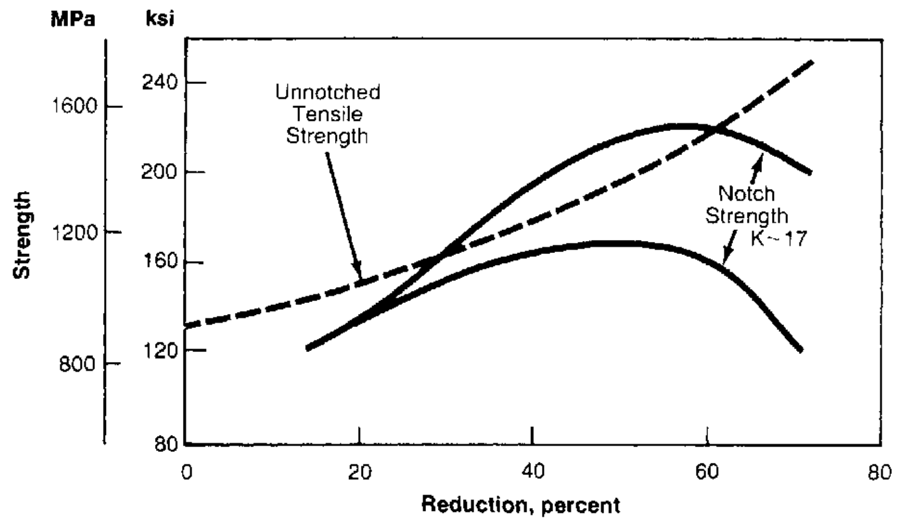


Figure 17
Representative Stress-Strain Curve for Half-Hard Stainless Steel and Mild Steel (2)

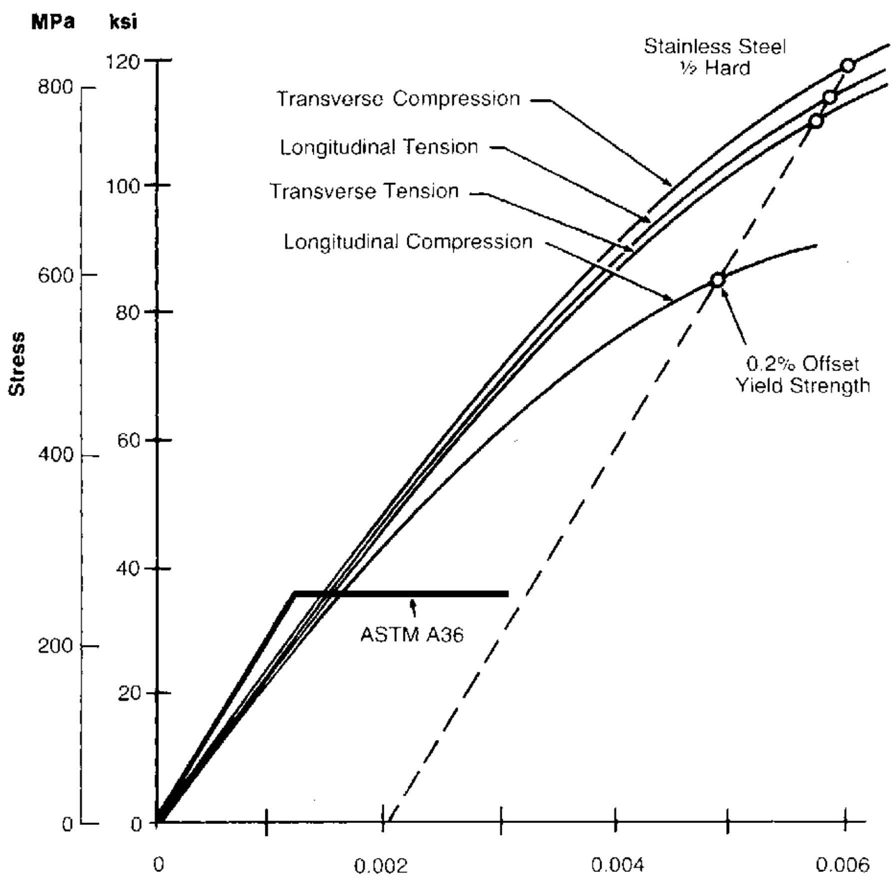


Figure 18

Izod Impact Values for Type 410 Quenched from 1800°F (982°C) and Tempered for 3 Hours at Indicated Temperature (2)

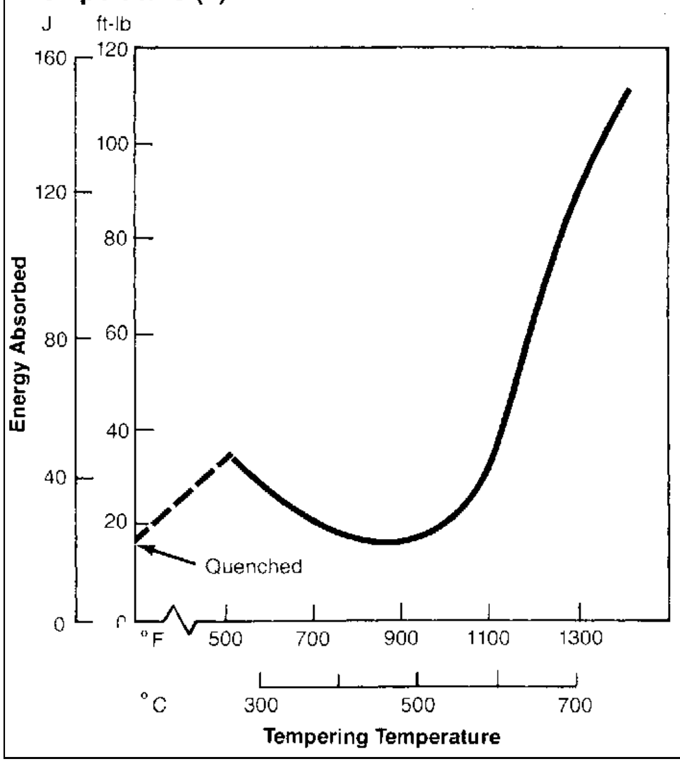


Figure 19

Izod Data for 410 After Quenching from 1800°F (982°C) and Tempering at 1150°F (621°C). (Bhn 228) (2)

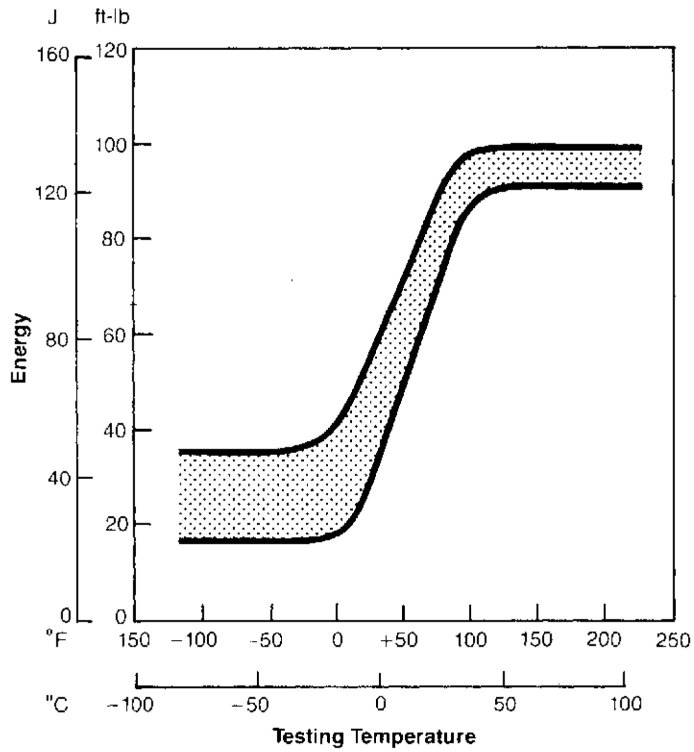


Figure 20

Fatigue Data for Quenched-and-Tempered Type 403 (Rockwell C 24 to 26) (2)

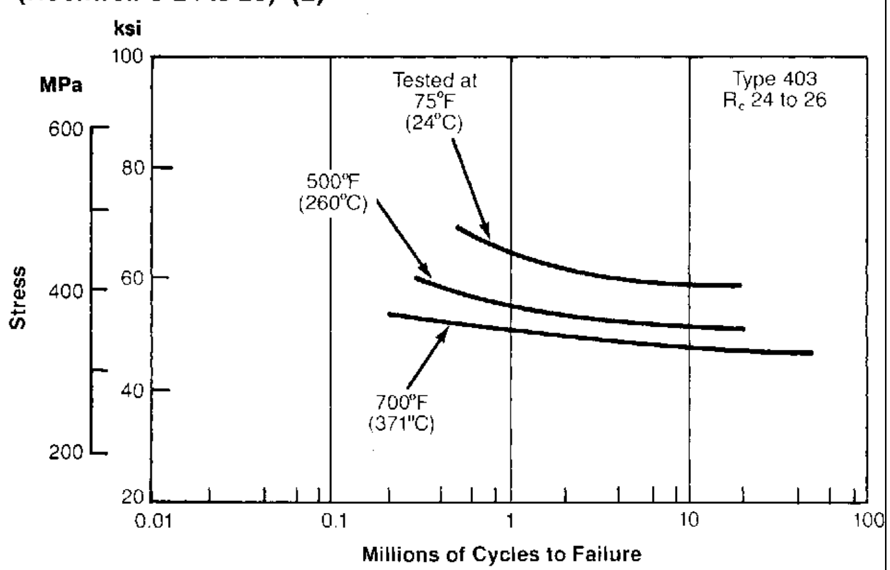
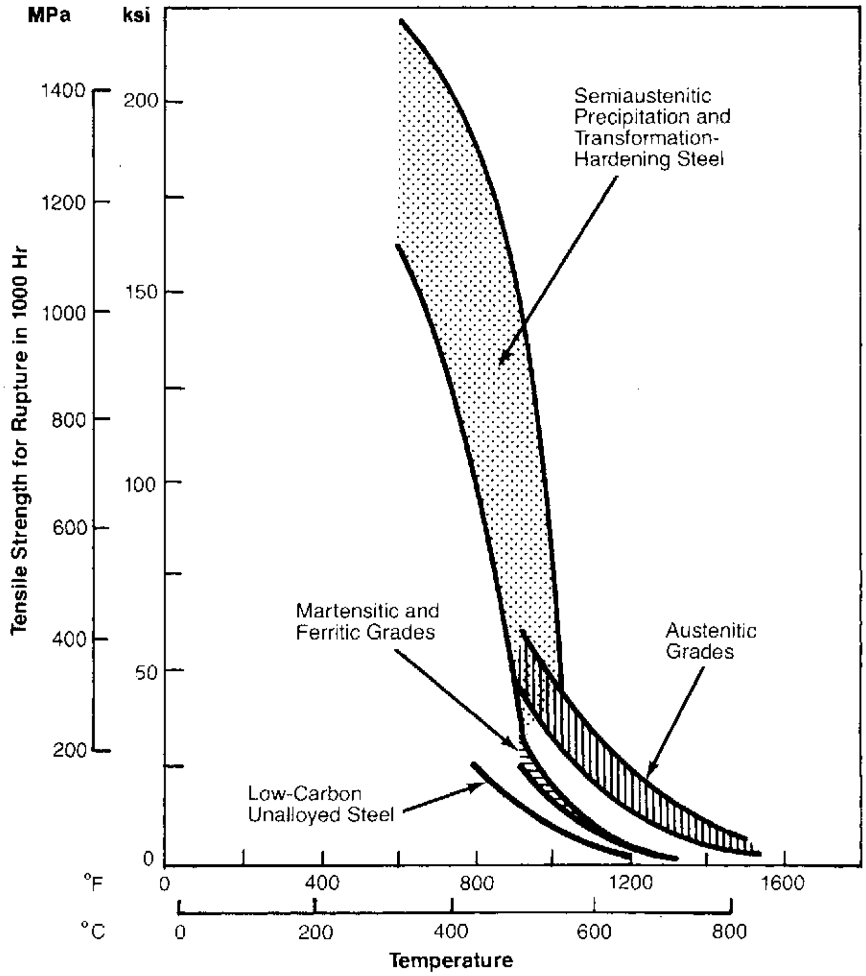


Figure 21
Hot-Strength Characteristics (2)



General comparison of the hot-strength characteristics of austenitic, martensitic and ferritic stainless steels with those of low-carbon unalloyed steel and semi-austenitic precipitation and transformation-hardening steels.

Figure 22

Effect of Cold Work on the Short-Time Tensile Properties of Type 301 at Elevated Temperature (2)

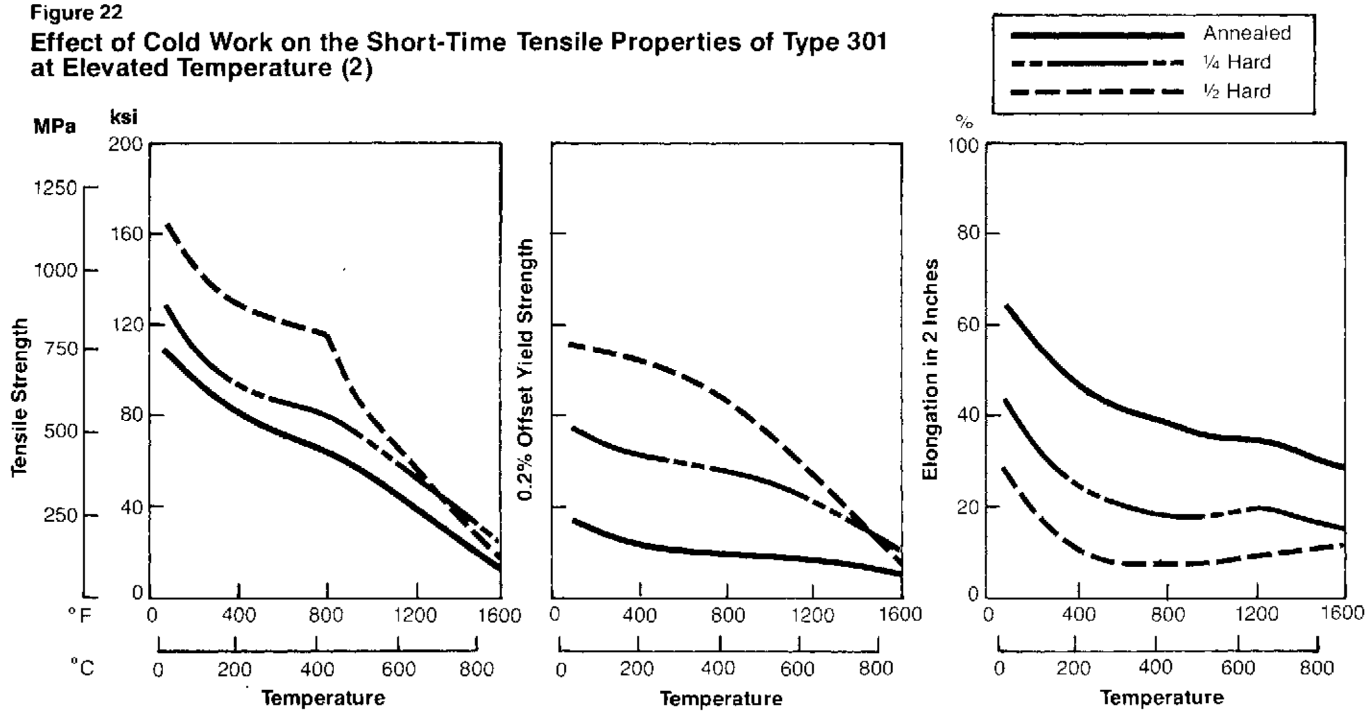
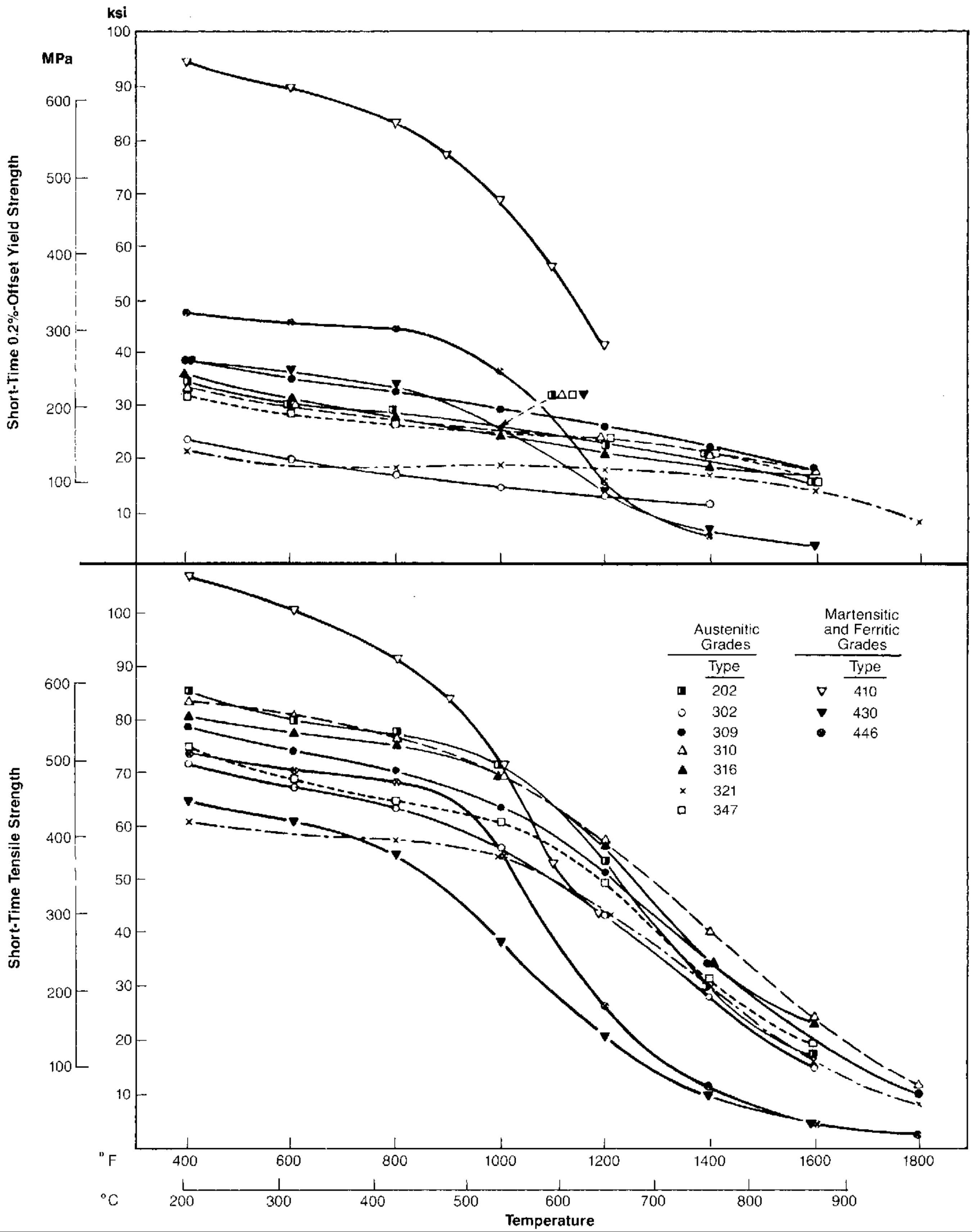


Figure 23 **Short-Time Tensile Strengths (2)**



Typical short-time tensile strengths of various standard stainless steels at elevated temperature. All steels were tested in the annealed condition except for the martensitic Type 410, which was heat treated by oil quenching from 1800 ºF (982 ºC) and tempering at 1200 ºF (649 ºC).

Figure 24, 25, 26

Comparative 100,000-hr Stress-Rupture Data for Types 316 and 347 Tube and Pipe and on Type 304 Bar. (2)

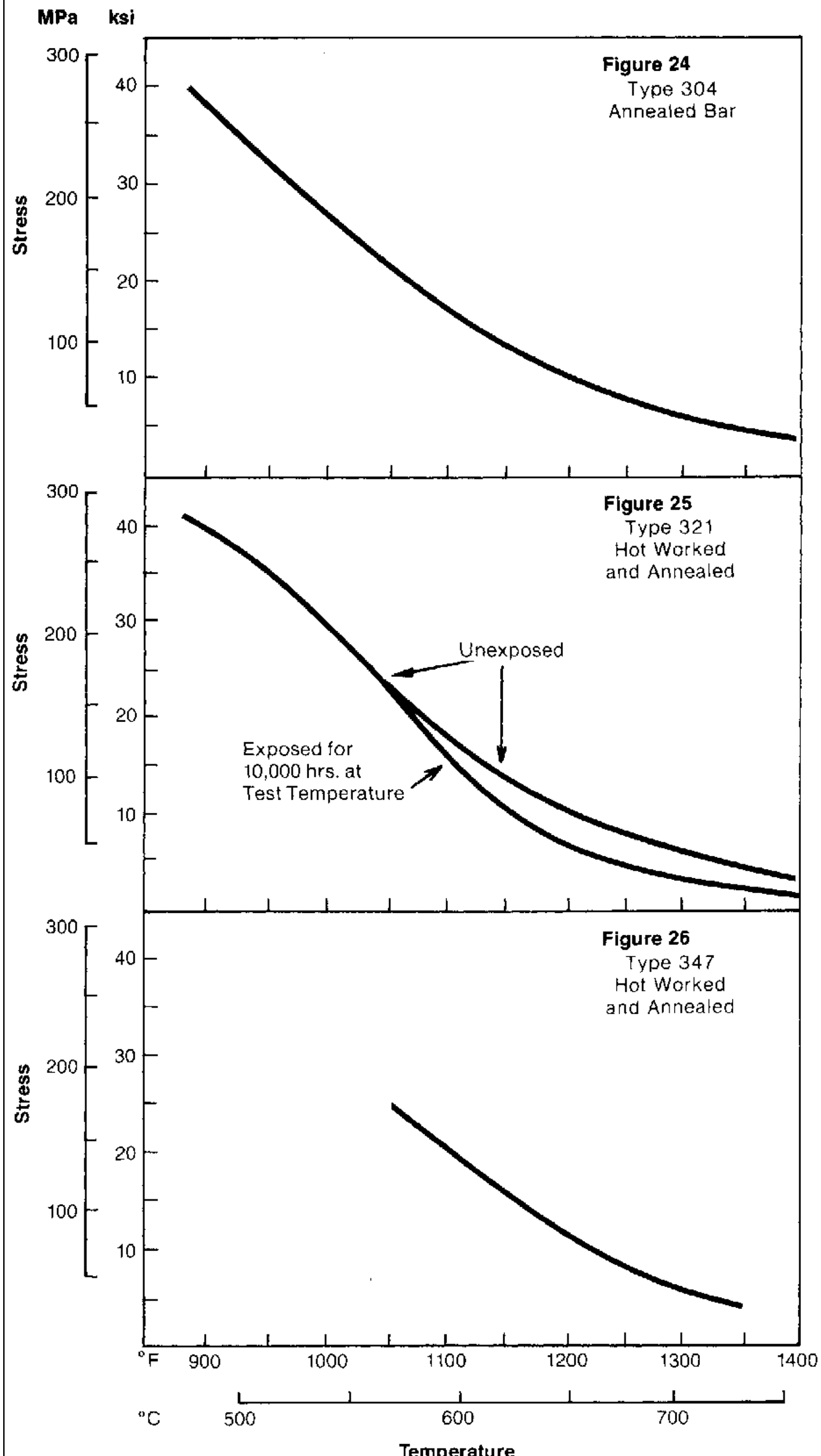
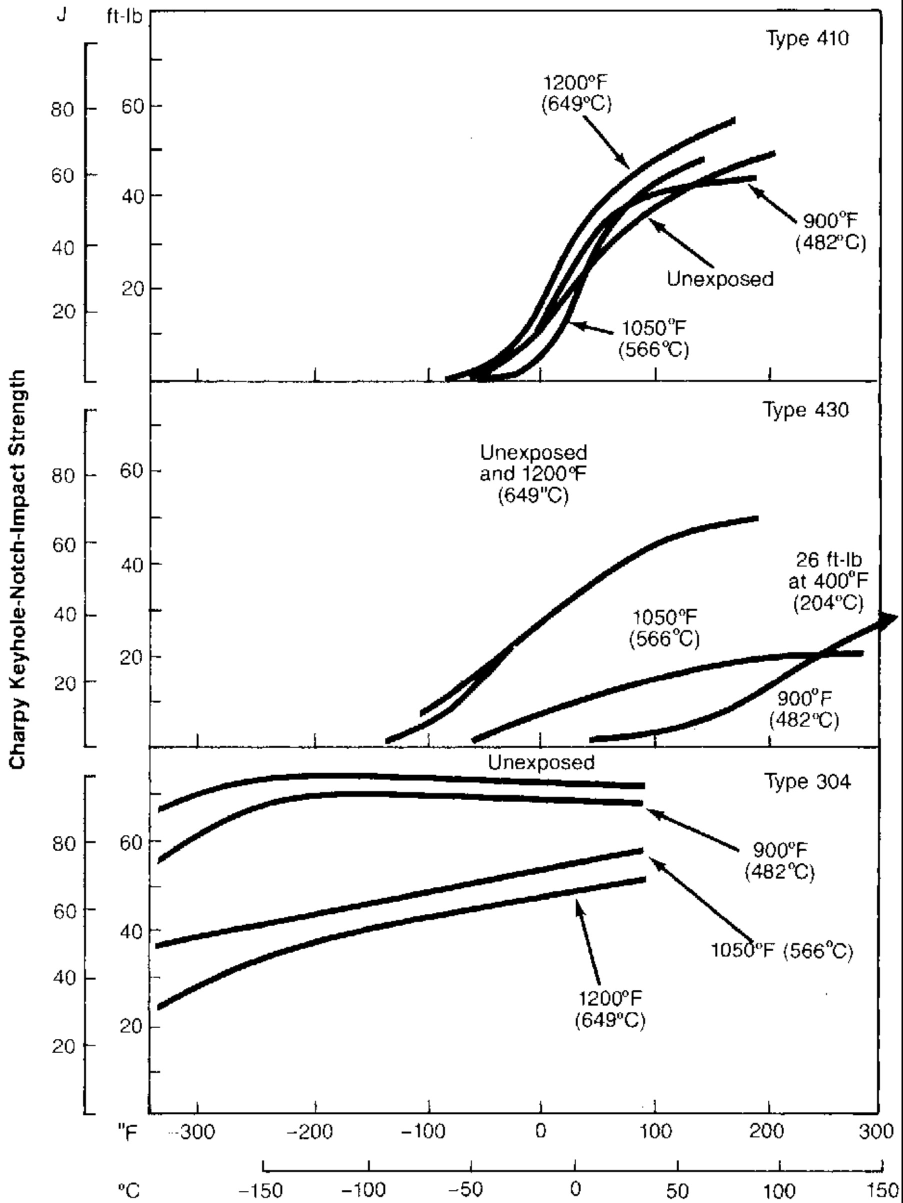


Figure 27

Effect of Holding 10,000 Hr at 900, 1050 and 1200°F (482, 566, and 649°C) on the Impact Characteristics of Type 410, 430 and 304 (11)



Hardness Values Were as Follows

Type	Unexposed	DPN Hardness — After Exposure for 10,000 hr at 900°F (482°C)	1050°F (566°C)	1200°F (649°C)
410	125	125	124	123
430	185	274	198	169
304	138	140	147	141

Figure 28

Linear Thermal Expansion of the Three Main Classes of Stainless Steel

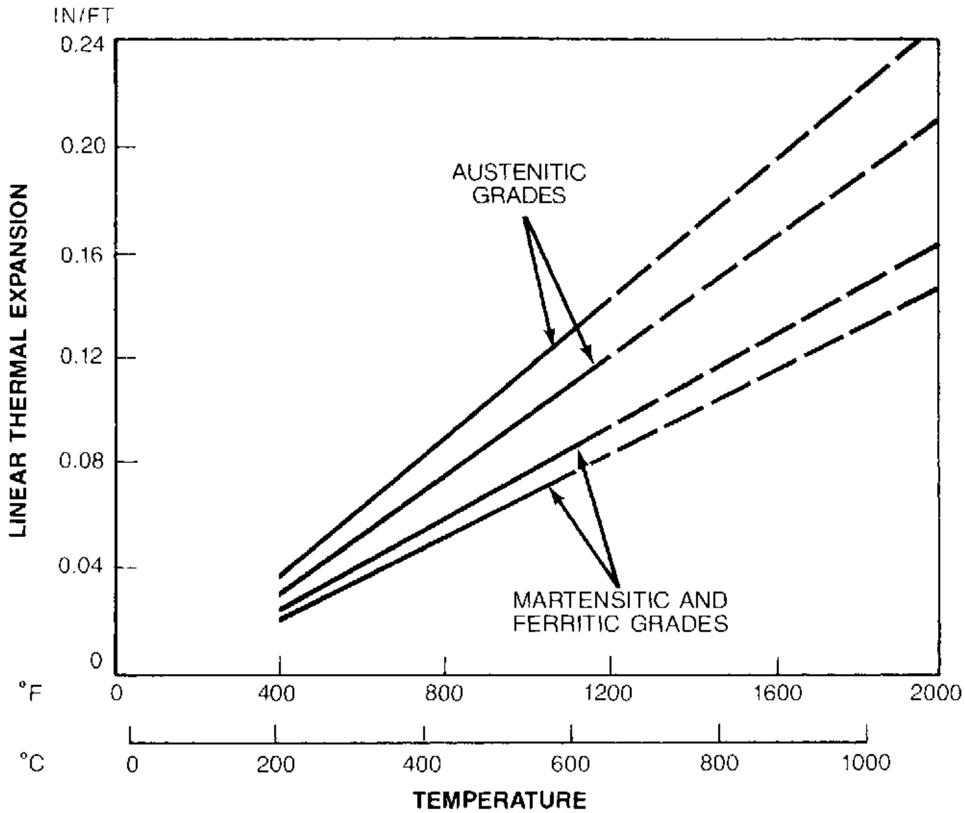
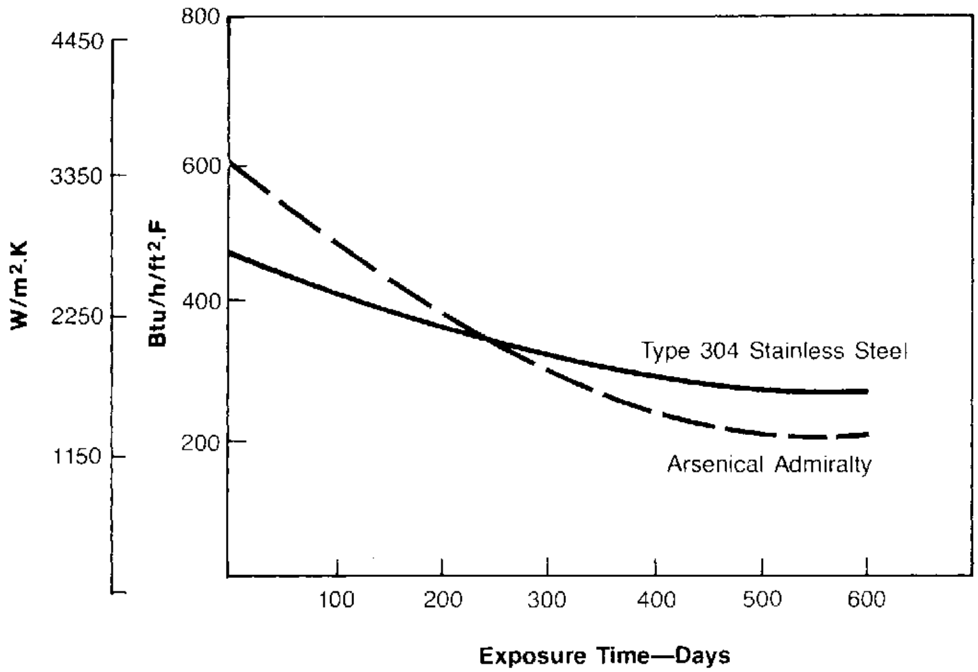


Figure 29

Factors Affecting Heat Transfer (12)

Steam Side Water Film	18%
Steam Side Fouling	8%
Tube Wall	2%
Water Side Fouling	33%
Water Side Film	39%

Figure 30
Overall Heat Transfer vs. Exposure Time (13)



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