Ni
22 Cr
18 Fe
9 Mo
1.5 Co
0.5 W

Hastelloy X

1 GENERAL

Hastelloy X is a nickel-base superalloy with good oxidation resistance at temperatures up to 2200 F and moderately good strength properties at temperatures up to 1600 F. It is essentially a single-phase austenitic alloy, which is solid-solution strengthened by additions of chromium, molybdenum, and tungsten. Wrought products are normally used in the solution-treated condition and cast products in the as-cast condition. The alloy has excellent welding and brazing characteristics, and it can be hot and cold formed satisfactorily if proper procedures and care are exercised. Aerospace applications for Hastelloy X include jet engine tail pipes, bolts, afterburner components, cabin heaters, and structural parts in the burner and turbine sections. It is also used in many industrial furnace applications because of its resistance to oxidizing, reducing, carburizing, and nitriding atmospheres. In the chemical and petrochemical industries, it is used for many components, such as retorts, support grids, baffles, tubing, and dryers, because of its excellent combination of corrosion resistance and heat resistance. In addition, a low-cobalt (0.50 percent maximum) version of the alloy, designated Hastelloy X-280, is used for structural parts in nuclear reactors. The difference in cobalt content has minimal effects on mechanical properties (1-7).

1.01 Commercial Designation

Hastelloy X.

1.02 Alternate Designations

Hastelloy Alloy X (Cabot Corp.), UNS N06002, AISI 680 (castings), Pyromet 680 (Carpenter Technology), Unitemp HX (Cyclops Corp.), and Simalloy HX (Simonds Steel).

1.03 Specifications

Specifications, Table 1.03.

1.04 Composition

Composition, Table 1.04.

1.05 Heat Treatment

1.051 Wrought products are normally supplied by the mills in the solution-treated condition, which provides the optimum combination of mechanical properties and corrosion resistance for practically all applications. This treatment consists of exposure to 2150 F followed by rapid cooling. The hold time at 2150 F varies with the section size of the product, size of load, and furnace characteristics; a rule of thumb that provides acceptable results for the product being treated is to hold for 1 hr per inch of thickness. The cooling rate from 2150 to 1000 F or below should be rapid enough to prevent carbide precipitation, which decreases corrosion resistance and toughness. For sheet products, rapid air cooling is adequate; oil or water quenching is frequently necessary for heavier sections. If surface oxidation can be tolerated, the solution treatment can be carried out in air or in the normal mixture of air and combustion products in gas-fired furnaces. Oxidation can be minimized by the use of an exothermic furnace atmosphere, or it can be almost entirely prevented by dry hydrogen, dry argon, or vacuum atmospheres (1,7,17).

1.052 Following all hot-forming and most cold-forming operations, solution treatment should be carried out to restore optimum properties. An exception would be, for example, the use of as-cold-rolled sheet to take advantage of its improved room-temperature strength (7).

1.053 Solution treatment is recommended after welding of wrought products to restore optimum corrosion resistance in the weld areas (7).

1.054 Intermediate softening during severe cold-forming operations should be accomplished with the full solution treatment because it provides optimum ductility and formability (7).

1.055 Stress relief at intermediate temperatures is not applicable because it tends to cause carbide precipitation and associated decreases in corrosion resistance, ductility, and toughness (7).

1.06 Hardness

1.061 Effects of exposures at various elevated temperatures on hardness of sheet and plate at room temperature, Figure 1.061.

1.062 Effect of cold work on hardness, Figure 1.062.

1.07 Forms and Conditions Available

1.071 Wrought products are available in the form of sheet, strip, plate, bar, tubing, wire welding electrodes, and billet stock.

1.072 Cast products are available in the form of sand castings, investment castings, and centrifugal castings.

1.08 Melting and Casting Practices

1.081 Hastelloy X can be produced by any of the electric-arc or induction melting processes either in air or vacuum. The use of vacuum, of course, tends to improve toughness and fatigue properties. Most wrought products are produced by electric furnace or vacuum induction melting followed by electroslag remelting (18).

1.09 Special Considerations

1.091 A pronounced reduction in ductility occurs in the temperature range 1000 to 1500 F, which is characteristic of most nickel-base superalloys. (See Figure 3.0313.)

1.092 Exposures in the temperature range 1000 to 2000 F cause carbide precipitation and age hardening followed by overaging. During the initial phases of carbide precipitation, room-temperature hardness and strength increase, but during overaging they decrease to ultimate levels considerably below those of the solution-treated alloy. The time period for the hardening phase, until the onset of overaging, varies from several thousands of hours at 1200 F and below, to practically zero at temperatures of 1700 F and above. Room-temperature ductility and impact energy, on the other hand, decrease continuously from the start of carbide precipitation to ultimate levels far below those of the solution-treated material. (See Figures 1.061, 3.0212, 3.0213, 3.0214, and 3.0231.) Simultaneous precipitation of small amounts of sigma phase can also contribute to the deterioration of ductility and toughness. In addition to its effects on mechanical properties, carbide precipitation also results in decreased corrosion resistance. The precipitates can be dissolved and original properties restored by solution treatment. (See Section 1.051.) Because of the harmful effects on ductility, toughness, and corrosion resistance, age hardening of Hastelloy X is not employed as a deliberate heat-treating technique before the alloy is used. A better overall combination of properties is provided by using wrought products in the solution-treated condition and castings in the as-cast condition (18).

1.093 Exposures for 100 hrs and more to hydrogen atmospheres at 1200 F and above result in the absorption of substantial amounts of hydrogen into Hastelloy X, which induces only a moderate degree of hydrogen embrittlement (25). Exposures for shorter times and at lower temperatures have little or no effect. (See Tables 3.0318 and 3.03711 and Figure 3.053.)

1.094 Although the effects of nuclear irradiation on the properties of Hastelloy X vary depending upon the irradiation and test temperatures, it should be noted that large doses drastically reduce ductility at test temperatures of 1100 and 1200 F (See Table 2.0412).

2 PHYSICAL AND CHEMICAL PROPERTIES

2.01 Thermal Properties

2.011 Melting range, 2300 to 2470 F (1).

2.012 Phase changes.

2.0121 Time-temperature-transformation diagrams.

2.0122 In the solution-treated condition, Hastelloy X is essentially a single-phase, solid-solution austenitic alloy. In the temperature range 1000 to 2000 F, carbides and sigma phase precipitate out of the solid solution. They redissolve at temperatures above 2000 F (18).

2.013 Thermal conductivity, Figure 2.013.

2.014 Thermal expansion, Figure 2.014.

2.015 Specific heat, Figure 2.015.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density, 0.297 lb/in.^{3} at 72 F (1).

2.022 Electrical properties, Figure 2.022.

2.023 Magnetic properties, Hastelloy X is not magnetic.

2.0231 Magnetic permeability at 75 F and 200 oersteds, <1.002.

2.024 Emittance, Figure 2.024.

2.025 Damping capacity.

2.03 Chemical Properties

2.031 Hastelloy X has long been known as an alloy with good oxidation resistance at temperatures up to 2200 F, although tests on potential alloys for the space shuttle have shown that some nickel-base superalloys containing aluminum along with chromium are somewhat superior (29). Elevated-temperature exposures to environments containing oxygen, sulfur, and various other corrodants indicate that Hastelloy X is among the more resistant of the superalloys to hot corrosion (sulfidation) (30).

2.0311 Loss of effective thickness due to oxidation of sheet continuously exposed to still air at a pressure of 8 torr at both 1800 and 1400 F, Figure 2.0311.

2.0312 Relative weight losses due to exposure to oxygen at 2200 F both continuously and cyclically; that is, once each day a sample was removed from the furnace, cooled, brushed clean, and returned to the furnace, Figure 2.0312.

2.0313 Metal weight loss due to dynamic and static oxidation for 100 hrs at various temperatures, Figure 2.0313.

2.0314 Metal weight loss due to oxidation and hot corrosion at various temperatures in air and in air contaminated with sodium chloride, Figure 2.0314.

2.0315 Total surface penetration of oxidation and hot corrosion caused by exposures at various temperatures to combustion products of No. 2 diesel oil at a velocity of 280 ft/sec, Figure 2.0315.

2.0316 Total surface penetration of oxidation and hot corrosion caused by exposures at various temperatures to the combustion products of No. 2 diesel oil plus 5 ppm sea salt at a velocity of 13 ft/sec, Figure 2.0316.

2.032 In static and flowing seawater, Hastelloy X is highly resistant to general corrosion, pitting corrosion, and stress corrosion, and is only slightly susceptible to crevice corrosion (34).

2.033 The alloy has good resistance to steam at temperatures up to at least 1200 F. Tests in superheated steam for 16,000 hrs at 900 psi pressure and 5 ft/sec velocity indicated 20-year metal-penetration depths of less than 0.0015 inch at 1100 F and less than 0.0030 inch at 1200 F. Additional tests on weld joints made with both Hastelloy X and IN-82 welding electrodes showed similar penetration resistance with no preferential corrosion in the fusion area (35).

2.034 Hastelloy X has excellent resistance to carburizing and nitriding. After 100 hrs at 1900 F in petroleum coke, for example, it showed no carburization. After 64 days at 1100 F and 15,000 psi in an atmosphere of hydrogen, nitrogen, and ammonia, it had a nitrided case of less than 0.001 inch (1).

2.035 The alloy is resistant to stress-corrosion cracking in most environments including those containing chloride ions (1).

2.04 Nuclear Properties

2.041 Hastelloy X and its low-cobalt version, Hastelloy X-280, are widely used for structural applications in nuclear reactors. Although their mechanical properties are almost the same, the X-280 version provides better neutron economy and minimizes the residual radioactivity after irradiation (2,3,4).

2.0411 Effects of fast neutron irradiation on tensile properties and hardness at room temperature, Table 2.0411.

2.0412 Effects of fast neutron irradiation on tensile properties at various temperatures, Table 2.0412.

2.0413 Effects of fast neutron irradiation on creep-rupture time at temperatures of 1000 and 1200 F, Figure 2.0413.

2.042 In environments of impure helium – containing small amounts of hydrogen, methane, carbon monoxide, and moisture – characteristic of advanced nuclear reactors, Hastelloy X carburizes with the depth of carburization increasing with increasing temperatures in the range 1200 to 1830 F and with increasing times up to 3,000 hrs. The effects of the carburization on mechanical properties, however, are minimal compared to the effects of thermal aging alone (37).

3 MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 AMS specified tensile properties and hardness, Table 3.011.

3.012 AMS specified stress-rupture properties and hardness, Table 3.012.

3.02 Mechanical Properties at Room Temperature

3.021 Tension – stress-strain diagrams – tension properties.

3.0211 Stress-strain curves (see Figures 3.0311 and 3.0312).

3.0212 Room-temperature tensile properties of sheet and plate after exposures to elevated temperatures at normal air pressure, Figure 3.0212.

3.0213 Room-temperature tensile properties of sheet after exposures to elevated temperatures at 8 torr air pressure both with and without stress, Figure 3.0213.

3.0214 Room-temperature tensile properties of plate after exposures to elevated temperatures in 1 atmosphere of impure helium (3,000 ppm each CO and H_2), Figure 3.0214.

3.0215 Effect of cold work on tensile properties of sheet, Figure 3.0215.

3.022 Compression – stress-strain diagrams – compression properties.

3.0221 Stress-strain curves (see Figure 3.0321).

3.023 Impact.

3.0231 Effects of exposures at various elevated temperatures on impact properties at room temperature, Figure 3.0231.

3.024 Bending.

3.025 Tension and shear.

3.026 Bearing.

3.027 Stress concentration.

3.0271 Notch properties.

3.0272 Fracture toughness.

3.028 Combined properties.

3.03 Mechanical Properties at Various Temperatures

3.031 Tension – stress-strain diagrams – tension properties.

3.0311 Tensile stress-strain curves for sheet at various temperatures, Figure 3.0311.

3.0312 Tensile stress-strain curves for bar at various temperatures, Figure 3.0312.

3.0313 Effects of elevated temperatures on tensile properties of sheet, plate, bar, and forgings, Figure 3.0313.

3.0314 Effects of elevated temperatures on tensile properties of tubing, Figure 3.0314.

3.0315 Effect of temperatures from 72 F down to -320 F on tensile properties of plate, Figure 3.0315.

3.0316 Effects of cold reduction on tensile properties of Hastelloy X-280 at 1390 F of strip produced from air-melted and vacuum-melted stock, Figure 3.0316.

3.0317 Effects of cold work and of subsequent multiple solution-and-aging cycles on tensile properties at room temperature and 1500 F, Table 3.0317.

3.0318 Tensile properties of bar after 10-minute exposure at 80 and 1250 F in high pressure helium and hydrogen, Table 3.0318.

3.0319 Effects of elevated temperatures on tensile properties of sand-cast and investment-cast test bars, Figure 3.0319.

3.03110 Tensile properties from room temperature to -423 F of sand castings from two foundries, Table 3.03110.

3.032 Compression – stress-strain diagrams – compression properties.

3.0321 Compressive stress-strain curves for bar at various temperatures, Figure 3.0321.

3.0322 Effect of elevated temperatures on compressive yield strength of bar, Figure 3.0322.

3.033 Impact.

3.0331 Effects of temperatures from -320 to 1500 F on impact properties of plate, Figure 3.0331.

3.034 Bending.

3.035 Torsion and shear.

3.0351 Effect of elevated temperatures on shear strength of bar, Figure 3.0351.

3.036 Bearing.

3.037 Stress concentration.

3.0371 Notch properties.

3.03711 Comparison of tensile strength and notch tensile strength of bar after 10-minute exposure at 80 and 1250 F in high pressure helium and hydrogen, Table 3.03711.

3.0372 Fracture toughness.

3.038 Combined properties.

3.04 Creep and Creep-Rupture Properties

3.041 Creep-deformation curves for sheet at temperatures from 1200 to 1800 F, Figure 3.041.

3.042 Creep-deformation curves for plate and bar at temperatures from 1200 to 1800 F, Figure 3.042.

3.043 Creep-deformation curves for investment castings at temperatures from 1200 to 1650 F, Figure 3.043.

3.044 Creep-rupture strength for sheet, plate, and bar for various temperatures and rupture levels, Figure 3.044.

3.045 Creep-rupture strength for investment castings for various temperatures and rupture times, Figure 3.045.

3.046 Minimum creep rate of sheet at various stresses and at temperatures from 1200 to 1800 F, Figure 3.046.

3.047 Average and minimum stress for 7 years to cause various amounts of creep and rupture at various temperatures, Table 3.047.

3.048 Tests on solution-treated Hastelloy X plate show that its creep-rupture properties at 1200 to 1600 F for times up to 20,000 hrs are the same in air and in impure helium (Section 2.042). This is the type of atmosphere the alloy is exposed to in the hottest regions of the high-temperature gas-cooled nuclear reactor (46).

3.05 Fatigue Properties

3.051 Fatigue life of plate at various temperatures in air and in impure helium at atmospheric pressure, Figure 3.051.

3.052 Low cycle fatigue life of bar at elevated temperatures in air and hydrogen at atmospheric pressure, Figure 3.052.

3.053 Low cycle fatigue life of bar at 75 F in helium and hydrogen at 5000 psi, Figure 3.053.

3.054 Fatigue crack-growth rate for plate tested at various temperatures in air, Figure 3.054.

3.055 Fatigue crack-growth rate for sheet tested at various temperatures in air, Figure 3.055.

3.056 Effects of variations in cycling frequency on fatigue crack-growth rate for sheet tested at 1400 F in air, Figure 3.056.

3.057 Effects of variations in cycling frequency on fatigue crack-growth rate for sheet tested at 1200 F in air, Figure 3.057.

3.06 Elastic Properties

3.061 Poisson's ratio, 0.320 at room temperature, and 0.328 at -108 F.

3.062 Modulus of elasticity.

3.0621 Effect of elevated temperatures on modulus of elasticity, Figure 3.0621.

3.063 Modulus of rigidity.

3.064 Tangent modulus.

3.0641 Compressive tangent modulus curves for bar at various temperatures, Figure 3.0641.

3.065 Secant modulus.

4 FABRICATION

4.01 Forming

4.011 Hastelloy X can be cold formed by most of the common methods including drawing, rolling, bending, spinning, drop hammering, punching, and shearing. The solution-treated condition is optimum for cold-forming operations because it provides minimum hardness and maximum ductility. Nevertheless, with the alloy's good toughness and work hardenability, relatively high energy levels and frequent intermediate solution treatments are required during severe cold-forming operations. Simple bending operations on a brake press seldom require lubrication, whereas severe forming requires heavy-duty lubricants such as metallic soaps, or chlorinated or sulfochlorinated oils; land oil, castor oil, or sperm oil lubricants are recommended for intermediate forming. Generally, after final cold-working, parts should be solution treated to restore the optimum combination of mechanical properties and corrosion resistance (1,7).

4.0111 In cold punching, the perforation diameter should be a minimum of twice the thickness, and the center-to-center dimension should be three to four times the hole diameter (7).

4.0112 Thickness up to 3/8 inch can be sheared, but greater thicknesses should be saw cut (7).

4.0113 In tube bending, the minimum bending radius should normally be three times the tube diameter, although under special circumstances two times the tube diameter can sometimes be tolerated (7).

4.0114 In formability tests on solution-treated sheet, the typical Ericksen cup depth is 0.35 to 0.45 inch (1).

4.0115 AMS specifies that sheet and strip must be capable of being bent 180 degrees without cracking around a diameter equal to one and a half times the thickness for thicknesses up to 0.050 inch, and equal to twice the thickness for greater thicknesses up to 0.187 inch (9).

4.012 Hastelloy X can be hot worked by forging, hot rolling, hot upsetting, and impact extrusion. Forging and hot rolling should be carried out in the temperature range 2150 to 1750 F with relatively moderate reductions per pass and frequent reheating. Hot upsetting is feasible when the length to be upset is no more than three times the diameter; and impact extrusion should be carried out at or near the upper end of the forging temperature range (7).

4.013 The alloy has good castability for the production of sand, investment, and centrifugal castings.

4.02 Machining and Grinding

4.021 Hastelloy X can be machined with conventional methods. Carbide tools are preferred, but high-speed steel cutting tools can also be used. Machinability is similar to that of austenitic stainless steels. The alloy is tough and, therefore, requires rigid fixturing, low cutting speeds, and ample cutting fluids, either water-base or sulfochlorinated oil. Finish grinding is recommended when very close tolerances are required (7).

4.03 Joining

4.031 The welding characteristics of Hastelloy X are similar to those of austenitic stainless steels. It can be readily welded by the SMAW, GMAW, and GTAW processes. Submerged-arc and oxyacetylene welding are not normally recommended because of possible pick up of carbon and silicon, which lower corrosion resistance and toughness. It can be welded to steel as well as to itself and to other nickel-base superalloys. Iron dilution when welded to steel tends to lower the corrosion resistance of the weld deposit. Preheat is not required, except that no welding should be done when the base metal is below 32 F, and interpass temperatures should not exceed 200 F. Normally, Hastelloy X welding electrodes are used but other compatible superalloy filler metals – Hastelloy C276, Hastelloy S, IN-112, and IN-625 – are also acceptable. Although many weldments are used in the as-welded condition, postweld solution treatment is desirable when feasible and when optimum corrosion resistance in the weld area is necessary (7).

4.0311 Hardness of weld joints made by various techniques, all with Hastelloy X filler metal, Table 4.0311.

4.0312 Effects of exposures to various elevated temperatures on the room-temperature hardness of weld metal deposited by the gas-tungsten-arc process, Figure 4.0312.

4.0313 Tensile strength of butt welds between Hastelloy X and IN-625 alloys produced by various methods with various filler metals, Table 4.0313.

4.0314 Effects of elevated temperatures on ultimate tensile strength of butt-welded sheets made with gas-tungsten-arc method using five different filler alloys, Figure 4.0314.

4.0315 Fatigue crack-growth rate at elevated temperatures for Hastelloy X weld metal deposited by gas-tungsten-arc method, Figure 4.0315.

4.0316 Fatigue crack-growth rate at 1000 F and various cycling rates for Hastelloy X weld metal deposited by gas-tungsten-arc method, Figure 4.0316.

4.0317 Creep-rupture time at various temperatures and stresses for butt-welded sheets made with gas-tungsten-arc method using five different filler alloys, Figure 4.0317.

4.032 Hastelloy X can be brazed with most of the silver-base, gold-base, and nickel-base brazing alloys. It is most commonly brazed with the nickel-chromium-silicon-boron type alloys in vacuum, high purity argon, or hydrogen atmospheres. With the lower-melting silver-copper type alloys, manual torch brazing with suitable flux protection is feasible. Control of joint clearance in the range 0.001 to 0.005 is necessary to obtain optimum strength. Special techniques, however, have recently been developed to braze with wider clearances by using as the brazing material a sintered combination of Hastelloy C and a standard nickel-base brazing alloy (Figure 4.0321) (7).

4.0321 Effects of elevated temperatures are tensile strength of butt joints with 0.010 inch clearance made by brazing at 2065 F with two different brazing materials, Figure 4.0321.

4.04 Surface Treating

4.041 After hot work or heat treatment, the oxide film on Hastelloy X, which is more adherent than that of stainless steels, is relatively inert to acid pickling. It is best removed by immersion in one of the commercially available caustic-base salt baths followed by pickling in hot sulfuric and hot nitric-hydrofluoric acid. Sand, shot, or vapor blasting are acceptable for removing scale under certain conditions. With sand and shot blasting, work hardening of the surfaces and distortion of thin parts can occur. After blasting, it is desirable to acid pickle in order to remove any imbedded iron or other particles (7).

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Alloy	Hastelloy X				
Forms					
Bars, Billets, Forgings, Rings, and Rods	Sheet, Strip, and Plate	Pipe and Tube	Castings	Welding Electrodes and Fittings	Rivets
AMS 5754G ASTM B572 ASME SB572	AMS 5536H ASTM B435 ASME SB435	AMS 5587C AMS 5588C ASTM B619 ASTM B622 ASTM B626 ASME SB619 ASME SB622 ASME SB626	AMS 5390B ASTM A567,Gr5	AMS 5798B AMS 5799B AWS 5.11 AWS 5.14 ASME SFA5.11 ASME SFA5.14 ASTM B366	AMS 7237

TABLE 1.03. SPECIFICATIONS (8-16)

Alloy	Hastelloy X	
	Percent	
Composition	Min	Max
C	0.05	0.15
Mn	–	1.00
Si	–	1.00
P	–	0.040
S	–	0.030
Cr	20.50	23.00
Co	0.50	2.50
Mo	8.00	10.00
W	0.20	1.00
Fe	17.00	20.00
B	–	0.010
Ni	Remainder	

Note: Some of the specifications deviate slightly from the above limits. For example, AMS 5587C and 5588C covering tubing specify maximum copper content of 0.30 percent. AMS 5536H on sheet, strip, and plate specifies maximum aluminum content of 0.50 percent, titanium content of 0.15, and copper content of 0.50. The casting specifications allow 0.20 percent maximum carbon.

Hastelloy X-280 has the same composition except that cobalt content is limited to a maximum content of 0.50 percent.

TABLE 1.04. COMPOSITION (1, 8-15)

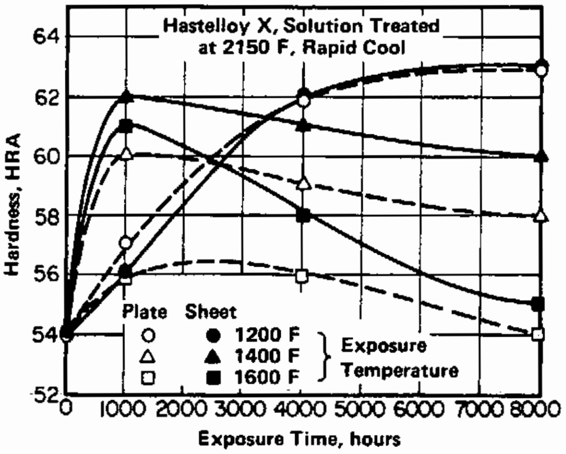


FIGURE 1.061. EFFECTS OF EXPOSURES AT VARIOUS ELEVATED TEMPERATURES ON HARDNESS OF SHEET AND PLATE AT ROOM TEMPERATURE (1)

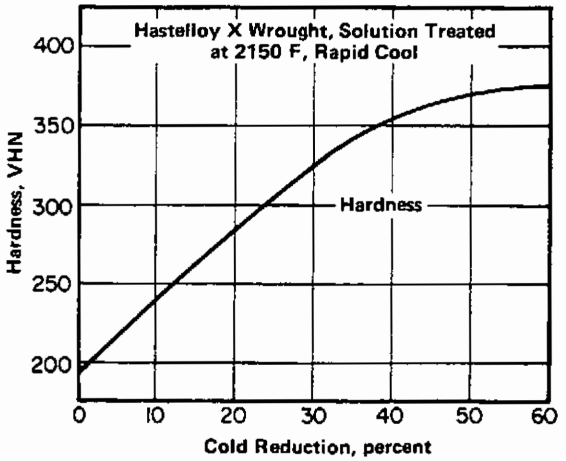


FIGURE 1.062. EFFECT OF COLD WORK ON HARDNESS (7)

	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

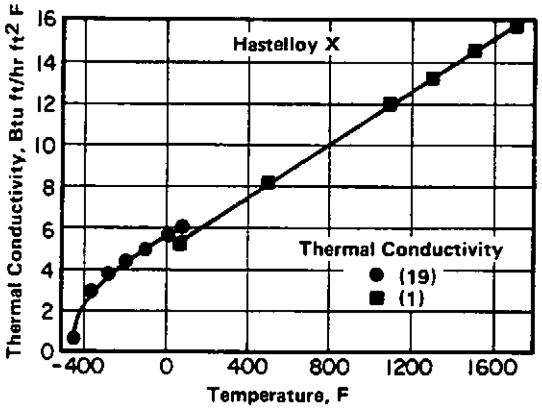


FIGURE 2.013. THERMAL CONDUCTIVITY (1, 19)

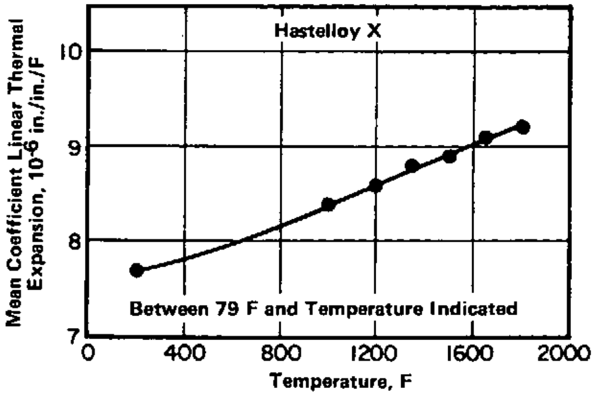


FIGURE 2.014. THERMAL EXPANSION (1)

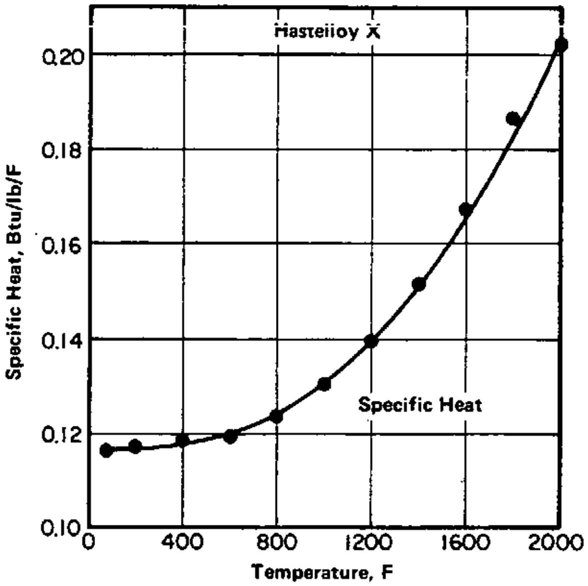


FIGURE 2.015. SPECIFIC HEAT (1)

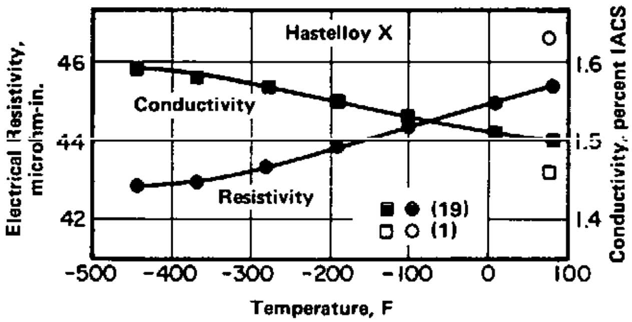


FIGURE 2.022. ELECTRICAL PROPERTIES (1, 19)

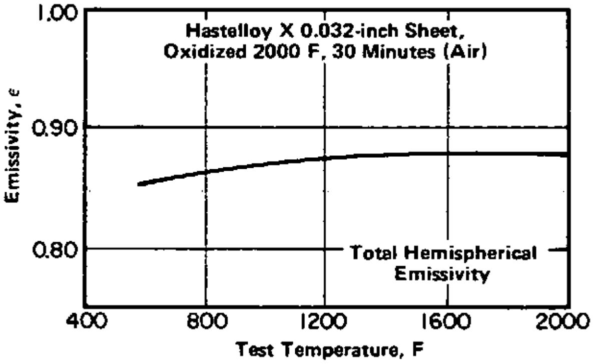


FIGURE 2.024. EMITTANCE (28)

	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

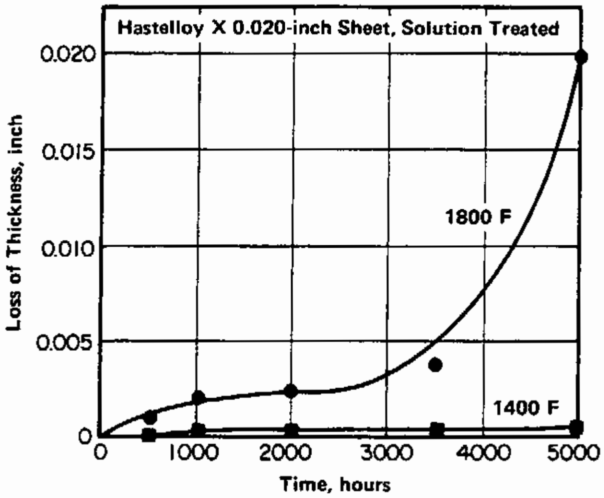


FIGURE 2.0311. LOSS OF EFFECTIVE THICKNESS DUE TO OXIDATION OF SHEET CONTINUOUSLY EXPOSED TO STILL AIR AT A PRESSURE OF 8 TORR AT BOTH 1800 AND 1400 F (22)

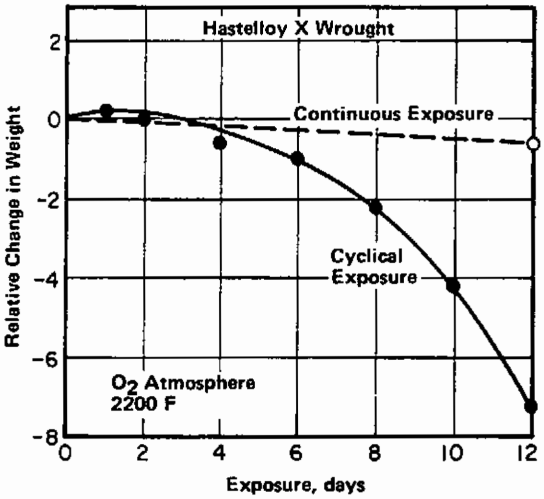


FIGURE 2.0312. RELATIVE WEIGHT LOSSES DUE TO EXPOSURE TO OXYGEN AT 2200 F BOTH CONTINUOUSLY AND CYCLICALLY, IN THAT ONCE EACH DAY A SAMPLE WAS REMOVED FROM THE FURNACE, COOLED, BRUSHED CLEAN, AND RETURNED TO THE FURNACE (31)

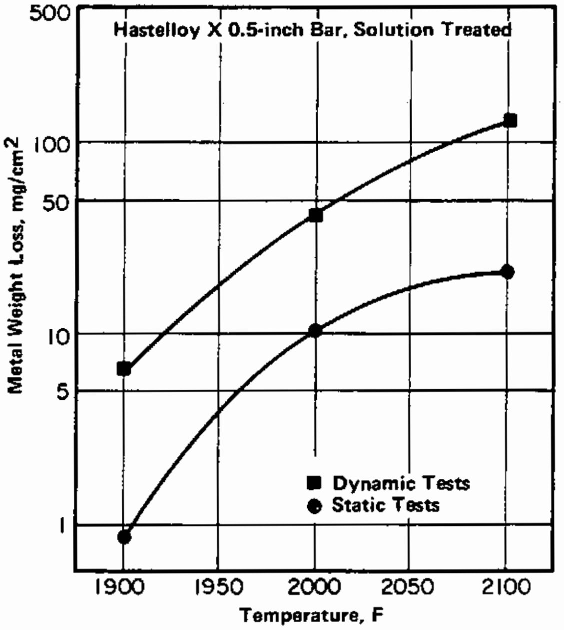


FIGURE 2.0313. METAL WEIGHT LOSS DUE TO DYNAMIC AND STATIC OXIDATION FOR 100 HOURS AT VARIOUS TEMPERATURES (32)

Dynamic tests consist of 100 1-hour cycles at indicated temperatures in natural gas combustion products at Mach 0.3, each followed by 3 minutes of cooling in Mach 0.7 air blast. Static tests consist of 100 1-hour cycles in still air at indicated temperature, each followed by cooling in ambient air for 40 minutes or more.

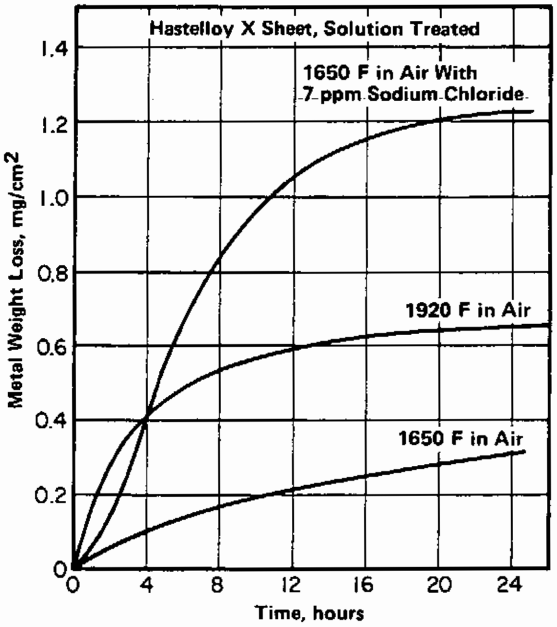


FIGURE 2.0314. METAL WEIGHT LOSS DUE TO OXIDATION AND HOT CORROSION AT VARIOUS TEMPERATURES IN AIR AND IN AIR CONTAMINATED WITH SODIUM CHLORIDE (33)

The air in these experiments was flowing at a rate of 0.35 ft/second.

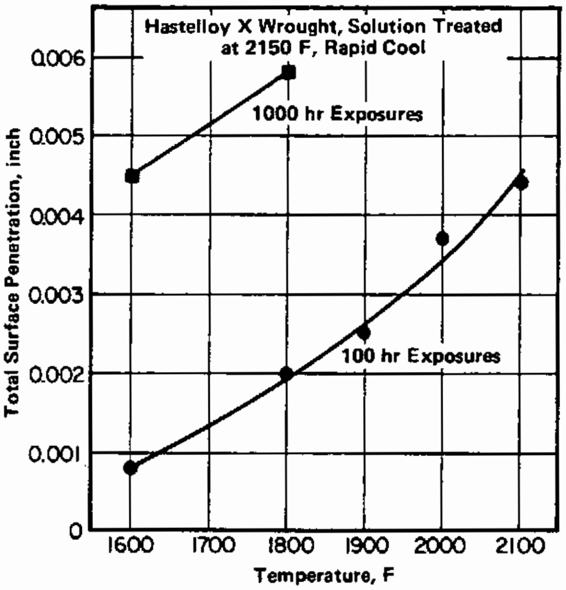


FIGURE 2.0315. TOTAL SURFACE PENETRATION OF OXIDATION AND HOT CORROSION CAUSED BY EXPOSURES AT VARIOUS TEMPERATURES TO COMBUSTION PRODUCTS OF NO. 2 DIESEL OIL AT A VELOCITY OF 280 FEET PER SECOND (1)

Temperature was cycled twice per hour to less than 500 F and back to test temperature in 2 minutes.

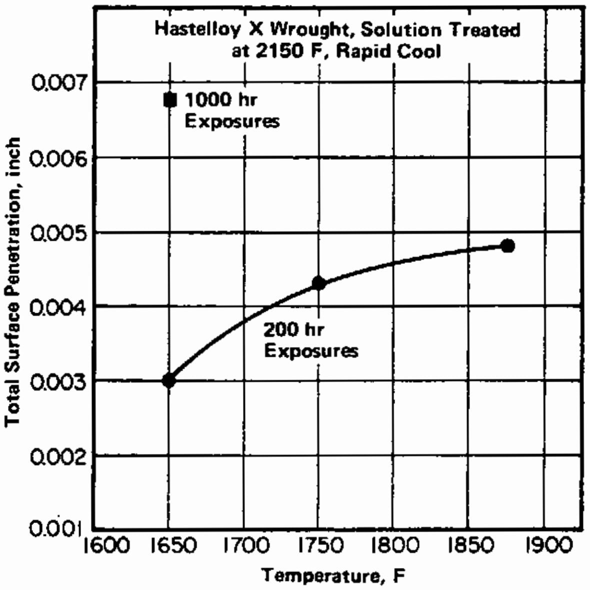


FIGURE 2.0316. TOTAL SURFACE PENETRATION OF OXIDATION AND HOT CORROSION CAUSED BY EXPOSURES AT VARIOUS TEMPERATURES TO THE COMBUSTION PRODUCTS OF NO. 2 DIESEL OIL PLUS 5 PPM SEA SALT AT A VELOCITY OF 13 FT PER SECOND (1)

Temperature was cycled once per hour to less than 500 F and back to temperature in 2 minutes.

Alloy	Hastelloy X					
Form	Wrought					
Condition	Solution Treated					
Irrad Temp, F	Neutron Fluence, n/cm^2 (E>1Mev)	F_{ty}, ksi	F_{tu}, ksi	e (4D), percent	RA, percent	Hardness, HRB
–	–	49.4	112.5	52	52	97
120	5.0×10^{19}	100.2	129.3	50	62	96
120	1.8×10^{20}	104.0	130.7	43	64	99
120	2.5×10^{20}	106.3	131.0	42	49	100

TABLE 2.0411. EFFECTS OF FAST NEUTRON IRRADIATION ON TENSILE PROPERTIES AND HARDNESS AT ROOM TEMPERATURE (36)

Alloy	Hastelloy X				
Form	Wrought				
Condition	ST Prior to Irradiation				
Test Temp, F	Irrad Temp, F	Neutron Fluence, n/cm^2 (E>1Mev)	F_{ty}, ksi	F_{tu}, ksi	e (4D), percent
75	–	–	56.1	118.0	46
	120	1 x 10^{20}	95.0	125.0	40
	535	6 x 10^{19}	72.5	118.0	48
	750	4 x 10^{20}	74.2	–	45
	1200	3 x 10^{19}	42.0	107.0	30
570	–	–	47.4	110.0	24
	1365	9 x 10^{19}	45.8	110.0	21
	1365	2.3 x 10^{20}	41.0	102.0	18
1100	–	–	49.2	111.0	34
	750	4 x 10^{20}	41.5	–	14
	1200	2 x 10^{21}	59.0	93.0	5
1200	–	–	40.5	88.8	45
	535	1 x 10^{20}	26.0	49.0	9
	1365	9 x 10^{19}	32.5	62.6	6
	1365	2.2 x 10^{20}	34.7	67.4	6
	1365	4 x 10^{20}	37.0	67.7	7
1290	–	–	35.0	71.0	48
	1200	3 x 10^{19}	23.0	87.0	24

TABLE 2.0412. EFFECTS OF FAST NEUTRON IRRADIATION ON TENSILE PROPERTIES AT VARIOUS TEMPERATURES (2)

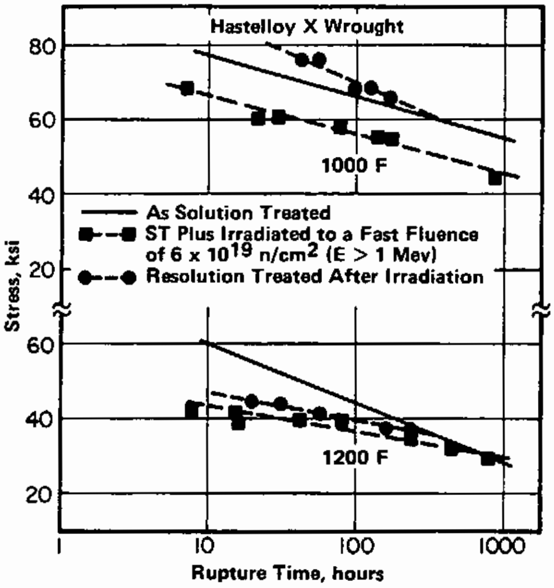


FIGURE 2.0413. EFFECTS OF FAST NEUTRON IRRADIATION ON CREEP-RUPTURE TIME AT TEMPERATURES OF 1000 AND 1200 F (2)

Alloy	Hastelloy X						
Source	Form	Condition	Temp, F	F_{ty}, ksi (Min)	F_{tu}, ksi (Min)	e (4D), percent (Min)	Hardness, HRB (Max)
AMS 5587C(10)	Tubing, Seamless	ST	RT	45	100	20(a)	–
AMS 5588C(11)	Tubing, Welded	ST	RT	45	100	20(a)	–
ASM 5536H(9)	Sheet, Strip, and Plate						
	<0.010-inch Thick	ST	RT	45	105	–	–
	0.010-0.019 inch	ST	RT	45	105	29	–
	0.020-0.187 inch	ST	RT	45	105	35	–
	0.188-2.000 inch	ST	RT	40	100	35	–
	>2.000 inch	ST	RT	40	95	35	–
AMS 5390B(12)	Investment Castings	As-Cast	RT	35	55	8	96(b)
			1500	–	35	12	–
ASTM A567	Castings	As-Cast	1500	–	35	12	–

(a) Applies to strip specimens; 25 percent for full section specimens.
(b) After exposure to 1475 F for 50 hrs, HRC shall not exceed 24.

TABLE 3.011. AMS SPECIFIED TENSILE PROPERTIES AND HARDNESS

Alloy	Hastelloy X						
Source	Form	Condition	Temp, F	Stress, ksi	Rupture Time, hr (Min)	e (4D), percent (Min)	Hardness(a), HRB (Max)
AMS 5754G(8)	Bars, Forgings, and Rings	ST	1500	15	24	10	241(b)
AMS 5536H(9)	Sheet, Strip, and Plate						
	0.010-0.019-inch Thick	ST	1500	16	15	3	–
	0.020 inch and Over	ST	1500	16	24	8	–
ASTM A567	Castings	As-Cast	1500	15	15	10	–

(a) Room-temperature hardness.
(b) Applies to bars and forgings; for flash welded rings maximum BHN is 277.

TABLE 3.012. AMS SPECIFIED STRESS-RUPTURE PROPERTIES AND HARDNESS

	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

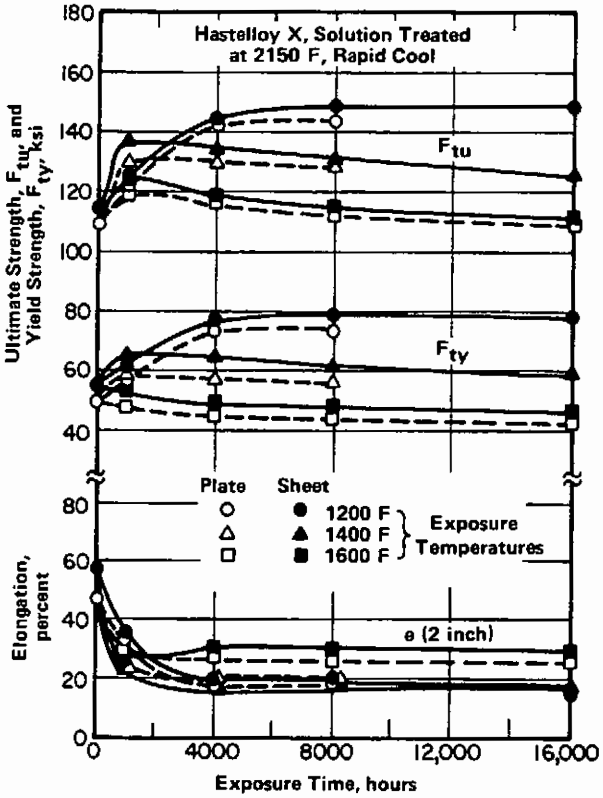


FIGURE 3.0212. ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET AND PLATE AFTER EXPOSURES TO ELEVATED TEMPERATURES AT NOMINAL AIR PRESSURE (1)

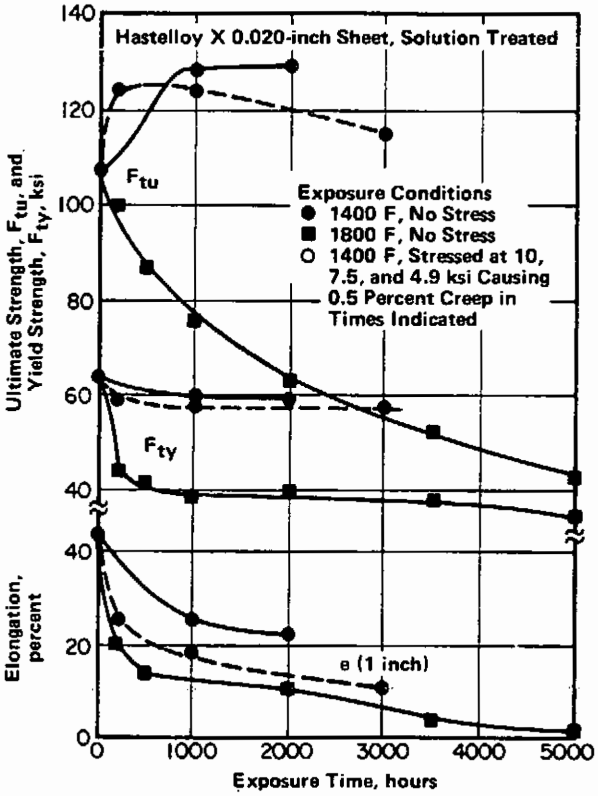


FIGURE 3.0213. ROOM-TEMPERATURE TENSILE PROPERTIES OF SHEET AFTER EXPOSURES TO ELEVATED TEMPERATURES AT 8 TORR AIR PRESSURE BOTH WITH AND WITHOUT STRESS (22)

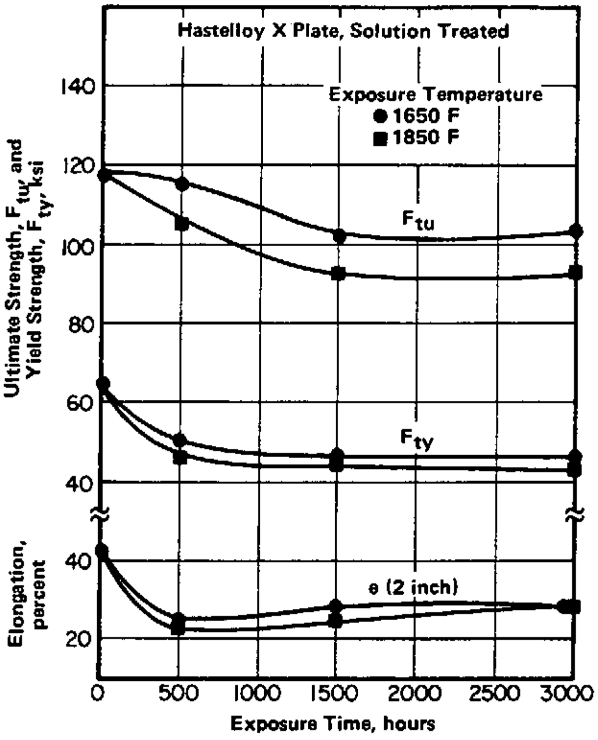


FIGURE 3.0214. ROOM TEMPERATURE TENSILE PROPERTIES OF PLATE AFTER EXPOSURES TO ELEVATED TEMPERATURES IN 1 ATMOSPHERE PRESSURE OF IMPURE HELIUM (3000 PPM EACH CO AND H_2) (23)

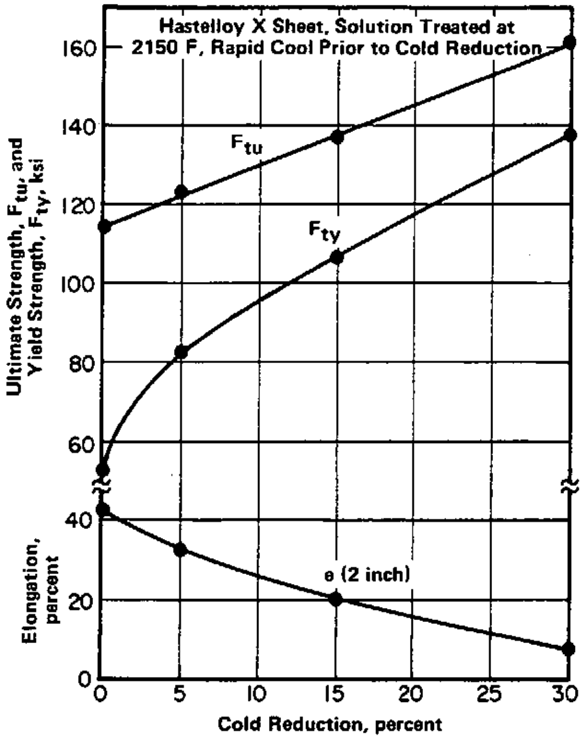


FIGURE 3.0215. EFFECT OF COLD WORK ON TENSILE PROPERTIES OF SHEET (1)

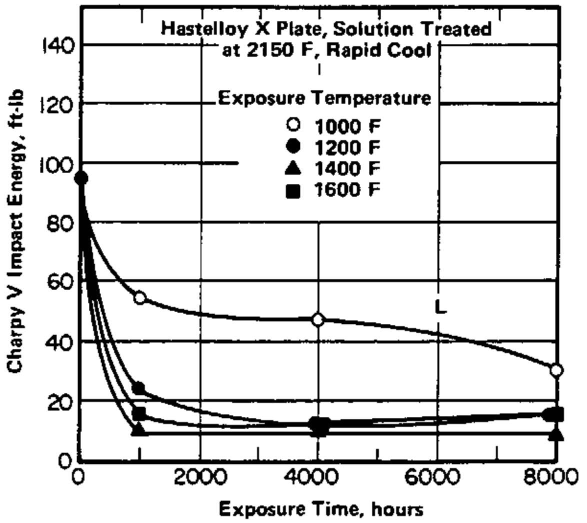


FIGURE 3.0231. EFFECTS OF EXPOSURES AT VARIOUS ELEVATED TEMPERATURES ON IMPACT PROPERTIES AT ROOM TEMPERATURE (1, 24)

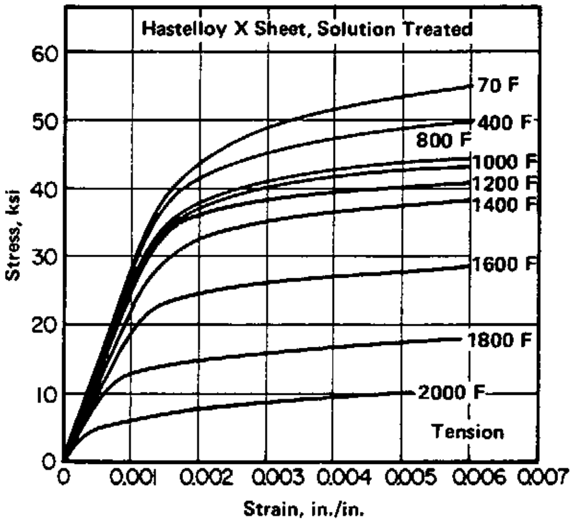


FIGURE 3.0311. TENSILE STRESS-STRAIN CURVES FOR SHEET AT VARIOUS TEMPERATURES (6)

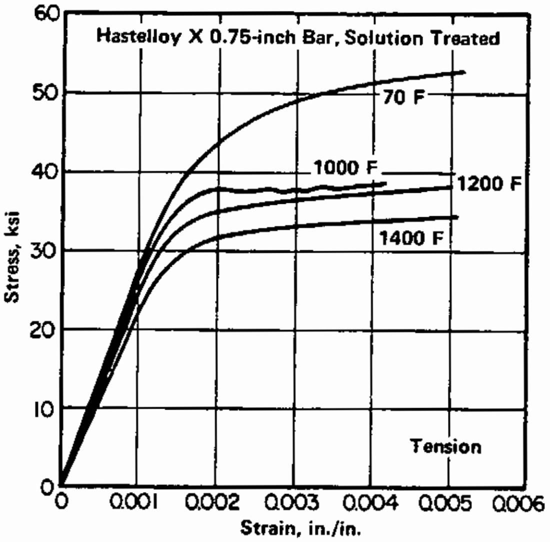


FIGURE 3.0312. TENSILE STRESS-STRAIN CURVES FOR BAR AT VARIOUS TEMPERATURES (38)

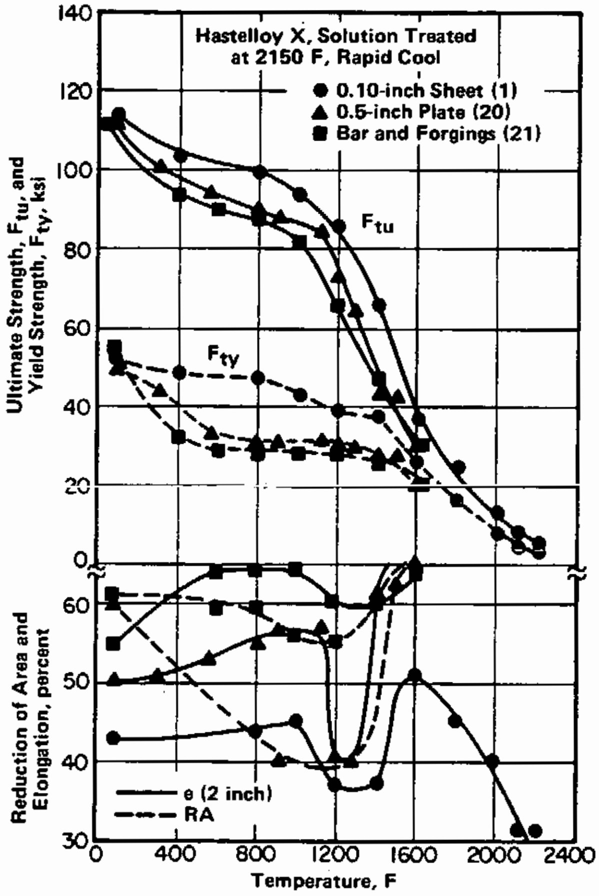


FIGURE 3.0313. EFFECTS OF ELEVATED TEMPERATURES ON TENSILE PROPERTIES OF SHEET, PLATE, BAR, AND FORGINGS (1, 20, 21)

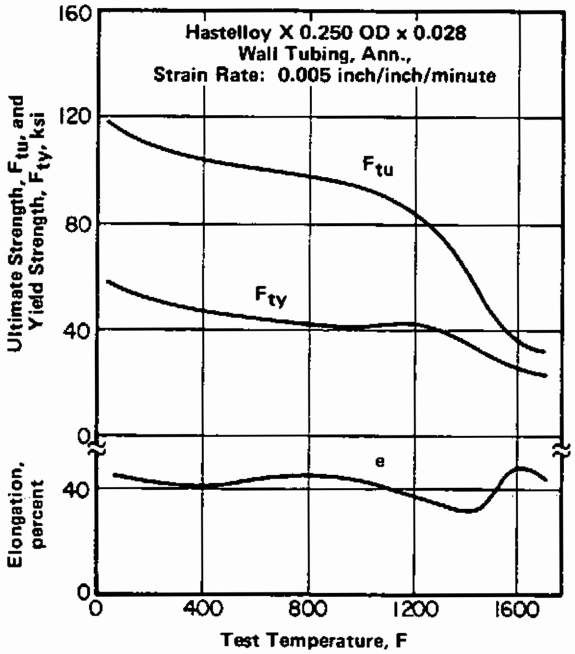


FIGURE 3.0314. EFFECTS OF ELEVATED TEMPERATURES ON TENSILE PROPERTIES OF TUBING (36)

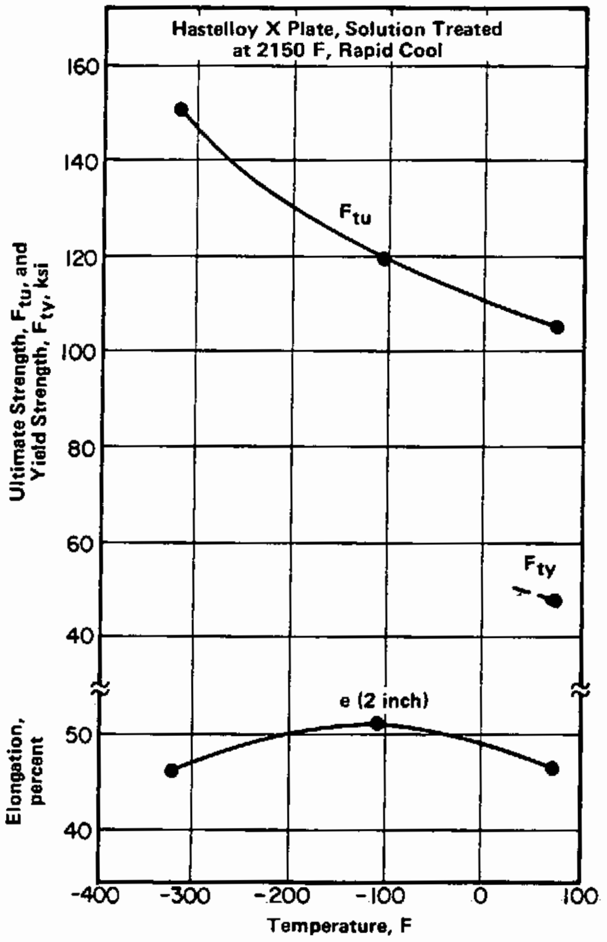


FIGURE 3.0315. EFFECT OF TEMPERATURES FROM 72 F DOWN TO -320 F ON TENSILE PROPERTIES OF PLATE (1)

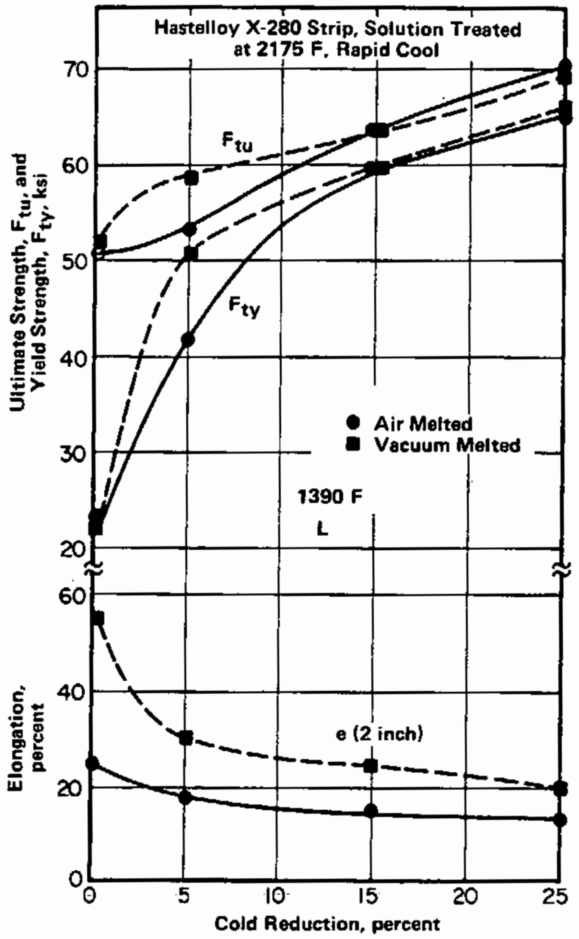


FIGURE 3.0316. EFFECTS OF COLD REDUCTION ON TENSILE PROPERTIES OF HASTELLOY X-280 AT 1390 F OF STRIP PRODUCED FROM AIR MELTED AND VACUUM MELTED STOCK (3)

	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

Alloy	Hastelloy X				
Form	0.160-inch Sheet				
Condition	Test Temp, F	Held at Temp, sec	F_{ty}, ksi	F_{tu}, ksi	e (2-inch) percent
Solution Treated	70 1500 1500	– 0 500	66.7 33.6 36.3	119.3 49.7 56.0	41.3 78.0 47.8
Solution Treated plus Cold Reduced 8 percent	70 1500 1500	– 0 500	128.5 44.0 47.7	139.0 54.8 54.8	20.0 75.5 76.0
Solution Treated plus – 1975 F 45 min, Rapid Cool to 1400 F, Hold 16 hrs, Air Cool – Four Times	70 1500 1500	– 0 500	53.8 32.3 34.0	117.0 48.3 47.1	36.5 34.8 60.0
Solution Treated Plus Cold Reduced 8 percent plus – 1975 F 45 min, Rapid Cool to 1400 F, Hold 16 hrs, Air Cool – Four Times	70 1500 1500	– 0 500	54.0 34.4 33.7	119.5 46.5 45.7	32.0 89.0 94.5

TABLE 3.0317. EFFECTS OF COLD WORK AND OF SUBSEQUENT MULTIPLE SOLUTION-AND-AGING CYCLES ON TENSILE PROPERTIES AT ROOM TEMPERATURE AND 1500 F (39)

	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

Alloy	Hastelloy X					
Form	0.75-inch Bar					
Condition	Solution Treated to 2150 F Rapid Cool					
Temp. F	Atmosphere	Pressure, psi	F_{ty}, ksi	F_{tu}, ksi	e (1-inch) percent	RA, percent
80	Helium	5000	46.6	104.9	53.8	62.9
	Hydrogen	5000	49.4	105.4	53.0	63.5
1250	Helium	5000	34.1	79.8	53.0	57.6
	Hydrogen	5000	34.0	80.6	51.2	53.5

TABLE 3.0318. TENSILE PROPERTIES OF BAR AFTER 10-MINUTE EXPOSURE AT 80 AND 1250 F IN HIGH PRESSURE HELIUM AND HYDROGEN (26,27)

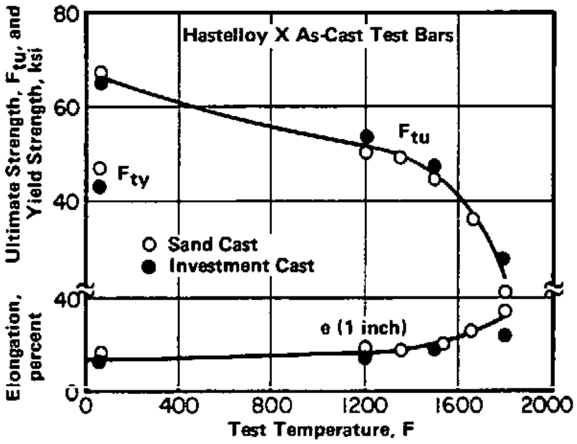


FIGURE 3.0319. EFFECTS OF ELEVATED TEMPERATURES ON TENSILE PROPERTIES OF SAND CAST AND INVESTMENT CAST TEST BARS (40)

Alloy	Hastelloy X					
Form	Cast					
Foundry	Condition[a]	Temp, F	F_{ty}, ksi	F_{tu}, ksi	e (4D), percent	RA, percent
1	AC	70	40.2	76.8	23.0	13.7
1	ST	70	39.9	74.6	22.5	24.2
2	ST	70	38.4	81.2	41.0	36.8
1	AC	-110	47.0	86.6	16.3	14.0
1	ST	-110	51.7	84.0	20.0	22.0
2	ST	-110	48.3	84.9	42.0	34.8
1	AC	-320	70.2	111.4	11.3	13.7
1	ST	-320	76.7	111.5	15.5	11.5
2	ST	-320	81.3	121.6	23.0	22.0
1	AC	-423	84.0	121.5	9.7	10.7
1	ST	-423	88.1	110.0	10.0	14.5
2	ST	-423	–	110.0	15.0	20.8

(a) AC = as-cast; ST = solution treat 2225 F, rapid cool.

TABLE 3.03110. TENSILE PROPERTIES FROM ROOM TEMPERATURE TO -423 F OF SAND CASTINGS FROM TWO FOUNDRIES (41)

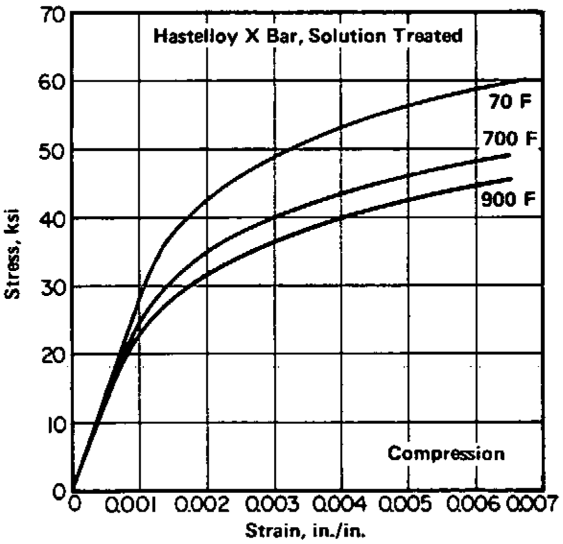


FIGURE 3.0321. COMPRESSIVE STRESS-STRAIN CURVES FOR BAR AT VARIOUS TEMPERATURES (6)

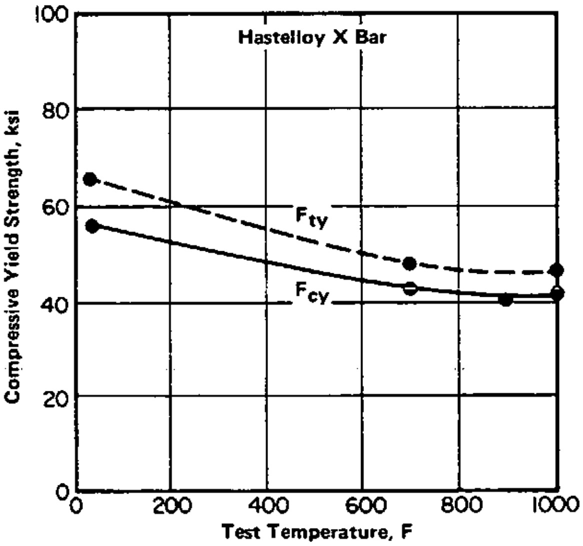


FIGURE 3.0322. EFFECT OF ELEVATED TEMPERATURES ON COMPRESSIVE YIELD STRENGTH OF BAR (42)

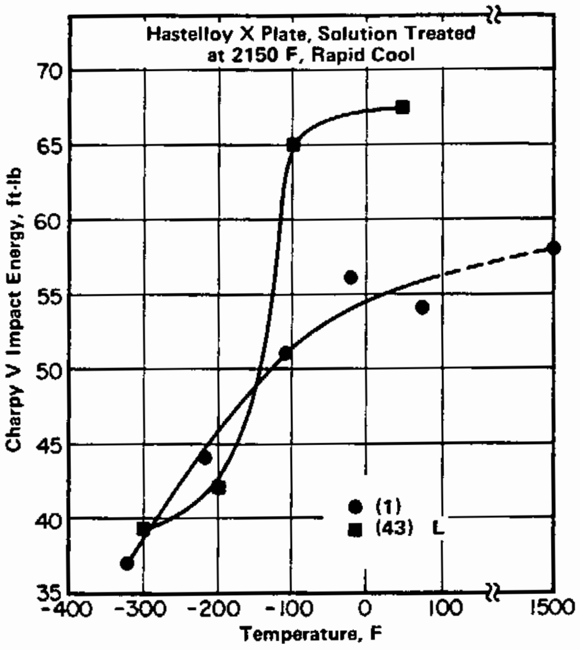
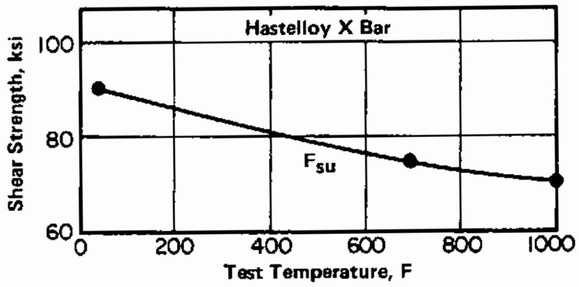


FIGURE 3.0331. EFFECTS OF TEMPERATURES FROM -320 TO 1500 F ON IMPACT PROPERTIES OF PLATE (1, 43)



	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

FIGURE 3.0351. EFFECT OF ELEVATED TEMPERATURES ON SHEAR STRENGTH OF BAR (42)

Alloy	Hastelloy X				
Form	0.75-inch Bar				
Condition	Solution Treated to 2150 F, Rapid Cool				
Temp, F	Atmosphere	Pressure, psi	F_{tu}, ksi	NTS(a), ksi	Ratio, NTS/F_{tu}
80	Helium	5000	104.9	127.6	1.22
80	Hydrogen	5000	105.4	126.8	1.20
1250	Helium	5000	79.8	90.7	1.14
1250	Hydrogen	5000	80.6	90.1	1.12

(a) $K_t = 8.0$

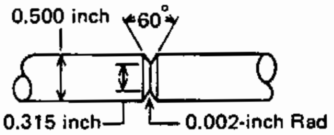


TABLE 3.03711. COMPARISON OF TENSILE STRENGTH AND NOTCH TENSILE STRENGTH OF BAR AFTER 10-MINUTE EXPOSURE AT 80 AND 1250 F IN HIGH PRESSURE HELIUM AND HYDROGEN (26,27)

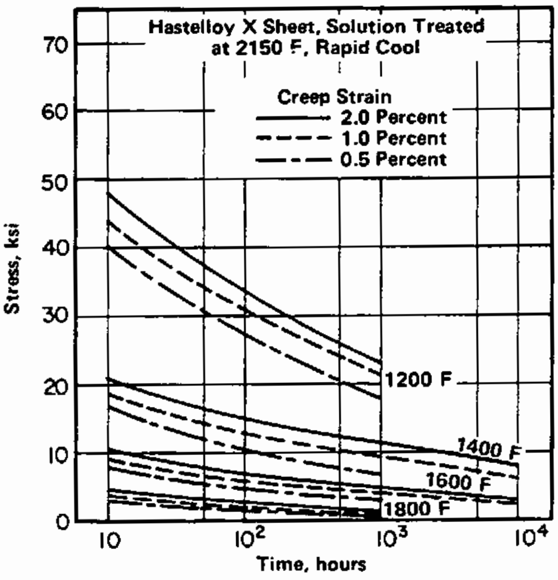


FIGURE 3.041. CREEP-DEFORMATION CURVES FOR SHEET AT TEMPERATURES FROM 1200 TO 1800 F (1)

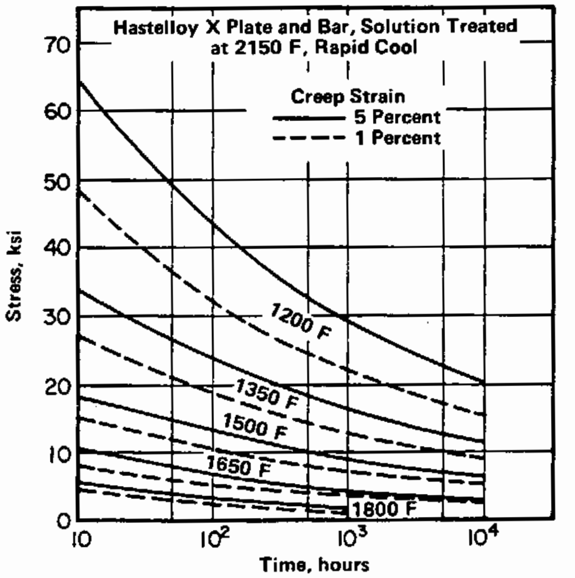


FIGURE 3.042. CREEP-DEFORMATION CURVES FOR PLATE AND BAR AT TEMPERATURES FROM 1200 TO 1800 F (7)

	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

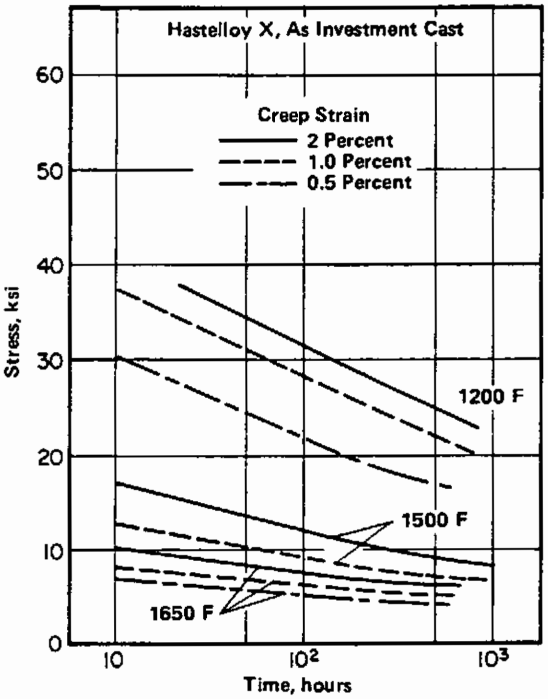


FIGURE 3.043. CREEP-DEFORMATION CURVES FOR CASTINGS AT TEMPERATURES FROM 1200 TO 1650 F (40)

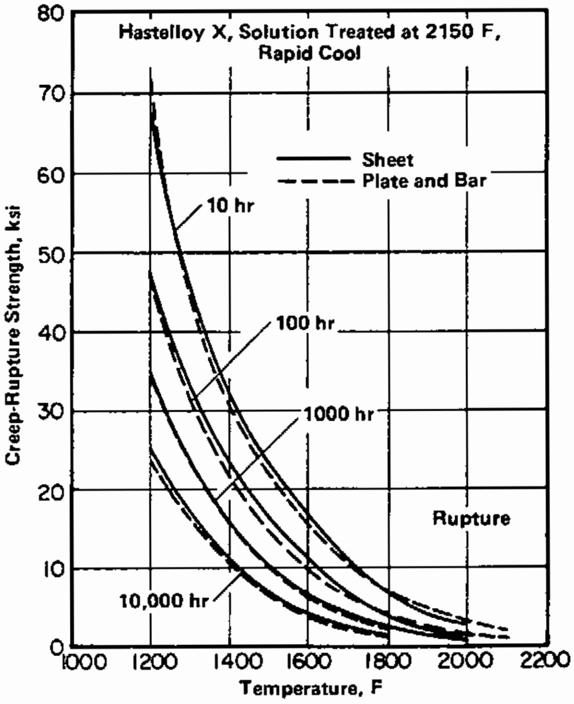


FIGURE 3.044. CREEP-RUPTURE STRENGTH FOR SHEET, PLATE, AND BAR FOR VARIOUS TEMPERATURE AND RUPTURE TIMES (1)

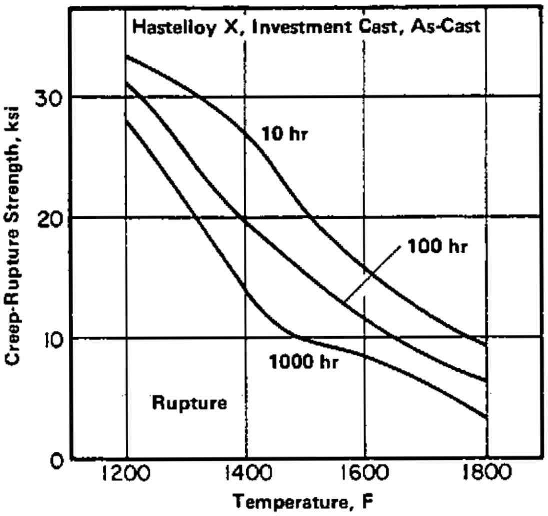


FIGURE 3.045. CREEP-RUPTURE STRENGTH FOR INVESTMENT CASTINGS FOR VARIOUS TEMPERATURES AND RUPTURE TIMES (44)

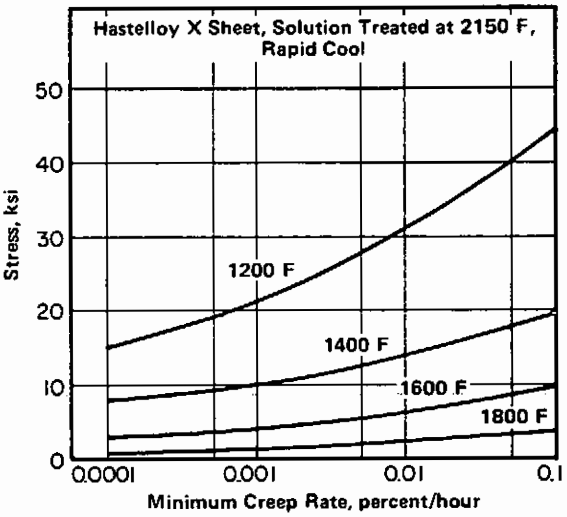


FIGURE 3.046. MINIMUM CREEP RATE OF SHEET AT VARIOUS STRESSES AND AT TEMPERATURES FROM 1200 TO 1800 F (1)

Alloy	Hastelloy X					
Form	Sheet					
Condition	Solution Treated					
	Stress, ksi for 7 Years to Cause					
	1% Creep Strain		Rupture		Onset of Tertiary Creep	
Temp, F	Avg	Min	Avg	Min	Avg	Min
1200	10.6	8.6	18.4	15.5	16.1	13.5
1300	6.5	5.2	12.8	9.9	10.3	8.4
1400	4.1	3.2	7.4	5.9	6.2	5.1
1500	2.6	2.0	4.4	3.5	3.6	2.9
1600	1.6	1.2	2.6	2.0	2.0	1.6

TABLE 3.047. AVERAGE AND MINIMUM STRESSES FOR 7 YEARS TO CAUSE VARIOUS AMOUNTS OF CREEP AND RUPTURE AT VARIOUS TEMPERATURES (45)

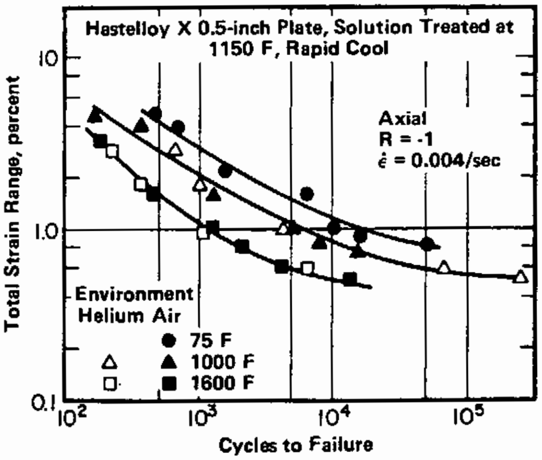


FIGURE 3.051. FATIGUE LIFE OF PLATE AT VARIOUS TEMPERATURES IN AIR AND IMPURE HELIUM AT ATMOSPHERIC PRESSURE (20, 47)

Ni	
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

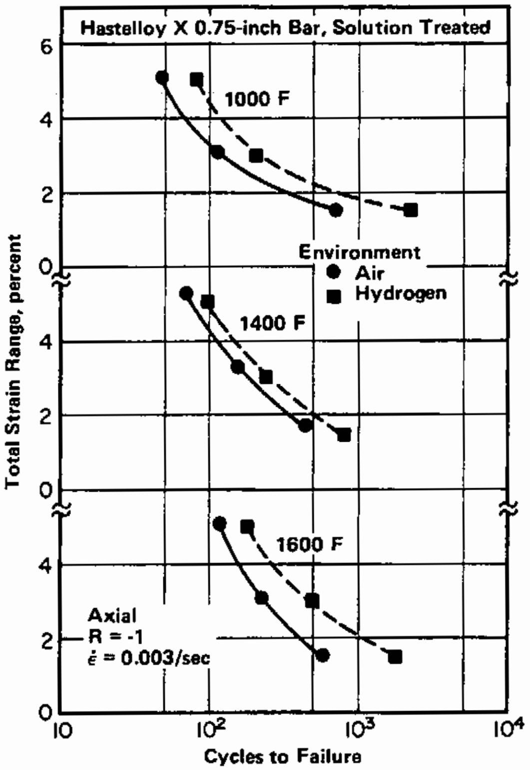


FIGURE 3.052. LOW CYCLE FATIGUE LIFE OF BAR AT ELEVATED TEMPERATURES IN AIR AND HYDROGEN AT ATMOSPHERIC PRESSURE (38)

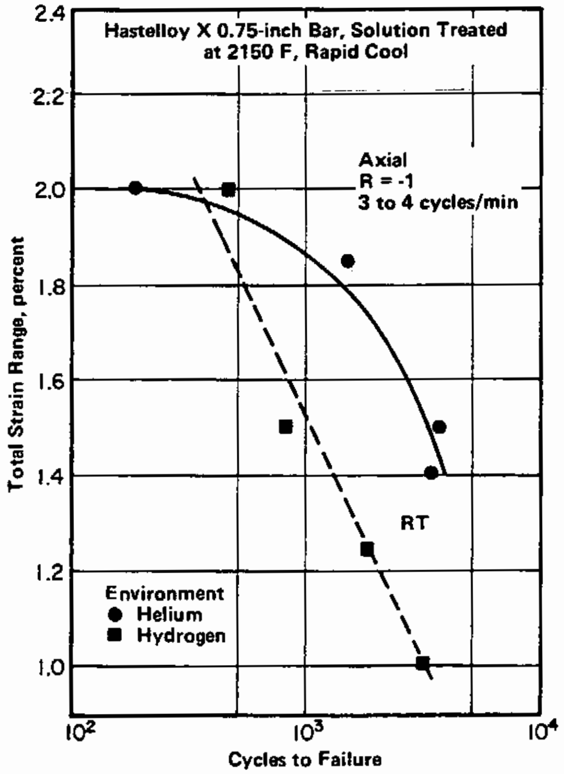


FIGURE 3.053. LOW CYCLE FATIGUE LIFE OF BAR AT 75 F IN HELIUM AND HYDROGEN AT 5000 PSI (27)

	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

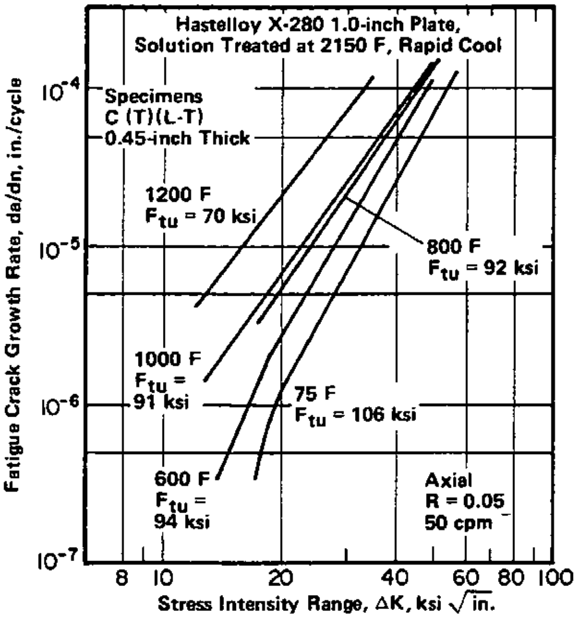


FIGURE 3.054. FATIGUE CRACK-GROWTH RATE FOR PLATE TESTED AT VARIOUS TEMPERATURES IN AIR (4)

For explanation of specimen type see reference 48.

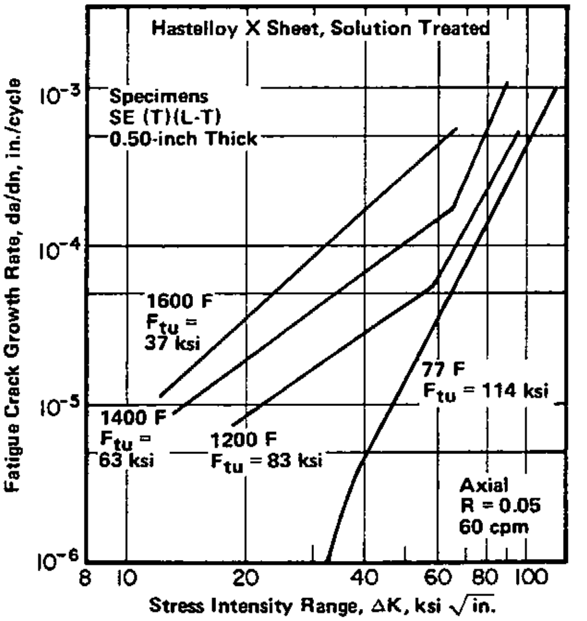


FIGURE 3.055. FATIGUE CRACK-GROWTH RATE FOR SHEET TESTED AT VARIOUS TEMPERATURES IN AIR (49)

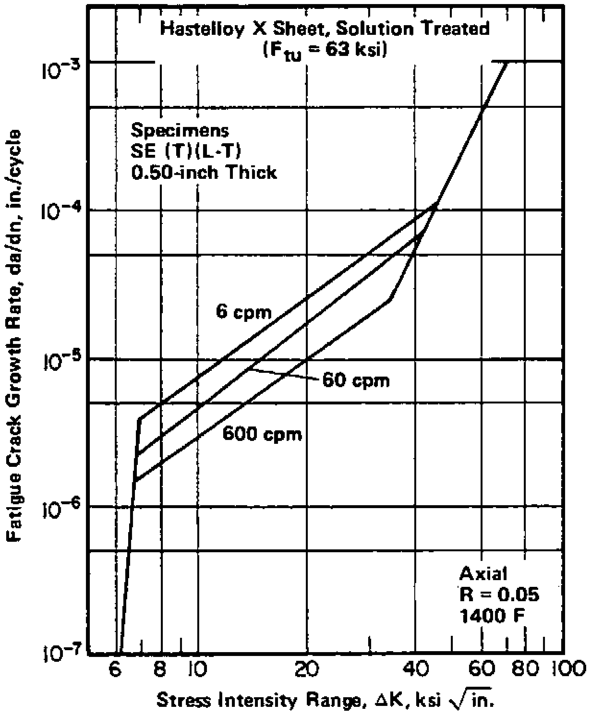


FIGURE 3.056. EFFECTS OF VARIATIONS IN CYCLING FREQUENCY ON FATIGUE CRACK-GROWTH RATE FOR SHEET TESTED AT 1400 F IN AIR (49)

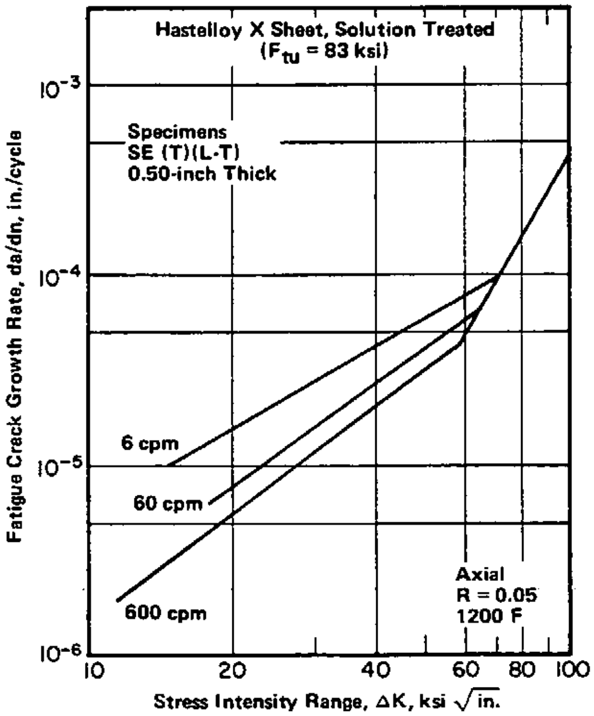


FIGURE 3.057. EFFECTS OF VARIATIONS IN CYCLING FREQUENCY ON FATIGUE CRACK-GROWTH RATE FOR SHEET TESTED AT 1200 F IN AIR (49)

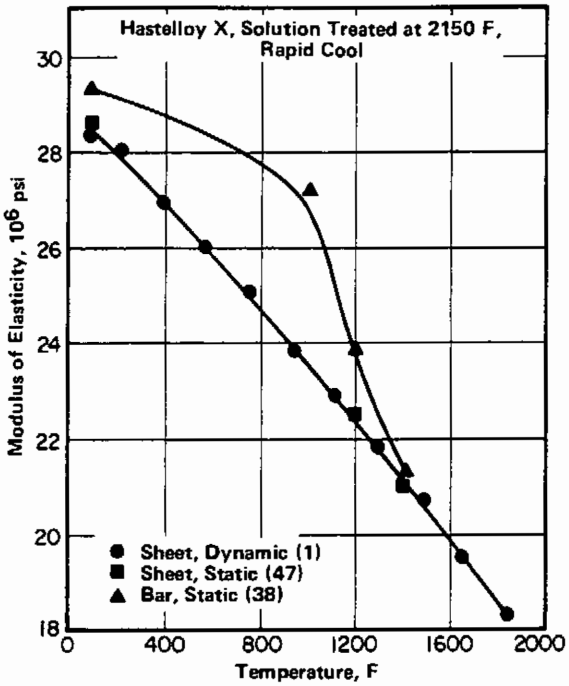


FIGURE 3.0621. EFFECT OF ELEVATED TEMPERATURES ON MODULUS OF ELASTICITY (1,38,49)

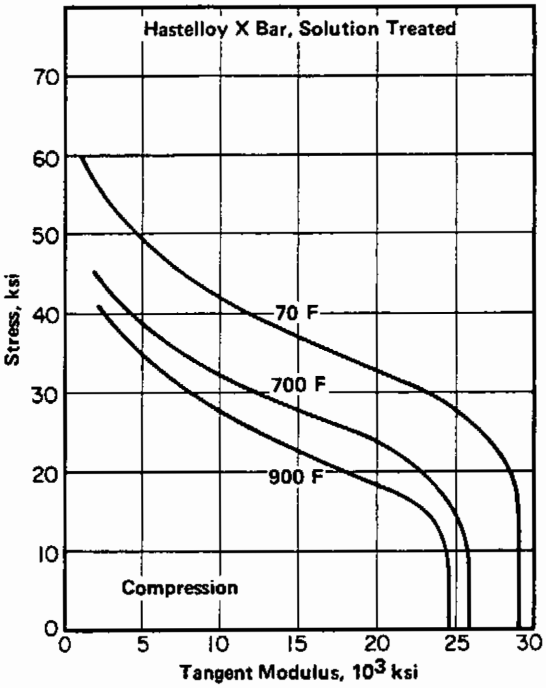


FIGURE 3.0641. COMPRESSIVE TANGENT MODULUS CURVES FOR BAR AT VARIOUS TEMPERATURES (6)

Alloy	Hastelloy X		
Form	Butt Welded Sheet		
Condition	ST 2150 F Rapid Cool Before Welding, Tested in As-Welded Condition		
	Hardness, HRB		
Weld Method	Base Metal	Heat-Affected Zone	Weld Metal
Shielded Metal Arc	91	93	92
Gas Tungsten Arc	91	93	89
Gas Metal Arc	91	93	90

TABLE 4.0311. HARDNESS OF WELD JOINTS MADE BY VARIOUS TECHNIQUES, ALL WITH HASTELLOY X FILLER METAL (1)

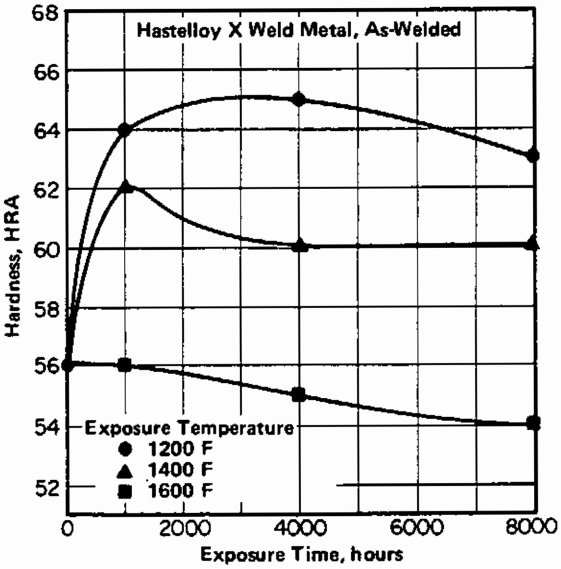


FIGURE 4.0312. EFFECTS OF EXPOSURES TO VARIOUS ELEVATED TEMPERATURES ON THE ROOM TEMPERATURE HARDNESS OF WELD METAL DEPOSITED BY THE GAS-TUNGSTEN-ARC PROCESS (1)

	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

Alloy	Hastelloy X Welded to IN-625		
Form	3/8-inch Plate		
Condition	ST Prior to Welding, As-Welded		
Welding Method	Filler Metal	F_{tu}, ksi	Fracture Location
SMAW	IN-112	118.5	Hastelloy X
GTAW	IN-625	119.7	Hastelloy X
GMAW	IN-625	121.2	Hastelloy X

TABLE 4.0313. TENSILE STRENGTH OF BUTT WELDS BETWEEN HASTELLOY X AND IN-625 ALLOYS PRODUCED WITH VARIOUS METHODS AND FILLER METALS (50)

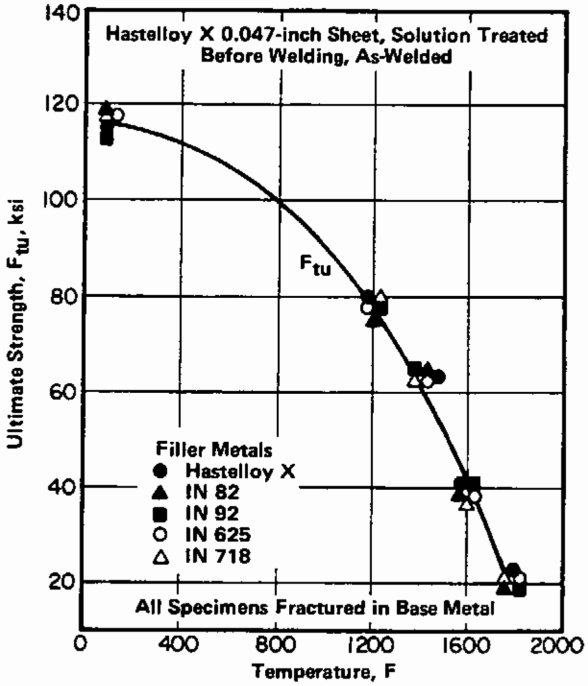


FIGURE 4.0314. EFFECTS OF ELEVATED TEMPERATURES ON ULTIMATE TENSILE STRENGTH OF BUTT WELDED SHEETS MADE WITH GAS-TUNGSTEN-ARC METHOD USING FIVE DIFFERENT FILLER ALLOYS (51)

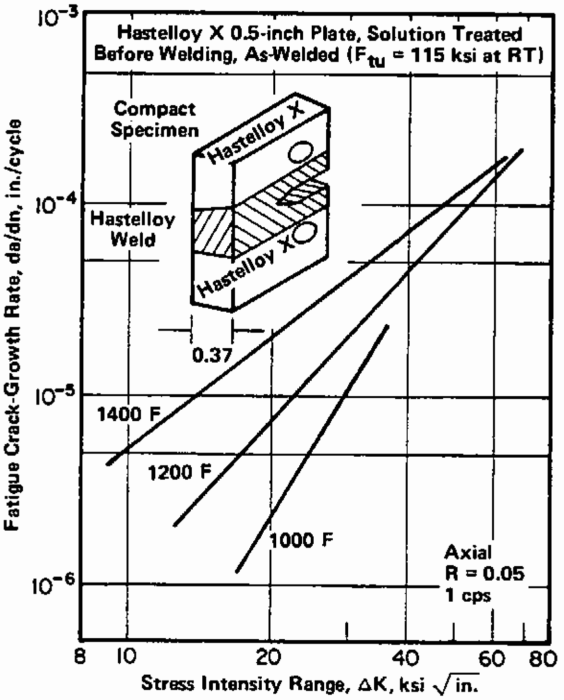


FIGURE 4.0315. FATIGUE CRACK-GROWTH RATE AT ELEVATED TEMPERATURES FOR HASTELLOY X WELD METAL DEPOSITED BY GAS-TUNGSTEN-ARC METHOD (5)

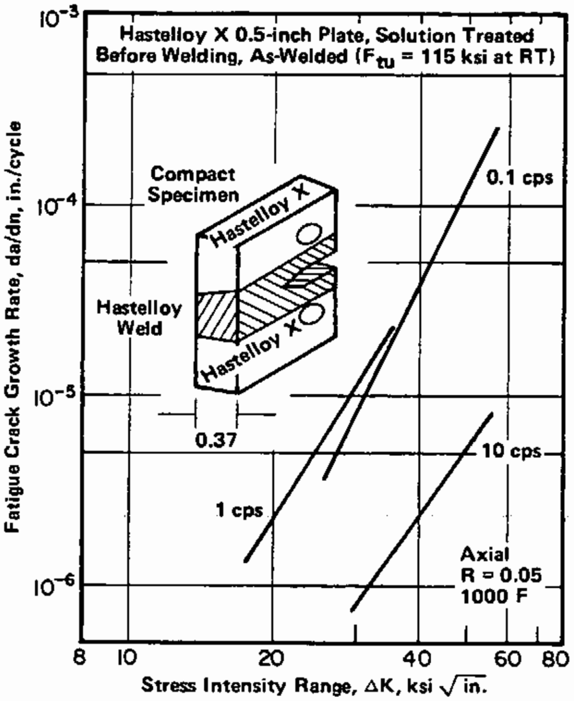


FIGURE 4.0316. FATIGUE CRACK-GROWTH RATE AT 1000 F AND VARIOUS CYCLING RATES FOR HASTELLOY X WELD METAL DEPOSITED BY GAS-TUNGSTEN-ARC MELTED (5)

	Ni
22	Cr
18	Fe
9	Mo
1.5	Co
0.5	W

Hastelloy X

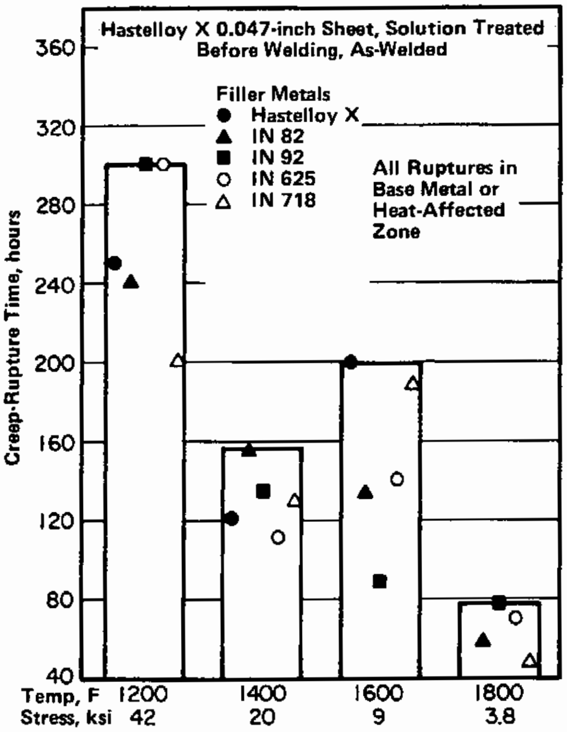


FIGURE 4.0317. CREEP-RUPTURE TIME AT VARIOUS TEMPERATURES AND STRESSES FOR BUTT WELDED SHEETS MADE WITH GAS-TUNGSTEN-ARC METHOD USING FIVE DIFFERENT FILLER ALLOYS (51)

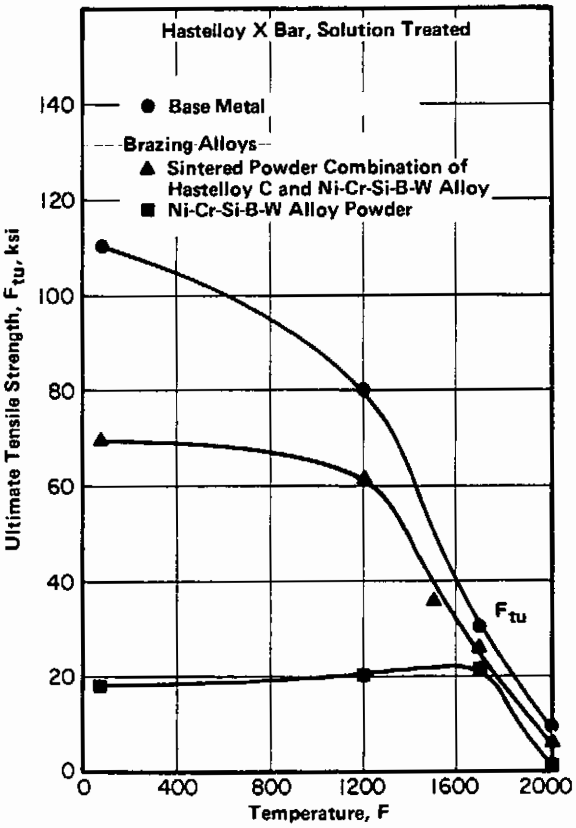


FIGURE 4.0321. EFFECTS OF ELEVATED TEMPERATURES ON TENSILE STRENGTH OF BUTT JOINTS WITH 0.10-INCH CLEARANCE MADE BY BRAZING AT 2065 F WITH TWO DIFFERENT BRAZING MATERIALS (52)