

1. GENERAL

Custom 455 is a versatile low carbon, martensitic, age-hardening Cr-Ni stainless steel with good corrosion resistance and favorable fabrication characteristics, intended for service up to 800F. A single aging treatment in the range of 900-1050F develops high tensile and yield strengths. Fracture toughness and ductility in tensile tests decrease with increasing strength level. K_{Isc} values in salt solution drop with decreasing aging temperature and are relatively low for the fully-aged condition. The alloy can be readily cold-formed, welded, and machined in the annealed condition.

Applications include high-strength aircraft fasteners and forgings, components for nuclear reactors, bolts, load hooks, drive pins, ball screw assemblies, springs, valve stems, gears, shafts, ring seals, retaining rings, pressure vessels, and parts for use at cryogenic temperatures to -60F.

1.1 Commercial Designation - Custom 455 stainless steel.

1.2 Alternate Designations - Carpenter Custom 455; AMS 5617; Almar 455; UNS S45500.

1.3 Specifications

1.3.1 [Table] Specifications.

1.4 Composition

1.4.1 [Table] Composition.

1.5 Heat Treatment

(See also Sections 1.9.9 and 2.1.2)

1.5.1 **Anneal.** Annealing is done at 1500-1650F, holding at temperature for 15 minutes to 1 hour, and rapid cooling. The preferred annealing range is 1500-1550F, and water quenching is recommended for small sections. (Ref. 105)

1.5.2 **Solution Heat Treatment.** Solution treating is done at 1500-1550F, holding for 5 to 30 minutes depending on section thickness and rapid cooling. The producer recommends (Ref. 106) water quenching sections less than 1.5 inches, oil quenching sections 1.5 to 6.0 inches, and air cooling sections greater than 6.0 inches. (See Section 1.9.9) Low solution temperatures result in incomplete solution. Temperatures over 1650F produce recrystallization and excessive grain growth. (Ref. 8)

1.5.2.1 Embrittlement is reported for solution treating at 1700F followed by aging in the 850-950F range (See Table 1.5.2.2 and Figure 3.2.1.8), and for 850F aging following the recommended 1500F solution treatment. (See

Fe
12 Cr
8.5 Ni
0.3 Cb+Ta
1.1 Ti
2.0 Cu
< .05 C

Table 1.5.2.2 and Figure 3.2.1.10) Superior toughness is achieved by double solution treating 1250F + 1500F for product aged 850-900F; but the double solutioning offers no advantage for 950F aged product. (See Table 1.5.2.1) (Ref. 26) It appears that triple solution treating 1700F + 1250F + 1500F further improves notch strength and impact energy of product aged 950-1000F, but with some penalty in tensile strength. (See Table 1.5.2.2)

1.5.2.2 [Table] Effect of solution treatment on room temperature smooth and mild-notch tensile strengths, and Charpy-V impact energy of solution treated and aged bar.

1.5.3 **Aging Treatment.** Precipitation hardening consists of heating to a selected temperature within the range of 900-1000F, holding for 4 hours, and air cooling. The optimum combination of room temperature tensile properties is obtained by aging at 950F. Aging at 900F produces the highest strength, whereas aging at 1000F results in improved ductility with slightly lower strength.

1.5.3.1 **Effect of aging treatment on dimensions.** The 4-hour aging treatment results in a contraction of 0.0007 inch per inch when aged at 900F and 0.0012 inch per inch at 1000F. (Ref. 5)

1.5.4 **Nitriding.** (See also Section 4.4.2)

1.5.4.1 [Table] Nitriding depth and hardness.

1.6 Hardness

1.6.1 **AMS specified hardness.** (See Table 3.1.1)

1.6.2 [Table] Typical hardness.

1.6.3 [Figure] Effect of aging time at 980F on hardness of forged block.

1.6.4 [Figure] Effect of aging time at 995-1000F on hardness of forged block.

1.6.5 [Table] Effect of cold drawing on hardness of wire.

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1.6.6 Nitriding depth and hardness. (See Table 1.5.4.1)

1.7 Forms and Conditions Available

The alloy is available as forging billets, wire, bars, shapes, forgings, cold-finished rounds, hot- and cold-finished sheet, strip, and plate, and tubing, all in a wide range of commercial sizes and conditions. (Ref. 5)

1.8 Melting and Casting Practice

Double vacuum melted only (vacuum induction followed by vacuum arc remelting). (Ref. 13)

1.9 Special Considerations

- 1.9.1 When parts are machined in the annealed or solution treated condition, allowance should be made for a slight contraction of about 0.001 inch per inch on aging. (See Section 1.5.3.1)
- 1.9.2 See Section 2.3 for a thorough discussion of corrosion resistance. Pitting and crevice corrosion, galvanic corrosion, and stress corrosion cracking, or a combination of these may be a problem, particularly for product aged below 1000F. K_{Isc} values in 3.5 percent NaCl solution decrease with increasing section size for all aging temperatures. (See Figure 2.3.4.1) Yield strength has a strong influence on K_{Isc} in a variety of corrosive media, with resistance increasing with decreasing yield strength. (See Figure 2.3.4.10)
- 1.9.3 As with other high strength martensitic stainless steels, Custom 455 is susceptible to hydrogen embrittlement. (Ref. 5)
- 1.9.4 Solution temperature above 1600F results in substantial drop in notch strength and presumably in fracture toughness. (See Figure 3.2.1.8)
- 1.9.5 Material aged at 950F exhibits an increase in tensile and yield strengths when exposed for 1000 hours at 700 or 800F, coupled with decrease in Charpy-V impact energy. (See Table 3.2.1.13)
- 1.9.6 Plane strain fracture toughness decreases with decreasing test temperature. Values at -65F for forging aged at 1000F are about one-half those at 75F. (See Table 3.3.7.2.4)
- 1.9.7 The response of plane strain fracture toughness to test temperature depends on heat treated section size and on the characteristics of a given heat, so that a substantial variability in toughness values can be encountered at a particular aging temperature. (See Figure 3.3.7.2.1)
- 1.9.8 Available evidence indicates no K_{Ic} directionality effects for forgings. (See Table 3.3.7.2.4)
- 1.9.9 The more rapid the cooling from the anneal/solution temperature, the finer the martensite lattice and lesser the amount of retained austenite. Both are desirable for toughness. The alloy producer therefore recommends water quenching thin sections (< 1.5 inches). Water quenching heavy sections (> 6.0 inches) carries the risk of surface cracking from induced stresses. Air cooling

is recommended for heavy sections. Oil quenching is recommended for intermediate section sizes (1.5 to 6.0 inches). An exception to these producer recommendations is that of SAE-AMS 5860D which specifies water quenching for plate exceeding 1.25 inches (as indicated in Table 3.1.1). No explanation was found for this contrary AMS recommendation.

2. Physical Properties and Environmental Effects

2.1 Thermal Properties

2.1.1 Melting Range.

2.1.2 Phase Changes. M_s and M_f temperatures, 325F and 150F, respectively. (Ref. 26) Recrystallization temperature, 1650F. (Ref. 8)

The reaction kinetics of this alloy have been studied by Widge. (Ref. 26) His conclusions are summarized in the following paragraphs.

Custom 455 transforms completely to martensite on cooling from the solution temperature. Increasing aging temperature lowers strength and hardness and raises ductility and toughness. This is explained in terms of overaging the precipitation hardening phase and/or accompanying austenite reversion.

The conventional 1500F solution treated structure contains precipitated Fe_2Ti . Pretreatment at 1250F for 4 hours enhances Fe_2Ti precipitation. Higher temperature solution treatment (e.g., 1700F) results in a coarsened martensite lath structure and no Fe_2Ti .

Age hardening occurs by the precipitation of coherent, h.c.p. Ni_3Ti . Coherency appears to persist at aging temperatures to 1050F. Beyond that, increasing aging temperature produces a precipitate of increasing coarseness; progressing from very fine spherical particles to rods, to particles that give the appearance of needles but are in fact agglomerates of many rods. Increasing solution temperature appears to reduce the rate of coarsening of the aging precipitate.

The Ni_3Ti precipitates along <111> directions of the b.c.c. alloy matrix, inhibiting slip, and making the alloy prone to lath boundary failure. Ductility of the alloy can be improved by austenite reversion at the martensite lath boundaries. (A detrimental effect on toughness would be obtained if reverted austenite were to precipitate at prior austenite grain boundaries.)

Solution treatments that precipitate Fe_2Ti promote austenite reversion at the lath boundaries (due to increased available matrix Ni), simultaneously with

Ni₃Ti matrix precipitation (even at low aging temperatures), thus improving toughness. Solution treatments that thwart austenite reversion (due to a shortage of Fe₂Ti precipitate) embrittle due to excessive Ni₃Ti aging precipitate.

Absence of Fe₂Ti, presence of excessive Ni₃Ti, and enlarged lath size of the alloy's structure all contribute to reduced toughness and notch ductility by reducing austenite reversion. But precipitation of Fe₂Ti by use of the 1250F + 1500F solution treatment restores loss in toughness related to precipitation; however, the reduction in austenite reversion related to lath size is not restored.

The amount of reverted austenite required for significant toughness improvement is only about 3 percent. For aging at 850-900F, a double 1250F + 1500F solution treatment (compared to the standard 1500F treatment) produces satisfactory austenite reversion. It is hypothesized that following the 1250F treatment the structure contains reverted austenite and overaged precipitation hardening phase in a martensitic matrix. When this structure is solution annealed at 1500F, the overaged precipitate goes into solution but the reverted austenite laths are relatively unaffected. Upon cooling to room temperature, the reverted austenite is stable primarily due to the alloy's high nickel content, and the aging precipitate is re-precipitated in a finer morphology via final aging treatment. It is reasoned that this microstructure obtains its strength from the precipitation hardening phase and its toughness from the reverted austenite.

At higher aging temperatures, satisfactory austenite reversion occurs following the simple 1500F solution treatment.

The mechanical response, especially toughness, is thus influenced by the interplay of: (1) Fe₂Ti precipitate present in the solution treated structure; (2) coherent h.c.p. Ni₃Ti aging precipitate; (3) martensite lath (grain) size; and, (4) reverted austenite at the martensite lath boundaries.

The amount of Ti in matrix solution varies with the amount of precipitated Fe₂Ti. The more Fe₂Ti present, the more Ni available to promote austenite reversion. The less Fe₂Ti present, the more Ni₃Ti precipitated on aging. The more Ni₃Ti precipitated, the less matrix Ni available to promote austenite reversion. When 1100-1200F exposure follows high temperature solution treatment, austenite reversion is almost completely restored due to Fe₂Ti precipitation (i.e., no lath size role). This explains the observed lesser austenite reversion for 1700F + 1250F + 1500F solution treatment

compared to 1250F + 1500F. Solution treating 1100F + 1500F produces no more Fe₂Ti than the standard 1500F solution treatment and consequently results in identical aging and austenite reversion.

High aging temperatures increase austenite reversion accompanied by coarser precipitation and corresponding decrease in strength. The increase in toughness for 1050F aging obtained by solution treatments that precipitate Fe₂Ti appears to be related to this decrease in strength. Results indicate that it is only worthwhile to use a 1250F + 1500F solution treatment, compared to the standard 1500F treatment, if the aging temperature is to be 850-900F. Use of the double treatment offers no benefit for aging at 950F. Higher aging temperature causes austenite reversion to occur even with the standard 1500F solution treatment. The 1250F + 1500F treatment is also effective in restoring toughness loss caused by a higher solution treatment, related to the ability of the pretreatment to precipitate Fe₂Ti.

2.1.3 [Figure] Thermal conductivity.

2.1.4 [Figure] Thermal expansion.

2.1.5 Specific Heat.

2.1.6 Thermal Diffusivity.

2.2 Other Physical Properties

2.2.1 Density. 0.280 lb per cu.in. , 7.75 gr per cu.cm. in 950F aged condition. (Refs. 5, 9)

2.2.1.1 Specific gravity. 7.7 - 7.8 in 950F aged condition. (Refs. 5, 9)

2.2.2 Electrical Properties.

2.2.2.1 [Figure] Electrical resistivity.

2.2.3 Magnetic Properties.

2.2.3.1 [Figure] DC normal induction.

2.2.4 Emission.

2.2.5 Damping Capacity.

2.3 Chemical Environments

2.3.1 General Corrosion.

2.3.1.1 The general corrosion resistance of Custom 455 lies between that of Types 410 and 430 stainless steel. It resists staining in normal air atmospheres and shows no corrosion in fresh water. (Ref. 5) Oxidation resistance is judged to be excellent up to 1100F. (Ref. 5)

Corrosion resistance in acetic and sulfuric acids is better than Types 410 and 431 stainless steel, and slightly inferior to Type 430. Aging temperature has no significant effect on corrosion rate in acetic acid. Corrosion rate in sul-

furic acid is aging temperature dependent with lowest aging temperature resulting in highest corrosion rate. (Ref. 5)

In the more oxidizing nitric acid environment which tends to attack precipitate phases, the corrosion rate is also influenced by aging temperature with lowest aging temperature resulting in lowest corrosion rate. (Ref. 5)

2.3.1.2 [Figure] Corrosion rates in acetic, sulfuric, and nitric acid media.

2.3.1.3 Pitting and Crevice Corrosion. Tests in 5 percent salt spray at 95F show good resistance to pitting. (Ref. 5)

Pitting resistance is comparable to other precipitation hardening grades of reasonably similar compositions when tested by immersion in 5 w/o ferric chloride at room temperature for 10 minutes. (Ref. 5) Bolts with tape-wrapped shanks exhibited corrosion grooves at the tape edges after six-hours immersion at room temperature in 10 w/o ferric chloride solution. This result suggests likely susceptibility to crevice corrosion in fastener thread crests or wherever else a differential aeration cell is produced. (Refs. 45, 49)

Stressed (to 75 percent F_{ty}) and unstressed specimens of base and weld metal (950F and 1050F age), with and without protective coating, were immersed at approximately one-mile depth in the Atlantic (23 deg 52 min N, 76 deg 46.6 min W, identified as the Tongue of the Ocean) and Pacific (33 deg 51 min N, 120 deg 35 min W, approximately 75 miles west of Port Hueneme, California) Oceans. Unstressed Atlantic specimens exposed four years with protective coating showed no corrosion attack. Companion unstressed specimens without protective coating experienced substantial pitting and crevice corrosion attack ranging from less than 0.005 in. to 0.12 in. in depth under adhesive tape and at fixture contact areas. There were no occurrences of cracking of the Atlantic stress corrosion specimens. The performance of specimens exposed six months in the Pacific was similar to that of specimens exposed four years in the Atlantic. Crevice corrosion attack ranged from a depth of 0.07 in. to 0.10 in. The difference between the Pacific and Atlantic specimens in maximum crevice corrosion was only 0.020 in. (0.10 versus 0.12 in.), indicating that the Pacific site with its very low oxygen content initiates loss of passivity (at local crevices) much more rapidly than the higher-oxygen-content test site in the Atlantic. The results show the alloy to be highly susceptible to pitting and crevice corrosion. (Ref. 65)

2.3.1.4 Galvanic Corrosion. The alloy may come into contact with more active metals during service, for example in aerospace applications where aluminum is widely used. Not stress corrosion cracking, but rather hydrogen cracking due to hydrogen produced on the alloy which serves as the electrode, may be a problem that must be considered. In this situation, if the alloy's resistance to stress corrosion cracking is due to high toughness, then this property will be useful in resisting hydrogen cracking when in contact with active metals. On the other hand, if it owes its stress corrosion cracking resistance primarily to good corrosion and crevice corrosion resistance, then these properties are of no use in avoiding the galvanic corrosion problem and could in fact aggravate it by increasing one of the driving forces (potential difference). Toughness, potential differences, area ratios, design parameters and polarization characteristics (particularly for the active metal) may be more useful for predicting performance in some situations than are stress corrosion data.

In aircraft applications where fasteners are used in contact with aluminum, the open circuit potential (voltage) between the noble metal in the fastener and the active metal in the structure is about 0.5v in the presence of an aqueous electrolyte containing chlorides. With a potential this high, galvanic corrosion of the aluminum is inevitable. Sacrificial coating of the fastener may be employed not to protect the bolt, as with low alloy steels, but to protect the structure around the bolt. (Ref. 49)

The alloy is susceptible to electrochemical attack (galvanic crevice corrosion) in environments containing combinations of N_2O_4 and salt solution. (Ref. 28)

2.3.2 Stress Corrosion. Eight direct tension specimens aged at 950F were stressed to 90-95 percent of F_{ty} in artificial seawater; no failures occurred and tests were discontinued after 154 days. (Ref. 5) Bolts loaded to 75 percent of F_{tu} in 7075-T651 blocks were swabbed with 3.5 percent NaCl solution to examine the possibility of embrittlement cracking due to hydrogen formation by intense galvanic reaction between the bare bolt (cathode) and the aluminum block (anode). No cracking was observed in 1,800 hours and the tests were terminated. Bolt shanks notched to $K_t = 3.5$ and 6.0 and either charged or plated to produce hydrogen were then hung at sustained load at 75 percent of NTS. An acid charging solution consisting of 0.1N NaOH with 0.1N NaCN was used for charging at 1 ampere for 30 minutes. Plating was done in production cyanide cadmium or sulfamate nickel baths at normal current densities.

The alloy was only affected when acid charged, showing that it is susceptible to hydrogen embrittlement in certain circumstances. (Ref. 49)

The alloy exhibits a marked increase in saltwater K_{Isc} as the aging temperature is increased, largely a reflection of K_{Ic} changes. Saltwater K_{Isc} is about 85% K_{Ic} for all conditions. [Carter et al (Ref. 103) also obtained no failures at stresses up to 85% of K_{Ic} .] There appears to be an almost linear relationship between saltwater K_{Isc} and yield strength. (Ref. 7)

Figure 2.3.2.1 shows a marked influence of product size and emphasizes the need to consider product size in the application of K_{Isc} to design. Again, changes due to product size are largely a function of K_{Ic} changes. Grain size decreased in Figure 2.3.2.1 from ASTM 2 for the 9-inch square to ASTM 7 for the 1-1/4-inch square. All data in Figure 2.3.2.1 are for the LT orientation; TL specimens exhibited K_{Ic} and K_{Isc} values about 10 percent lower. Caution must be exercised when using K_{Isc} as a design criterion. Failure of Custom 450 precracked cantilever beam specimens across the cantilever plane (i.e., the plane of maximum stress), rather than the notch/crack plane, has been observed to originate at a pit formed in the crevice between the corrosion cell and the specimen. (Ref. 7) Scale left on the specimen is thought to have accelerated the attack. The same phenomenon has been observed by Brown (Ref. 104) for a precipitation hardening 13Cr-8Ni-2Mo stainless steel. Brown logically uses that type of failure as evidence that the prime function of a precrack is to serve as a crevice for local chemistry changes - more specifically a lowering of the pH to produce a potential -pH condition favorable to the formation of hydrogen. In the case of the cited aberrant failures, the crevice at the cell wall (cantilever plane) was more capable of producing corrosion and hydrogen than the one at the notch/crack bottom. The fact that a crevice existed all around the specimen at the cell wall provided a potential greater source of hydrogen. Ostensibly the stress intensity in the corrosion crack area exceeded the K_{Isc} or the corrosion resistance at the site was less crack resistant than K_{Isc} would suggest. It is necessary, then, that for applications where stress corrosion is a consideration, both toughness and general corrosion resistance be considered. In this regard, it is noticed that Custom 455 has good general corrosion resistance owing to the fact that the hardening precipitate (Laves - Fe, Ti) does not deplete the matrix of large amounts of corrosion resistant elements (e.g., chromium).

2.3.2.1 [Figure] Effect of section size and age temperature on room temperature K_{Isc} in 3.5 percent NaCl solution (pH 5).

2.3.2.2 [Figure] Delayed failure of fatigue precracked cantilever bend specimens (from billet) in 3.5 percent aqueous NaCl solution.

- 2.3.2.3 [Figure] Delayed failure of fatigue precracked cantilever bend specimens (from forging) in 3.5 percent aqueous NaCl solution.
- 2.3.2.4 [Figure] Effect of aging temperature on delayed failure characteristics of fatigue precracked cantilever beam specimens in 3.5 percent aqueous NaCl solution.
- 2.3.2.5 [Table] Effect of aging temperature on cracking time of U-bend specimens exposed to salt-water atmospheres.
- 2.3.2.6 0.062-in-thick C-ring specimens, annealed 1500F, 30 min, WQ + aged at 1000F, 1100F, or 1150F, 4 hr in vacuum, cooled in Argon, were stressed in the transverse direction to 50, 75, 90 and 100 percent of longitudinal F_{ly} and alternately immersed in 3.5 percent NaCl solution, 10 minutes in solution and 50 minutes out of solution, for 180 days with no evidence of cracking. (Ref. 80)
- 2.3.2.7 [Table] Effect of alternate immersion in NaCl solution, under tension stress, on room temperature strength, ductility, hardness, and elastic modulus.
- 2.3.2.8 [Figure] Delayed failure of smooth tensile specimens in alternating salt spray.
- 2.3.2.9 [Table] Delayed failure in 5 percent salt fog atmosphere of notched specimens variously plated.
- 2.3.2.10 Following the procedure of MIL-STD-13212, a total of thirteen bolts were loaded to 75 percent of F_{tu} and alternately immersed in 3.5 percent NaCl solution, 10 minutes in solution followed by 50 minutes of forced air drying. No failures were observed in some specimens exposed as long as 6,534 hours; three specimens failed in the shank area in 2,316 to 2,735 hours. (Refs. 40, 49)
- 2.3.2.11 [Table] Susceptibility to hydrogen sulfide stress cracking.
- 2.3.2.12 [Figure] K_{Isc} as a function of F_{ly} in various environments containing water, aqueous chlorides, air, H_2S gas, or H_3BO_4 solution.

2.4 Nuclear Environments

2.4.1 [Table] Helium embrittlement at 1300F.

3. Mechanical Properties

3.1 Specified Mechanical Properties

3.1.1 [Table] AMS specified mechanical properties.

3.1.2 [Table] AMS specified mechanical properties for spring temper wire.

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3.1.3 [Table] Producer's specified mechanical properties.

3.2 Mechanical Properties at Room Temperature

3.2.1 Tension Stress-strain Diagrams and Tensile Properties.

- 3.2.1.1 [Figure] True stress-true strain curves.
- 3.2.1.2 [Table] Typical mechanical properties for billet and bar.
- 3.2.1.3 [Table] Typical mechanical properties for plate.
- 3.2.1.4 [Table] Typical mechanical properties for sheet.
- 3.2.1.5 [Table] Typical mechanical properties for strip.
- 3.2.1.6 [Table] Typical mechanical properties for foil.
- 3.2.1.7 [Table] Typical mechanical properties for welded tubing.
- 3.2.1.8 [Figure] Effect of solution temperature on smooth and sharp-notch tensile strengths of bar aged at 950F.
- 3.2.1.9 [Table] Effect of cooling rate from the solution temperature on strength, hardness, and Charpy-V impact energy of billet aged at 950F.
- 3.2.1.10 [Figure] Effect of aging temperature on smooth and sharp-notch tensile properties of bar.
- 3.2.1.11 [Figure] Effect of aging time on smooth and sharp-notch tensile properties of bar.
- 3.2.1.12 [Figure] Smooth tensile properties of sheet aged in the 1000-1150F range.
- 3.2.1.13 [Table] Effect of 1000-hour exposure in air at elevated temperature on the room temperature smooth and sharp-notch tensile properties and Charpy-V impact energy of solution treated and aged bar.
- 3.2.1.14 [Figure] Effect of cold work on the smooth tensile properties of wire in the as-drawn and cold-drawn plus aged conditions.
- 3.2.1.15 [Table] Comparison of bolt strength to material strength.

3.2.2 Compression Stress-strain Diagrams and Compression Properties.

- 3.2.2.1 Stress-strain diagrams. (See Figure 3.3.2.1)
- 3.2.2.2 Compressive yield strength. Average F_{cy} of 261 ksi in the 900F aged condition and 265 ksi for the 950F aged condition have been reported for longitudinal specimens taken from 4-inch square billets (Ref. 8), somewhat higher than the values shown in Table 3.2.2.3.

3.2.2.3 [Table] Compressive yield strength and elastic modulus.

3.2.3 Impact. (See also Tables 1.5.2.2, 3.2.1.9, and 3.2.1.13)

- 3.2.3.1 [Table] Effect of aging temperature on Charpy-V impact energy of bar and billet.
- 3.2.3.2 [Table] Effect of aging temperature on tensile and Izod impact properties of bar.
- 3.2.3.3 [Table] Effect of aging temperature on Charpy-V and precracked Charpy impact energy.
- 3.2.3.4 [Table] Effect of 100-hour exposure in air at elevated temperature on room temperature precracked Charpy impact energy.

3.2.4 Bending.

3.2.5 Torsion and Shear.

- 3.2.5.1 Torsional yield strength. F_{sty} is approximately 50 percent of F_{tu} in the aged condition. (Ref. 5)
- 3.2.5.2 Shear strength. The double shear strength for 1/4-inch to 3/4-inch diameter bars in the 900F aged condition ranges from 141 to 152 ksi or approximately 56 to 60 percent of F_{tu} . (Refs. 5, 14)
 - 3.2.5.2.1 [Table] Tensile and double shear strengths of bolts.

3.2.6 Bearing.

3.2.7 Stress Concentration.

- 3.2.7.1 Notch properties. (See also Section 3.3.7.1)
 - 3.2.7.1.1 AMS specified mild-notch tensile strength. (See Table 3.1.1)
 - 3.2.7.1.2 Typical sharp-notch tensile strength for billet and bar. (See Table 3.2.1.2)
 - 3.2.7.1.3 Effect of solution treatment on sharp-notch tensile strength of solution treated and aged bar. (See Table 1.5.2.2)
 - 3.2.7.1.4 Effect of solution temperature on sharp-notch tensile strength of bar aged at 950F. (See Figure 3.2.1.8)
 - 3.2.7.1.5 Effect of aging temperature on sharp-notch tensile strength of bar. (See Figure 3.2.1.10)
 - 3.2.7.1.6 Effect of aging time on sharp-notch tensile strength of bar. (See Figure 3.2.1.11)

- 3.2.7.1.7 Effect of 1000-hour exposure in air at elevated temperature on room temperature sharp-notch tensile strength of bar. (See Table 3.2.1.13)
- 3.2.7.1.8 [Table] Effect of notch acuity on mild-notch tensile strength.
- 3.2.7.2 Fracture toughness. (See also Section 3.3.7.2)
 - 3.2.7.2.1 [Figure] Relationship between yield strength and plane strain fracture toughness.

3.2.8 Combined Loading.

3.3 Mechanical Properties at Various Temperatures

3.3.1 Tension Stress-strain Diagrams and Tensile Properties.

- 3.3.1.1 [Figure] Typical stress-strain curves at room and elevated temperatures for aged bar.
- 3.3.1.2 [Figure] Effect of test temperature on tensile properties of billet and bar in the 900F aged condition.
- 3.3.1.3 [Figure] Effect of test temperature on smooth tensile properties and notch strength ratio of bar in the 950F aged condition.
- 3.3.1.4 [Figure] Effect of test temperature on smooth tensile properties and notch strength ratio of bar in the 1000F aged condition.
- 3.3.1.5 [Figure] Effect of test temperature on smooth tensile properties and notch strength ratio of bar in the 1050F aged condition.
- 3.3.1.6 [Figure] Effect of cryogenic test temperature on the tensile properties of sheet in the 950F aged condition.
- 3.3.1.7 [Figure] Effect of cryogenic test temperature on the tensile properties of sheet in the 1000F aged condition.
- 3.3.1.8 [Figure] Smooth and mild-notch tensile properties at cryogenic temperatures for sheet aged at 1000F.
- 3.3.1.9 [Figure] Effect of cryogenic test temperature on the tensile properties of sheet in the 1050F aged condition.
- 3.3.1.10 [Figure] Smooth and sharp-notch tensile properties at cryogenic temperatures for sheet aged at 1100F.
- 3.3.1.11 [Figure] Smooth and sharp-notch tensile properties at cryogenic temperatures for sheet aged at 1150F.

3.3.2 Compression Stress-strain Diagrams and Compression Properties.

- 3.3.2.1 [Figure] Typical compression stress-strain and tangent modulus curves for aged bar.
- 3.3.2.2 [Figure] Effect of test temperature on compressive yield strength of bar aged at 950F.

3.3.3 Impact.

- 3.3.3.1 [Table] -70F Charpy-V impact energy for bar aged at 1050F.
- 3.3.3.2 [Figure] Effect of test temperature on the impact strength of bar in the 900-1050F aged condition.
- 3.3.3.3 [Table] Charpy-V impact energy at cryogenic temperature for bar aged in the 1000-1150F range.

3.3.4 Bending.

3.3.5 Torsion and Shear.

- 3.3.5.1 [Table] Effect of age temperature and test temperature on double restrained shear strength.

3.3.6 Bearing.

3.3.7 Stress Concentration.

- 3.3.7.1 Notch properties.
 - 3.3.7.1.1 Effect of cryogenic test temperature on notch tensile strength of bar. (See Figures 3.3.1.3, 3.3.1.4, and 3.3.1.5)
 - 3.3.7.1.2 [Figure] Effect of cryogenic test temperature on notch tensile strength of sheet in the longitudinal direction.
 - 3.3.7.1.3 [Figure] Effect of cryogenic test temperature on notch tensile strength of sheet in the transverse direction.
- 3.3.7.2 Fracture Toughness.
 - 3.3.7.2.1 [Figure] Effect of aging temperature on room temperature tensile properties and low temperature plane strain fracture toughness of bar in a variety of sizes and shapes from seven heats.
 - 3.3.7.2.2 [Table] Symbols legend for Figure 3.3.7.2.1.
 - 3.3.7.2.3 [Table] Effect of quenched section size on -65F, LS orientation plane strain fracture toughness of forged block variously heat treated to a common strength level of approximately 200 ksi.

3.3.7.2.4 [Table] Room temperature, -65F, and -110F smooth and mild-notch tensile strength and plane strain fracture toughness of forging.

3.3.8 Combined Properties.

3.4 Creep and Creep Rupture Properties

3.4.1 [Table] Plastic deformation in 100 and 1000 hours at 400-850F.

3.4.2 [Figure] Minimum creep rate for bar at 400F, 600F, and 850F.

3.4.3 [Figure] Stress-rupture and plastic deformation curves for bar at 400F, 600F, and 850F.

3.4.4 [Figure] Creep rupture curves at 400-900F for aged billet and bar.

3.4.5 [Figure] Loss of load in one hour at 400-600F during static loading of compression spring made from 0.060-inch wire.

3.5 Fatigue Properties

3.5.1 Conventional Fatigue.

3.5.1.1 [Figure] Effect of aging temperature on room temperature rotating beam smooth and mild-notch fatigue strength of bar.

3.5.1.2 [Figure] Room temperature axial-load smooth and mild-notch ($K_t = 3.3$) fatigue strength of billet aged at 950F.

3.5.1.3 [Figure] Room and elevated temperature axial-load smooth and mild-notch ($K_t = 3.0$) fatigue strength of bar aged at 950F.

3.5.1.4 [Figure] Typical axial-load smooth and mild-notch ($K_t = 3.0$) constant-life fatigue diagram for bar aged at 950F.

3.5.1.5 [Figure] Typical axial-load smooth and mild-notch ($K_t = 3.0$) constant-life fatigue diagram for bar aged at 1000F.

3.5.1.6 [Figure] Room temperature diametral-strain-controlled low-cycle fatigue life.

3.5.1.7 [Figure] Axial-load smooth fatigue strength at several stress ratios for specimens machined from bar after 950F age treatment.

3.5.1.8 [Figure] Axial-load mild-notch ($K_t = 2.5$) fatigue strength at several stress ratios for specimens machined from bar after 950F age treatment.

3.5.1.9 [Figure] Axial-load mild-notch ($K_t = 4.0$) fatigue strength at several stress ratios for specimens machined from bar after 950F age treatment.

3.5.1.10 [Figure] Haig diagram for axial-load smooth specimens machined from bar after 950F age treatment.

3.5.1.11 [Figure] Haig diagram for axial-load mild-notch ($K_t = 2.5$) specimens machined from bar after 950F age treatment.

3.5.1.12 [Figure] Haig diagram for axial-load mild-notch ($K_t = 4.0$) specimens machined from bar after 950F age treatment.

3.5.1.13 [Figure] Room temperature axial-load fatigue strength of sheet.

3.5.1.14 [Figure] Room temperature axial-load fatigue strength of two-hole ($K_t = 3.0$) sheet specimens.

3.5.1.15 [Table] Room temperature axial tension fatigue strength of bolts.

3.5.2 Fatigue Crack Propagation.

3.6 Elastic Properties

3.6.1 Poisson's Ratio. 0.30 in the 950F aged condition. (Ref. 5)

3.6.2 Modulus of Elasticity. 29×10^3 ksi; 200×10^3 MPa in the 950F aged condition. (Refs. 5, 9)

3.6.2.1 [Figure] Modulus of elasticity in tension (E) and compression (E_c) at temperatures ranging from -200F to 800F.

3.6.2.2 Modulus of elasticity at room temperature for sheet aged in the 1000-1150F range. See Figure 3.2.1.12)

3.6.3 Modulus of Rigidity. 11×10^3 ksi, 7.7×10^5 kg per cm^2 in the 950F aged condition. (Refs. 5, 9)

3.6.4 Tangent Modulus.

3.6.5 Secant Modulus.

4. Fabrication

4.1 Forming

4.1.1 Hot Workability. The alloy can be easily forged or rolled within the range of 2300-1650F. For optimum mechanical properties, heating prior to final hot reduction should be within the range 1900-2100F with adequate time at heat followed by hot finishing within 1500-1700F. This procedure should result in optimum grain size and properties after heat treatment. (Refs. 5, 9, 10)

4.1.2 Cold Workability. As in other low carbon martensitic, precipitation hardening steels, cold working can be readily performed in the annealed condition at the hardness level of Rockwell C 30-35. Since the elonga-

tion tends to be localized, deep drawing and similar stretching operations will require intermediate annealing. For other cold forming operations, such as cold-drawing and cold-rolling, the work-hardening rate in the annealed condition is extremely low, allowing considerable reduction without intermediate annealing. (See Figure 4.1.2.1) Cold- and warm-heading operations can also be performed easily. Cold working prior to aging increases the strength level in the heat treated condition. (See Tables 3.1.2, 3.2.1.4, and 3.2.1.6) (Refs. 5, 9, 10)

4.1.2.1 [Figure] Effect of cold drawing in the annealed condition on tensile strength of wire.

4.1.3 Primary and secondary deformation processes for precipitation-hardenable stainless steels are discussed in Ref. 55.

4.2 Machining and Grinding

4.2.1 Machining and grinding can be performed successfully using the same practices required for other high strength, heat-treated alloys; namely slow speeds, positive cuts, adequate use of coolants, and rigid tool and work supports. The machining characteristics are similar to those of the nickel maraging steels (Code 1220). Specific and detailed data for turning, milling, drilling, tapping, and grinding are given in Ref. 5.

4.3 Joining

4.3.1 The alloy can be successfully welded by resistance butt welding, spot welding, and the inert-gas-shielded methods. Pre-heating and post-weld annealing are not required. However, optimum ductility in the weld metal is obtained by post-weld annealing prior to aging, which also improves the resistance to corrosion. After aging, the joint efficiencies which are possible are 100 percent in small sections and 85 percent or greater in large sections. Some general recommendations for metal-gas-arc welding procedures are given in Refs. 5, 32, and 73. Other welding procedures used for the nickel maraging steels are applicable. (Refs. 5, 6, 9) Laser welding is discussed in Ref. 27.

4.3.2 Impact resistance of restraint pin welds in the post weld 950F aged condition are reported to be unacceptably low at service temperatures in the range -50F to -60F. Resolution treating after welding, prior to aging, restores impact strength to acceptable parent metal levels. (Refs. 67-71)

4.4 Surface Treating

4.4.1 Cleaning. After forging or annealing, descaling is accomplished by wet-grit blasting or acid cleaning. The latter consists of immersing for 2 to 3 minutes in 15 percent muriatic acid at 180F followed by 4 to 6 minutes in 15 percent nitric plus 3 percent hydrofluoric at room temperature (acid concentrations are in volume percent). Desmut by immersion in 20 percent nitric acid at room temperature. The heat tint from aging is removed by pickling for 5 to 10 minutes in 15 percent nitric plus 3 percent hydrofluoric followed by a water rinse. Fused-salt descaling baths that operate at 800-1000F should not be used during cleaning between intermediate anneals, since age-hardening can occur. All parts should be passivated in a 40 to 60 percent nitric solution as the final processing step. Machined parts should be degreased prior to heat treatment. (Refs. 5, 6, 9)

4.4.2 Nitriding. The surface hardness of the basic alloy is increased to improve wear resistance by nitriding, but at some sacrifice in corrosion resistance. Nitriding is performed in a cyanide salt bath or in a gas atmosphere, and aging is accomplished in the same operation. A chemically clean surface is imperative to achieve a uniform case. Nitriding at 960-1025F for 24 to 48 hours produces a case depth of 0.003-0.006 inch, a case hardness of 65-70 Rockwell C, and a core hardness of 39-45 Rockwell C. (Ref. 5)

Table 1.3.1 Specifications (Refs. 1-4, 83-87)

Alloy		Custom 455	
Form	Condition	Specification	Ref.
Welded Tubing	ST and ST + Age	AMS 5578D	1
Bar, Wire, Forging	ST and ST + Age	AMS 5617G	2
Wire	CD	AMS 5672B	3
Sheet, Strip, Plate	ST and ST + Age	AMS 5860D	4
Bar, Wire	ST and ST + Age	MIL-S-83311 ^a	83
Spring Wire	CD and CD + Age	ASTM A 313	84
Bar and Shapes	ST and ST + Age	ASTM A 564/A 564M	85
Plate, Sheet, Strip	ST and ST + Age	ASTM A 693	86
Forging	ST and ST + Age	ASTM A 705/A 705M	87

^a This specification active for replacement parts only. For new design and new purchases, use Refs. 2 and 3.

Custom 455

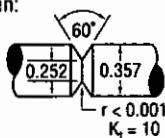
Table 1.4.1 Composition (Refs. 1-5, 83-87, 93)

Alloy	Custom 455																	
Source	Carpenter UNS	AMS 5578D	AMS 5617G	AMS 5617G	AMS 5672B	AMS 5860D	MIL-S-83311	ASTM A 313, A 693	ASTM A 564/A 564M, A 705/A 705M									
Reference	5, 93	1	2	2	3	4	83	84, 86	85, 87									
Form	All	Welded Tubing	Bar, Wire, Forging [Grade 1]	Bar, Wire, Forging [Grade 2]	Spring Temper Wire	Sheet, Strip, Plate	Bar, Wire	Plate, Sheet, Strip, Spring Wire	Bar, Shapes, Forging									
	Element (Percent)																	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Carbon		0.05		0.05		0.03		0.010		0.05		0.05		0.05		0.05		0.03
Manganese		0.50		0.50		0.50		0.50		0.50		0.50		0.50		0.50		0.50
Silicon		0.50		0.50		0.50		0.20		0.50		0.50		0.50		0.50		0.50
Phosphorous		0.040		0.015		0.015		0.010		0.025		0.025		0.025		0.040		0.015
Sulfur		0.030		0.015		0.015		0.010		0.025		0.025		0.025		0.030		0.015
Chromium	11.00	12.50	11.00	12.50	11.00	12.50	11.00	12.50	11.00	12.50	11.00	12.50	11.00	12.50	11.00	12.50	11.00	12.50
Nickel	7.50	9.50	7.50	9.50	7.50	9.50	7.50	9.50	7.50	9.50	7.50	9.50	7.50	9.50	7.50	9.50	7.50	9.50
Columbium + Tantalum	0.10	0.50	0.10	0.50		0.50		0.50	0.10	0.50	0.10	0.50	0.10	0.50	0.10	0.50	0.10	0.50
Titanium	0.80	1.40	0.80	1.40	0.90	1.40	1.00	1.35	0.80	1.40	0.80	1.40	0.80	1.40	0.80	1.40	0.90	1.40
Copper	1.50	2.50	1.50	2.50	1.50	2.50	1.50	2.50	1.50	2.50	1.50	2.50	1.50	2.50	1.50	2.50	1.50	2.50
Molybdenum		0.50		0.50		0.50		0.50		0.50		0.50		0.50		0.50		0.50
Nitrogen						0.015		0.010		0.015								
Iron		Balance		Balance		Balance		Balance		Balance		Balance		Balance		Balance		Balance

Table 1.5.2.2 Effect of solution treatment on room temperature smooth and sharp-notch tensile strengths, and Charpy-V impact energy of solution treated and aged bar (Ref. 26)

Alloy	Custom 455						
Form	Hot Rolled 2-in. Bar						
Condition	ST + Age						
ST	Age	F _{TU} (ksi)	F _{TY} (ksi)	e (percent)	RA (percent)	NTS ^a (ksi)	IE Charpy-V (ft-lb)
1500F, 30 min, WQ	850	254.6	248.6	10.2	40.4	210	5.5
	900	252.3	245.8	10.1	49.1	257	10.0
	950	238.2	234.1	10.1	56.6	326	18.0
	1000	194.0	181.1	17.6	63.0	293	34.0
1700F, 30 min, WQ	850	252.8	249.0	thread failure		69	2.0
	900	256.5	246.5	4.6	16.7	96	2.0
	950	243.8	234.8	11.4	48.0	154	3.5
	1000	190.4	175.9	16.1	63.4	291	36.5
1100F, 4 hr, AC + 1500F, 30 min, WQ	850	255.8	248.5	10.6	45.6	198	6.0
	900	255.1	249.5	10.8	48.7	257	9.0
	950	239.5	235.3	11.7	53.5	323	17.0
	1000	194.4	181.8	18.4	62.3	291	42.5
1250F, 4 hr, AC + 1500F, 30 min, WQ	850	251.1	246.3	11.2	46.8	269	11.0
	900	247.7	243.0	10.0	45.6	303	14.0
	950	233.4	230.5	11.7	54.5	323	18.5
	1000	189.5	176.5	17.7	63.0	287	46.5
1700F, 30 min, WQ + 1250F, 4 hr, AC + 1500F, 30 min, WQ	850	248.3	242.5	11.1	41.7	200	6.5
	900	245.0	240.0	11.3	49.0	300	13.5
	950	227.0	223.0	16.4	55.6	330	23.0
	1000	183.7	170.6	16.7	63.9	282	67.0

All values average duplicate tests.

^a Notch specimen:

Custom 455

Table 1.5.4.1 Nitriding depth and hardness (Ref. 5)

Alloy			Custom 455		
Nitriding			Hardness (R _C)		Case Depth (in.)
Procedure	Temperature (F)	Time (hr)	Case	Core	
Cyanide Bath	960 - 990	24	68 - 70	42 - 44	0.003
		48	65 - 70	43 - 45	0.006
Gas Nitriding	1025	24	68	39	0.004

Table 1.6.2 Typical hardness (Ref. 5)

Alloy		Custom 455			
Form		Bar, Plate, Strip			
Condition	ST ^a	ST + Age at ^b			
		900F	950F	1000F	1050F
Hardness (R _C)	31 - 34	49 - 51	47 - 48	44 - 46	40

^a 1500F, 30 minutes, WQ.

^b 1500F, 30 minutes, WQ + age temperature, 4 hours, AC.

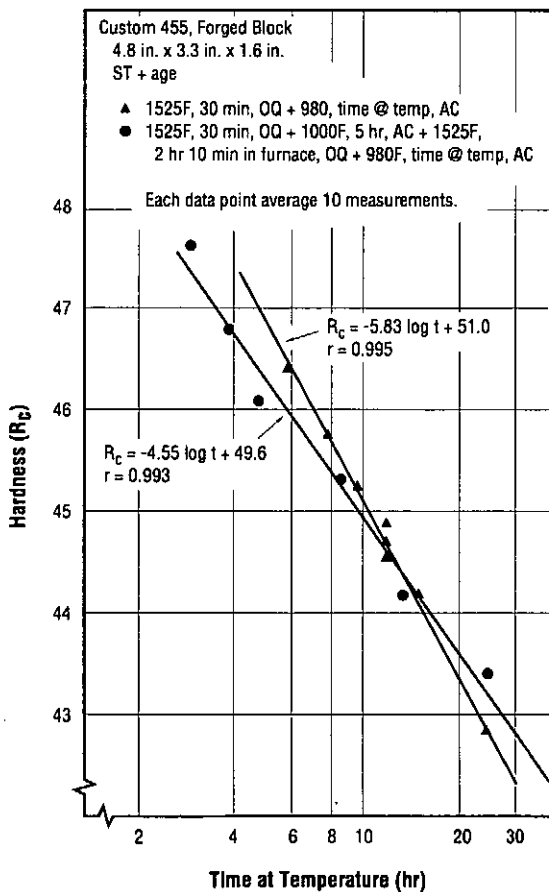


Figure 1.6.3 Effect of aging time at 980F on hardness of forged block (Ref. 98)

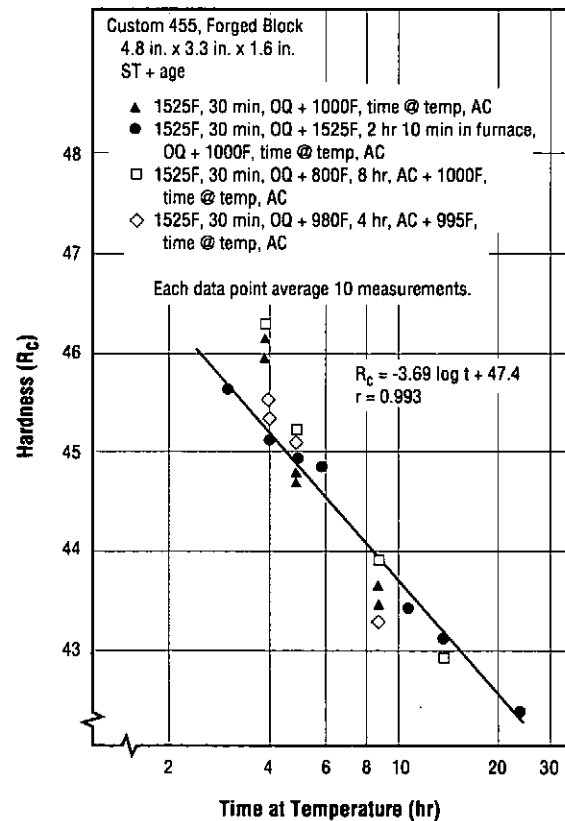


Figure 1.6.4 Effect of aging time at 995-1000F on hardness of forged block (Ref. 98)

Table 1.6.5 Effect of cold drawing on hardness of wire (Ref. 5)

Alloy		Custom 455						
Form		Wire						
Size	0.250-in. Initial Diameter							
Condition	Annealed ^a + CD				Annealed ^a + CD + Age ^b			
CD (percent)	0	20	40	60	0	20	40	60
Hardness (R _c)	31 - 32	33	35	37	49	50	52	53

^a 1500F, 30 minutes, WQ.

^b 900F, 4 hours, AC.

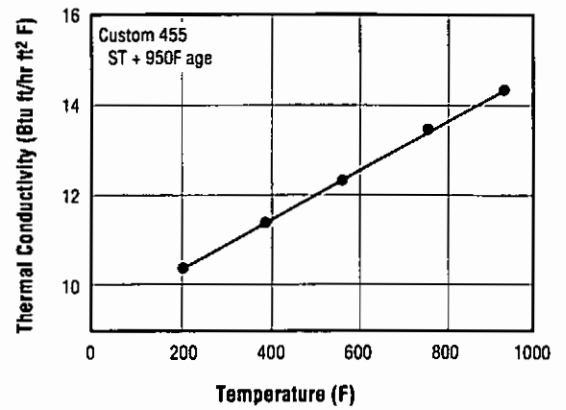


Figure 2.1.3 Thermal conductivity (Refs. 5, 9)

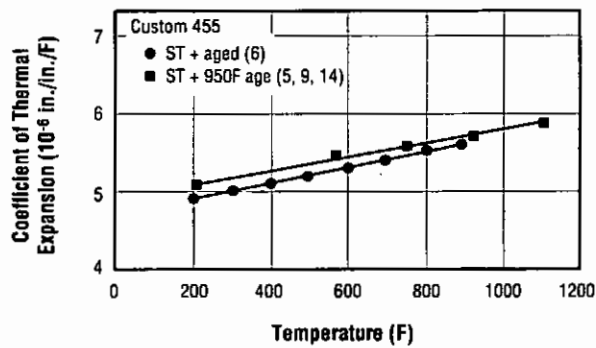


Figure 2.1.4 Thermal expansion (Refs. 5, 6, 9, 14, 54)

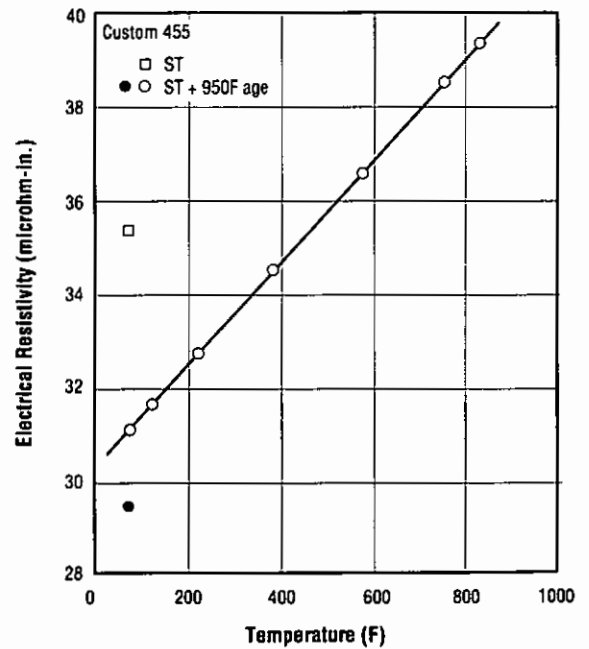


Figure 2.2.2.1 Electrical resistivity (Refs. 5, 9)

Custom 455

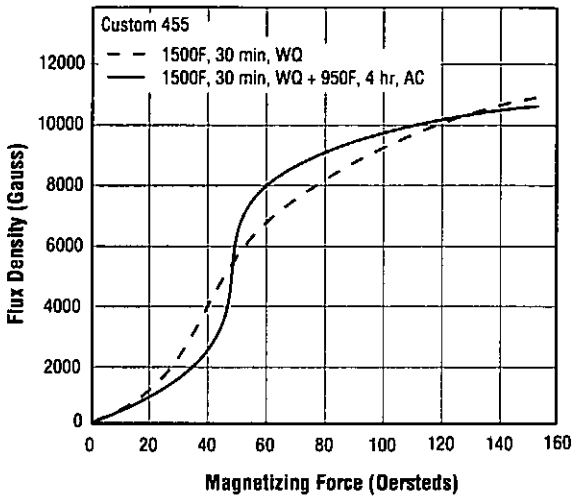


Figure 2.2.3.1 DC normal induction (Ref. 5)

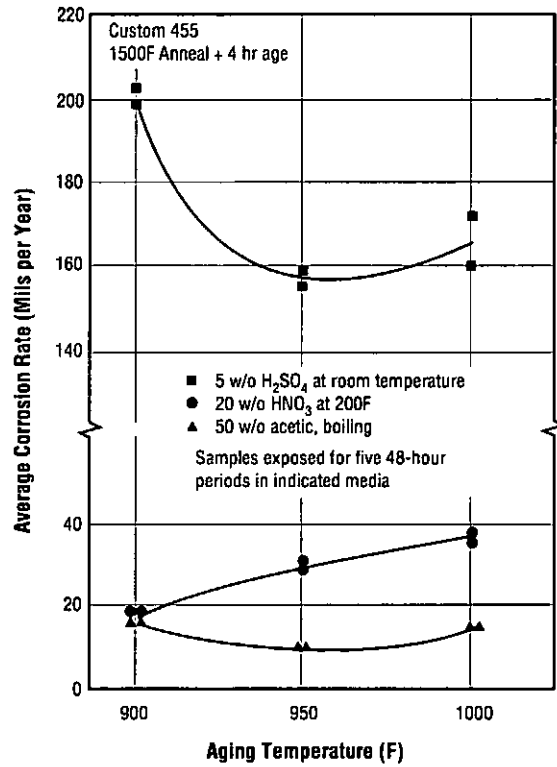


Figure 2.3.1.2 Corrosion rates in acetic, sulfuric, and nitric acid media (Ref. 5)

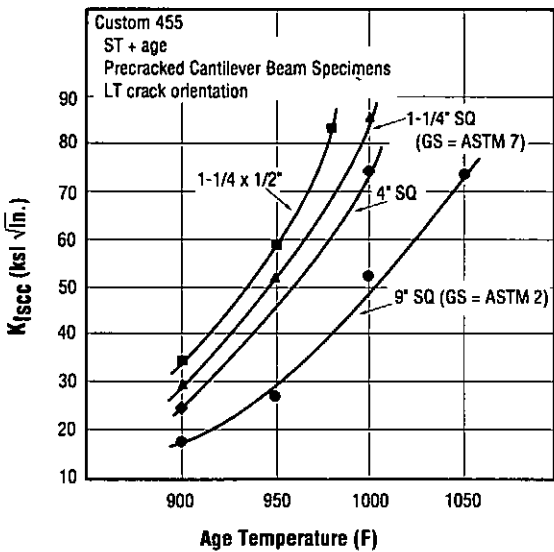


Figure 2.3.2.1 Effect of section size and age temperature on room temperature K_{Isc} in 3.5 percent NaCl solution (pH 5) (Ref. 7)

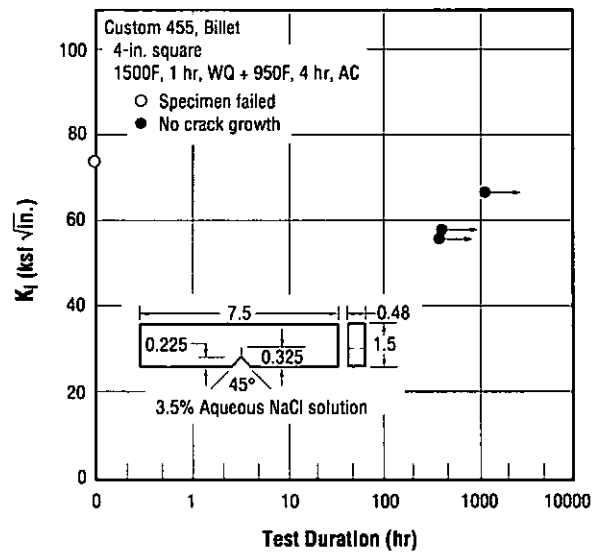


Figure 2.3.2.2 Delayed failure of fatigue precracked cantilever bend specimens (from billet) in 3.5 percent aqueous NaCl solution (Ref. 20)

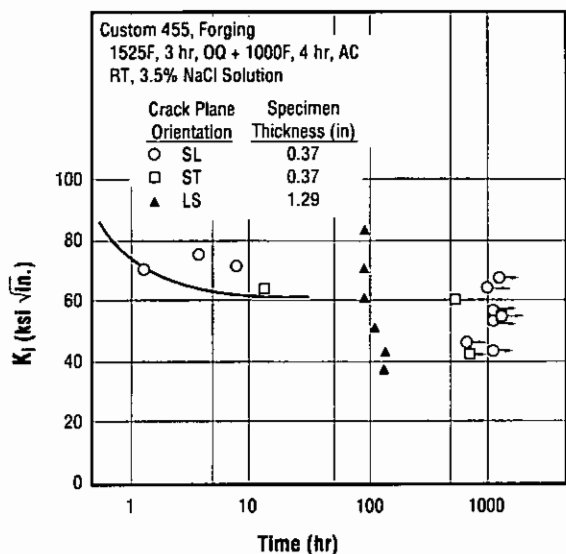


Figure 2.3.2.3 Delayed failure of fatigue precracked cantilever bend specimens (from forging) in 3.5 percent aqueous NaCl solution (Ref. 99)

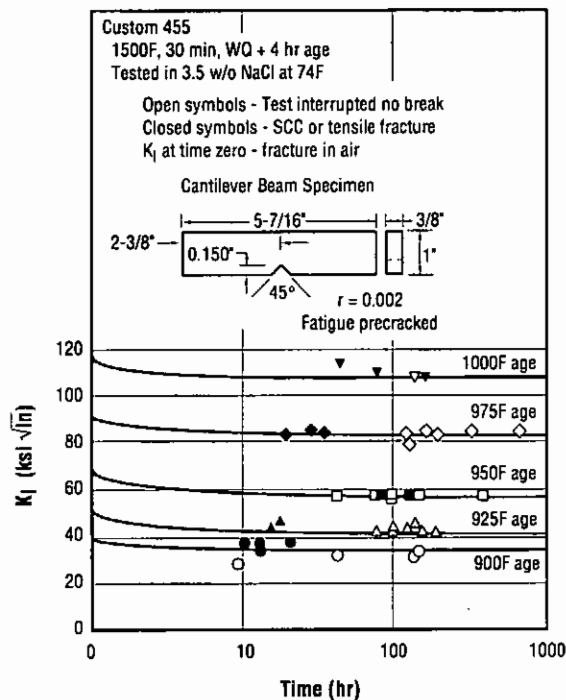


Figure 2.3.2.4 Effect of aging temperature on delayed failure characteristics of fatigue precracked cantilever beam specimens in 3.5 percent aqueous NaCl solution (Refs. 5, 7, 11)

Table 2.3.3.5 Effect of aging temperature on cracking time of U-bend specimens exposed to saltwater atmospheres (Refs. 5, 7, 11, 13)

Alloy		Custom 455					
Specimen		U-bend: 3.88-in. x 0.38-in. x 0.105-in., 0.5-in. Bend Radius					
Exposure		20 percent Salt Spray at 95F			Marine Atmosphere at INCO Kure Beach, 80-ft. from Atlantic Ocean		
Age Temperature (F)	Number of Specimens Tested	Number of Specimens Cracked	Duration of Test	Number of Specimens Tested	Number of Specimens Cracked	Duration of Test	
900	5	3	4, 141, 463, remainder uncracked after 485 days	3	3	1, 2, 3 days	
950	4	1	3, remainder uncracked after 278 days				
1000	5	0	No cracks in 278 days	3	0	No cracks in 1000 days	

Custom 455

Table 2.3.2.7 Effect of alternate immersion in NaCl solution, under tension stress, on room temperature strength, ductility, hardness, and elastic modulus (Ref. 80)

Alloy		Custom 455						
Form		0.034-in Sheet						
Condition		1500F, 30 min, WQ + Age, 4 hr in Vacuum, Argon Cool						
Age Temperature (F)	Hardness (R _c)	Exposure Time ^c (Days)	Exposure Stress ^c (Percent of F _{ty})	Properties After Exposure				Number of Specimens Tested
				F _{TU} (ksi)	F _{Ty} (ksi)	e, 2-in. (percent)	E (10 ³ ksi)	
Longitudinal								
Unaged	34.0	None	0	164.7	126.9	4.9	22.8	3
1000	49.0	None	0	249.9	240.6	4.8	26.4	3
		180	0	249.6	244.8	4.9	30.8	4
			75	249.7	243.9	4.3	31.0	3
			90	249.2	242.5	4.7	29.7	
			100	249.0	241.5	4.5	29.2	
1100	43.0	None	0	208.2	189.9	7.0	31.1	4
		180	0	209.0	191.9	7.8	29.3	
			75	208.9	183.4	7.2 ^a	30.7	
			100	207.8	184.3	7.6	27.7	
1150	37.0	None	0	173.4	124.0	13.0	24.9	4
		180	0	174.4	127.4	11.9	25.0	
			75	173.9	119.6	12.9	24.0	
			100	173.6	118.2	12.8	25.0	
Transverse								
Unaged	34.0	None	0	171.2	133.2	4.5	24.0	3
1000	49.0	None	0	259.7	252.9	3.2	32.5	3
		180	0	261.1	256.4	3.0 ^b	32.6	4
			75	256.2	243.0	3.5 ^a	33.1	3
			90	259.6	253.0	3.2 ^b	31.3	
			100	259.7	252.7	3.2	31.9	
1100	43.0	None	0	215.8	199.4	6.9	30.9	4
		180	0	215.7	200.1	7.0 ^a	30.4	
			75	215.9	195.1	6.8	32.0	
			100	216.4	195.6	7.0	29.5	
1150	37.0	None	0	179.7	137.4	12.4	29.4	4
		180	0	179.7	130.8	10.8	26.5	
			75	176.1	127.4	8.8	27.4	
			100	181.4	127.4	11.5	26.8	

^a One test.

^b Two tests.

^c Alternate immersion in NaCl solution: 10 minutes in; 50 minutes out.

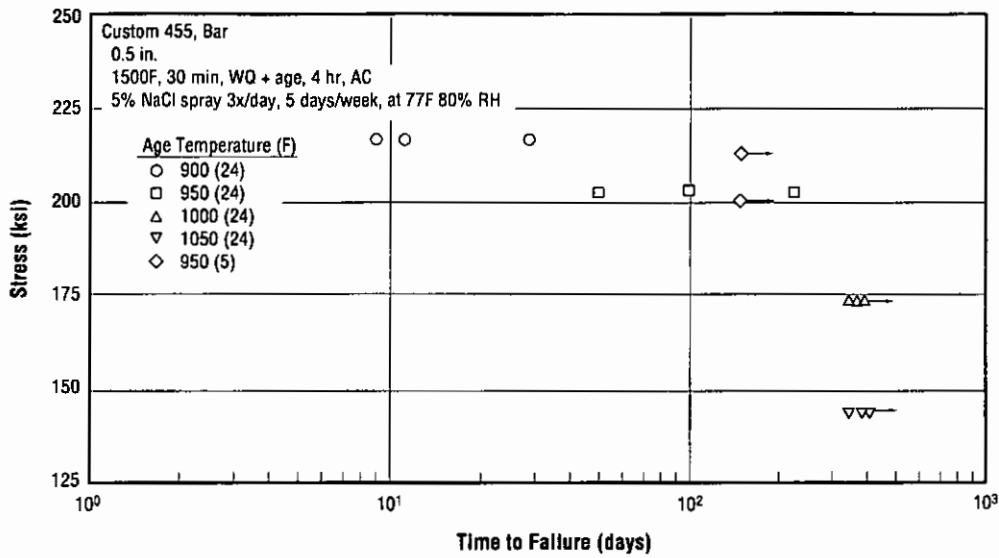
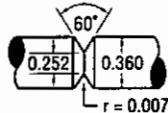


Figure 2.3.2.8 Delayed failure of smooth tensile specimens in alternating salt spray (Refs. 5, 24)

Table 2.3.2.9 Delayed failure in 5 percent salt fog atmosphere of notched specimens variously plated (Ref. 18)

Alloy	Custom 455					
Form	1-in. Bar					
Condition	Annealed + 950F, 4 hr, AC					
F _{tu} (ksi)	F _{ty} (ksi)	e, 1-in. (percent)	RA (percent)	Life in 5 percent salt fog atmosphere ^a (hr)		
				Unplated	Vacuum deposited cadmium plated ^b	Nickel-cadmium diffusion plated ^c
230.3	223.9	12.7	53.0	> 1000	95	> 1000

^a Notched longitudinal specimens stressed to 142 ksi. All values average from triplicate tests.



^b 0.002/0.005-inch vacuum deposited cadmium plate + chromate.

^c 0.002/0.004-inch diffusion (630F, 30 minutes) nickel-cadmium plate.

Custom 455

Table 2.3.2.11 Susceptibility to hydrogen sulfide stress cracking (Ref. 47)

Alloy		Custom 455		
Form		2.5-in. Bar		
Condition		Annealed + 1050F, 4 hrs, AC		
F_{tu} (ksi)	F_{ty} (ksi)	E (10^3 ksi)	Specimen No. ^a	Failure time, t , at yield stress (days) ^{b, c}
199.3	186.7	32.6	1	1 < t < 4
			2	1 < t < 4
			3	< 1
			4	1 < t < 4

- ^a C-ring specimen: outer fiber stress perpendicular to longitudinal grain of bar and equal to F_{ty} .
- ^b Corrodent: 5 w/o NaCl solution containing 0.5 w/o acidic acid (pH = 2.84), through which nitrogen bubbled prior to the addition of gaseous H_2S . Gases were flowed daily after inspection.
- ^c Cracked specimens all failed at position of maximum stress in C-ring, 90° to loading axis. All cracks were straight, with no branching, and followed prior austenite grain boundaries, suggesting hydrogen embrittlement as failure mode.

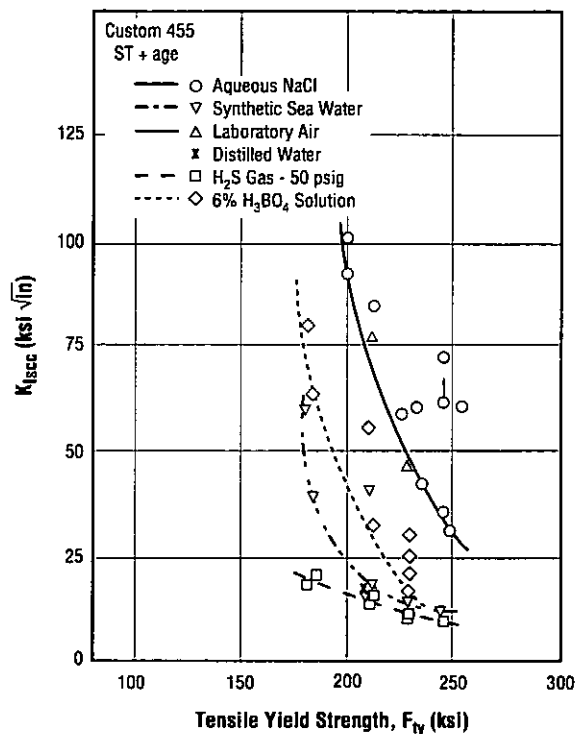


Figure 2.3.2.12 K_{Isec} as a function of F_{ty} in various environments containing water, aqueous chlorides, air, H_2S gas, or H_3BO_4 solution (Ref. 53)

Table 2.4.1 Helium embrittlement at 1300F (Ref. 64)

Alloy		Custom 455	
Condition		1500F, 30 min, WQ + 1000F, 4 hr, AC	
Helium Concentration ^a (appm)	Uniform Elongation ^b (percent)	Total Elongation ^b (percent)	
0	6	40	
25	5	8	

- ^a Helium injected into tensile specimen using α -particle irradiation from a cyclotron, and measured with gas-source mass spectrometer. Residual hardening due to α -particle irradiation annealed out during heating to 1300F test temperature.
- ^b Tensile strengths not reported since they are unaffected by presence of helium.

Table 3.1.1 AMS specified mechanical properties (Refs. 1, 2, 4)

Alloy		Custom 455														
Form		Welded Tubing (1)			Bar, Wire, Forging (Grades 1 and 2) (2)				Sheet, Strip, Plate (1)							
Condition		ST ^b	ST + 950 Age ^c		ST ^{d,h}	ST + 950 Age ^{l,h}		ST + 1000F Age ^{g,h}	ST ^j	ST + 950 Age ^{m,h}			ST + 1000 Age ^{n,h}			
Thickness ^a (in.)		—	< 0.020	0.020 - 0.062	> 0.062	—	≤ 4.000	4.000 - 6.000	≤ 8.000	—	≤ 0.020	> 0.020 - ≤ 0.062	> 0.062	≤ 0.020	> 0.020 - ≤ 0.062	> 0.062
F _{TU}	max (ksi)	165				175				175						
	min (ksi)		220	220	220		225	220	220		225	225	225	200	200	200
F _{TY}	max (ksi)									160						
	min (ksi)		205	205	205		210	205	185		210	210	210	185	185	185
e, 2-in. or 4D, min (percent)			As agreed upon	4	3		10 ⁱ	10 ⁱ	10	3	2	3	4	3	4	5
RA, min (percent)							40 ⁱ	40 ⁱ	40							
NTS (K _t ≥ 6), min (ksi)							225	220	220							
Hardness (R _c)	max									35 ^k						
	min		42	42	42						44 ^k	44 ^k	44 ^k	40 ^k	40 ^k	40 ^k
(BHN)	max					331 ^e										
	min															
Bending										l						

^a Nominal diameter or distance between parallel sides.

^b 1500 - 1550F, ≥ 5 minutes, WQ.

^c 1500 - 1550F, ≥ 5 minutes, WQ + 940 - 960F, 3.75 - 4.24 hours, AC.

^d 1500 - 1550F, ≥ 30 minutes, OQ or WQ.
Continuous-process wire: ≥1525F, time commensurate with thickness, AC.

^e Bar and forging.

^f 1500 - 1550F, ≥ 30 minutes, OQ or WQ + 940 - 960F, 3.75 - 4.25 hours, AC.

^g 1500 - 1550F, ≥ 30 minutes, OQ or WQ + 990 - 1010F, 3.75 - 4.25 hours, AC.

^h Specified properties apply equally to material re-solution heat treated, or re-solution heat treated + aged.

ⁱ For Grade 2 product ≤ 6 inches, e(4D) ≥ 5 percent and RA ≥ 20 percent.

^j Plate ≤ 1.25 inch: 1500 - 1550F, 5 - 30 minutes, Rapid Quench.
Plate > 1.25 inch: 1500 - 1550F, 5 - 30 minutes, WQ.
Continuous-process wire: 1625 - 1675F, time commensurate with thickness, AC.

^k Thickness ≥ 0.010 inch.

^l Thickness ≤ 0.1874 inch, bend angle 90° around 2.5t diameter with bend axis parallel to rolling direction.

^m 1500 - 1550F, 5 - 30 minutes, Rapid Quench (WQ for t > 1.25 inch) + 940 - 960F, 3.75 - 4.25 hours, AC.

ⁿ 1500 - 1550F, 5 - 30 minutes, Rapid Quench (WQ for t > 1.25 inch) + 990 - 1010F, 3.75 - 4.25 hours, AC.

Custom 455

Table 3.1.2 AMS specified mechanical properties for spring temper wire (Ref. 3)

Alloy	Custom 455			
Form	Spring Temper Wire			
Condition	CD		CD + 850F Age ^a	
Diameter (in.)	F _{TU} (ksi)		F _{TY} (ksi)	
	min	max	min	max
0.010 - 0.040	245	—	310	340
0.041 - 0.050	235	—	305	335
0.051 - 0.060	225	—	300	330
0.061 - 0.075	220	—	295	325
0.076 - 0.085	215	—	290	320
0.086 - 0.095	210	—	285	315
0.096 - 0.110	200	—	278	308
0.111 - 0.125	195	—	272	302
0.126 - 0.150	190	—	265	295
0.151 - 0.500	180	—	260	290

^a 840 - 860F, 27 - 30 minutes, AC.

Table 3.1.3 Producer's specified mechanical properties (Ref. 5)

Alloy	Custom 455			
Form	Bar, Wire, Forging			
Condition	Annealed + 900F Age ^a	Annealed + 950F Age ^b	Annealed + 1000F Age ^c	Annealed + 1050F Age ^d
F _{TU} (ksi)	235	220	205	180
F _{TY} (ksi)	220	205	185	165
e, 2-in. or 4D (percent)	8	10	10	12
RA (percent)	30	40	40	45
Hardness (BNH)	444	415	363	352

^a 1500 - 1550F, ≥ 30 minutes, WQ < 6-inch sections and OQ or rapid air cool > 6-inch sections + 900F, 4 hours, AC

^b 1500 - 1550F, ≥ 30 minutes, WQ < 6-inch sections and OQ or rapid air cool > 6-inch sections + 950F, 4 hours, AC

^c 1500 - 1550F, ≥ 30 minutes, WQ < 6-inch sections and OQ or rapid air cool > 6-inch sections + 1000F, 4 hours, AC

^d 1500 - 1550F, ≥ 30 minutes, WQ < 6-inch sections and OQ or rapid air cool > 6-inch sections + 1050F, 4 hours, AC

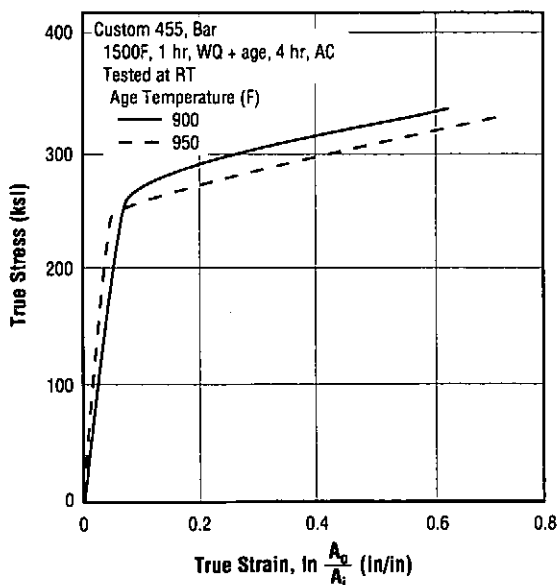


Figure 3.2.1.1 True stress-true strain curves (Ref. 13)

Table 3.2.1.2 Typical mechanical properties for billet and bar (Refs. 5, 13)

Alloy	Custom 455								
Form	4-in. x 4-in. Square Billet				1-in. Diameter Bar				
Condition	ST ^a	ST ^a + Age ^b at			ST ^a	ST ^a + Age ^b at			
		950F	1000F	1050F		900F	950F	1000F	1050F
F _{TU} (ksi)	140	230	205	190	145	250	235	210	190
F _{TY} (ksi)	115	220	195	175	115	245	225	200	175
e, 4D (percent)	12	10	12	14	14	10	12	14	15
RA (percent)	50	45	45	50	60	45	50	55	55
NTS ^c (ksi)	—	250	250	250	230	260	300	290	260
IE Charpy-V (ft-lb)	—	8	12	25	70	9	14	20	35
Hardness (R _c)	31	48	45	40	31	49	48	45	40

^a 1525F, 30 minutes, WQ.

^b 4 hours at temperature, AC.

^c Longitudinal Tests.

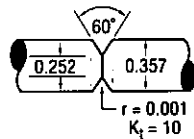


Table 3.2.1.3 Typical mechanical properties for plate (Ref. 5)

Alloy	Custom 455				
Form	0.375-in. Plate				
Condition	Test Direction	F _{TU} (ksi)	F _{TY} (ksi)	e, 2-in. (percent)	RA (percent)
1525F, 30 min, WQ	L	146	120	13	50
	T	152	128	15	60
1525F, 30 min, WQ + 900F, 4 hr, AC	L	252	248	9	33
	T	258	—	9	37
1525F, 30 min, WQ + 950F, 4 hr, AC	L	237	235	11	45
	T	240	237	9	40

Custom 455

Table 3.2.1.4 Typical mechanical properties for sheet (Ref. 5)

Alloy	Custom 455			
Form	0.030-in. Sheet			
Condition	Test Direction	F _{TU} (ksi)	F _{TY} (ksi)	e, 1-in. (percent)
As Rolled (50 percent)	L	174	—	3.6
	T	183		3.2
As Rolled + 950F, 4 hr, AC	L	254	252	3.5
	T	265	263	2.9

Table 3.2.1.5 Typical mechanical properties for strip (Ref. 5)

Alloy	Custom 455											
Form	0.050-in. Strip						0.160-in. Strip					
Condition	F _{TU} (ksi)	F _{TY} (ksi)	e, 1-in. (percent)	e, 2-in. (percent)	RA (percent)	Hardness (R _C)	F _{TU} (ksi)	F _{TY} (ksi)	e, 1-in. (percent)	e, 2-in. (percent)	RA (percent)	Hardness (R _C)
1525F, 30 min, WQ	160	150	10	6	—	34	160	135	18	8	54	33
1525F, 30 min, WQ + 900F, 4 hr, AC	260	250	6	3	—	51	260	250	8	3	25	51
1525F, 30 min, WQ + 950F, 4 hr, AC	250	240	8	4	—	47	250	240	10	4	40	48
1525F, 30 min, WQ + 1000F, 4 hr, AC	220	210	12	5	—	44	220	210	14	6	45	46

Table 3.2.1.6 Typical mechanical properties for foil (Ref. 5)

Alloy	Custom 455		
Form	0.001-in. Foil		
Condition	Test Direction	F _{TU} (ksi)	e, 1-in. (percent)
CR 60%	L	192	1.6
	T	200	
CR 60% + 850F, 30 min, AC	L	298	0.7
	T	287	1.0

Table 3.2.1.7 Typical mechanical properties for welded tubing (Ref. 5)

Alloy	Custom 455					
Form	Welded Tubing					
OD (in.)	Wall (in.)	Condition	Properties			
			F _{TU} (ksi)	F _{TY} (ksi)	e, 2-in. (percent)	Hardness (R _C)
1.130	0.107	Annealed	152	148	10.1	32
		900F Age	260	258	6.2	51
0.875	0.105	Annealed	138	131	14.5	32
		900F Age	254	253	3.9	50
1.000	0.083	Annealed	150	120	14.0	35
		900F Age	261	260	4.6	50
0.750	0.063	Annealed	148	139	14.0	32
		900F Age	252	250	10.0	50
0.500	0.060	Annealed	143	133	10.9	32
		900F Age	250	144	6.2	50

Custom 455

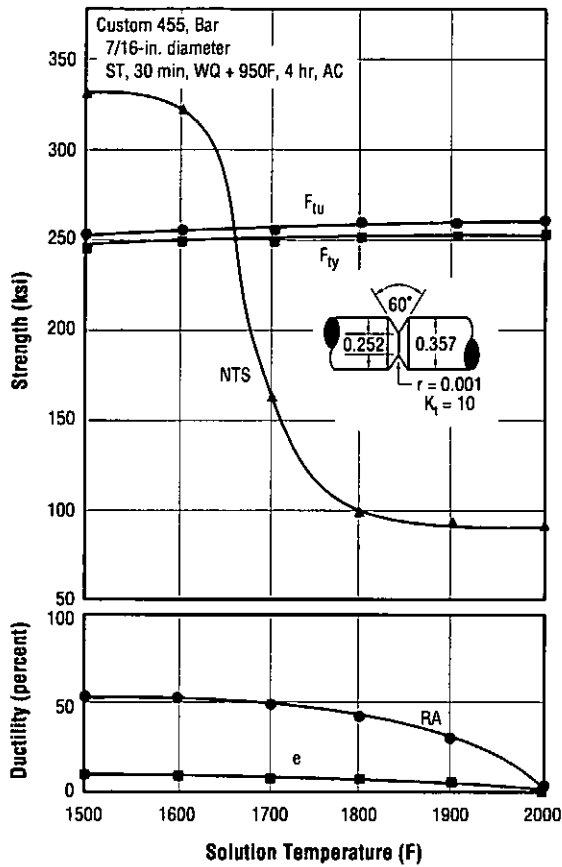


Figure 3.2.1.8 Effect of solution temperature on smooth and sharp-notch strength of bar aged at 950F (Ref. 5)

Table 3.2.1.9 Effect of cooling rate from the solution temperature on strength, hardness, and Charpy-V impact energy of billet aged at 950F (Ref. 5)

Alloy	Custom 455	
Form	4-in. Square Billet ^a	
Condition	1500F, 30 min, WQ + 950F, 4 hr, AC	1500F, 30 min, AC + 950F, 4 hr, AC
F_{tu} (ksi) ^b	220	210
F_{ty} (ksi)	210	205
e, 2-in. (percent)	9	11
RA (percent)	36	45
Hardness (R_c)	47	44
IE Charpy-V (ft-lb)	4	7

^a Billet rolled from 9-inch square to 4-inch square at 2000F.

^b All tests longitudinal direction.

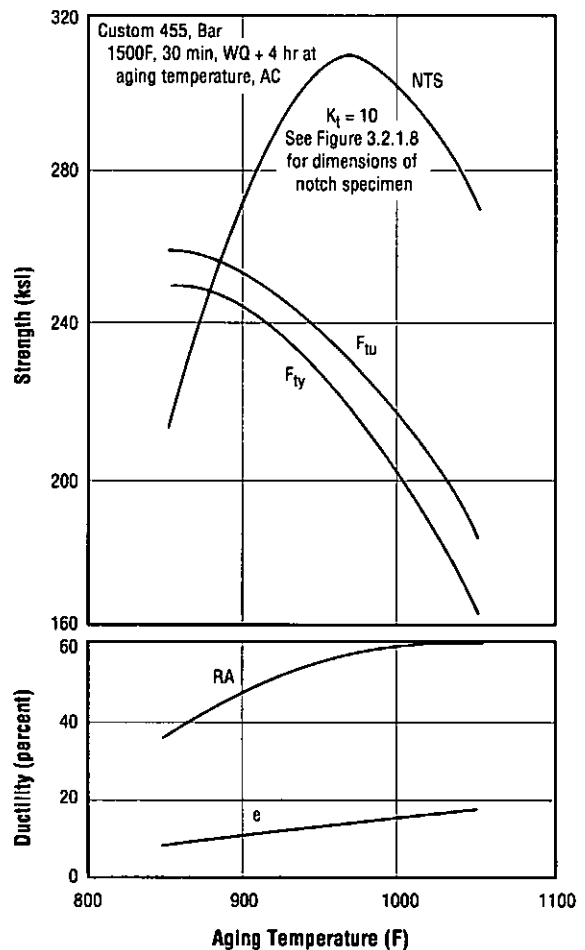


Figure 3.2.1.10 Effect of aging temperature on smooth and sharp-notch tensile properties of bar (Ref. 5)

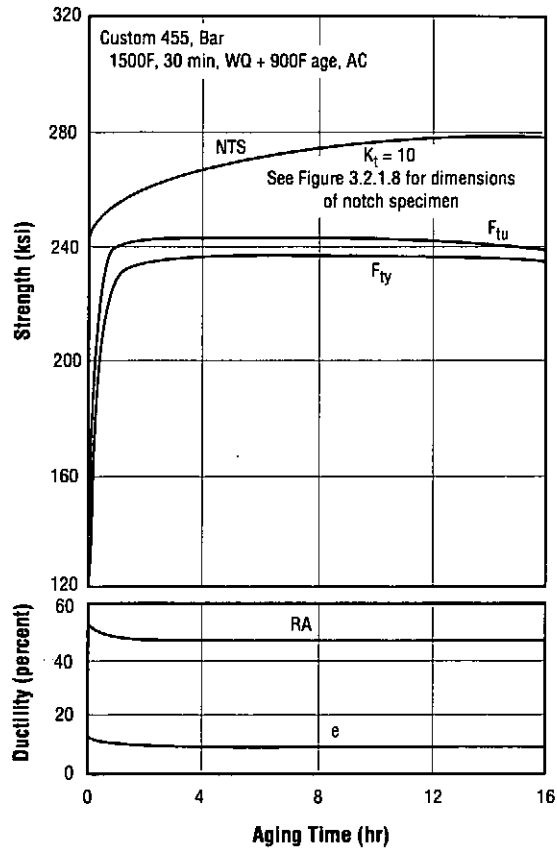


Figure 3.2.1.11 Effect of aging time on smooth and sharp-notch tensile properties of bar (Ref. 5)

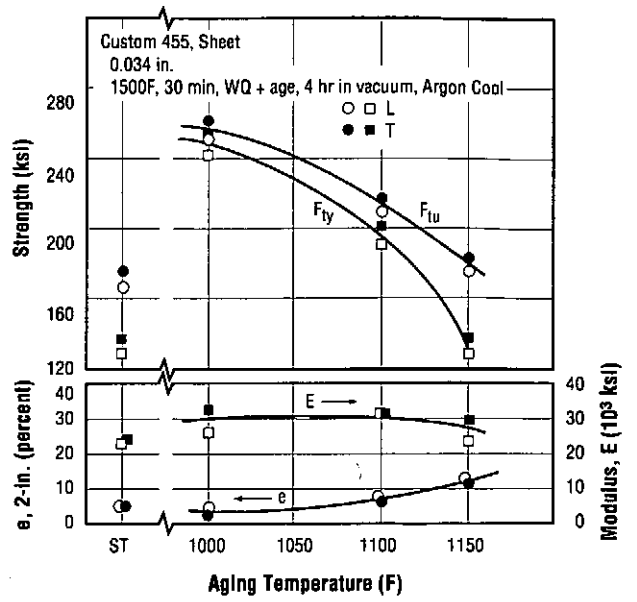


Figure 3.2.1.12 Smooth tensile properties of sheet aged in the 1000-1150F range (Ref. 80)

Table 3.2.1.13 Effect of 1000-hour exposure in air at elevated temperature on the room temperature smooth and sharp-notch tensile properties and Charpy-V impact energy of solution treated and aged bar (Ref. 5)

Alloy	Custom 455		
Form	Bar		
Condition	ST + 900F, 4 hr, AC + Exposure in Air		
Exposure in Air	None	1000 hr at 700F	1000 hr at 800F
F_{tu} (ksi)	250	272	270
F_{ty} (ksi)	240	264	262
e, 1-in. (percent)	11	10	10
RA (percent)	46	43	43
NTS ($K_t = 10$) ^a (ksi)	260	220	230
IE Charpy-V (ft-lb)	10	6	7

^a See Table 3.2.1.2 for notch specimen configuration.

Custom 455

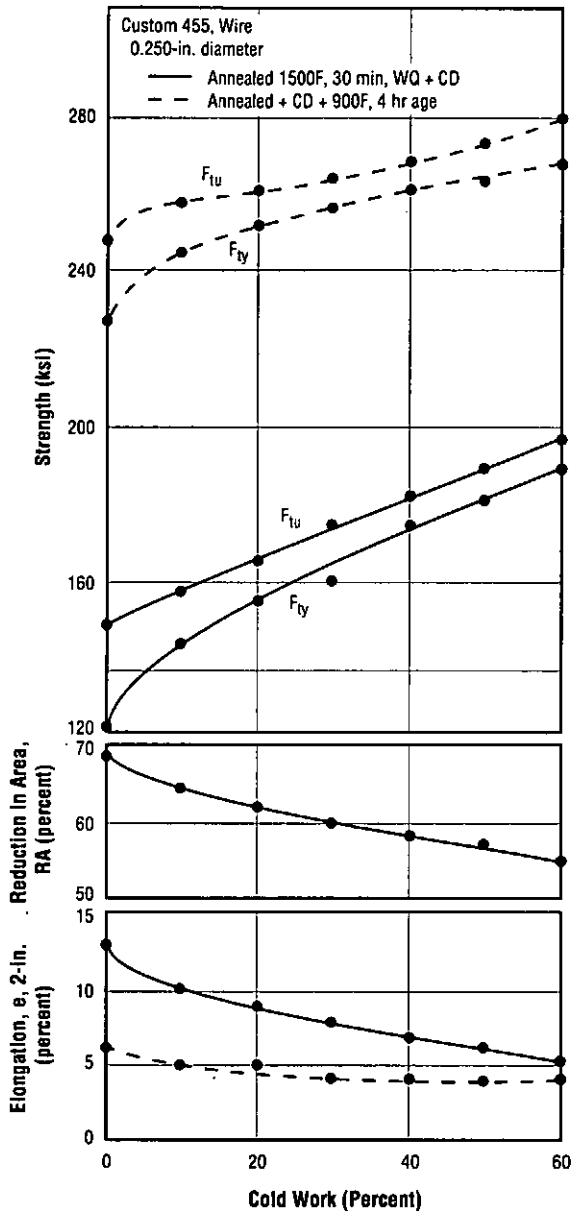


Figure 3.2.1.14 Effect of cold work on the smooth tensile properties of wire in the as-drawn and cold-drawn plus aged conditions (Refs. 5, 9)

Table 3.2.1.15 Comparison of bolt strength to material strength (Ref. 50)

Alloy		Custom 455	
Form		1/4-in. Diameter Hex Head Bolt	
Condition		Head + ST + 900F Age + Grind Shank and Thread Diameters + Roll Threads + Roll Head and Shank Fillet Radius	
Materials Properties		Bolt Properties	
F_{Tu} (ksi)	NTS ^a (ksi)	F_{Tu}^b (ksi)	F_{Tu}^c (ksi)
253.6	368.3	317.8	269.8

^a $K_t = 3.0$.

^b Stress area based on maximum minor diameter of MIL-S-8879 thread.

^c Stress area based on maximum pitch diameter of MIL-S-8879 thread.

Table 3.2.2.3 Compressive yield strength and elastic modulus (Ref. 5)

Alloy		Custom 455	
Condition		Annealed + Age, 4 hr, AC	
Age Temperature (F)	F_{Cy} (ksi)	E_c (10^3 ksi)	
950	246 - 251	30	
1000	212 - 216	29 - 30	

Table 3.2.3.1 Effect of aging temperature on Charpy-V impact energy of bar and billet (Refs. 5, 8, 12)

Alloy		Custom 455				
Form		Bar and Billet				
Condition		1525F, 30 min, WQ + Age, 4 hr, AC				
Age Temperature (F)		Unaged	900	950	1000	1050
Size, Form	Ref.	IE Charpy-V (ft-lb)				
1-in. Bar	5	70	9	14	20	35
1-1/16-in. Bar	5		10	17	27	43
4-in. Bar	5	—	—	8	12	25
1-in. Bar	12	—	—	12	23	35
Billet (size not reported) ^a	8	—	5	6	19	—

^a -1500F, 1 hour, OQ + age, 4 hours, AC.

Table 3.2.3.2 Effect of aging temperature on tensile and Izod impact properties of bar (Ref. 24)

Alloy		Custom 455			
Form		0.5-in. Bar			
Condition		ST + Age, 4 hr, AC			
Age Temperature (F)	F _{TU} (ksi)	F _{Ty} (ksi)	e (√A) (percent)	E (10 ³ ksi)	IE Izod, J ^a
900	253	243	12.8	28.8	11.2
950	237	230	15.2	29.4	20.0
1000	204	194	21.0	29.1	37.5
1050	184	165	20.0	29.2	51.5

^a Each value average six tests.

Table 3.2.3.3 Effect of aging temperature on Charpy-V and precracked Charpy impact energy (Ref. 8)

Alloy		Custom 455		
Form		Billet		
Condition		1500F, 1 hr, Rapid Cool + Age, 4 hr, AC		
Heat	Age Temperature (F)	F _{Ty} ^a (ksi)	IE Charpy-V ^b (ft-lb)	IE Precracked Charpy ^b (in-lb)
A	900	251	4.82	15.2
B	950	246	6.42	37.0
B	1000	212	19.1	124.6

^a L Direction.

^b LT Orientation.

Table 3.2.3.4 Effect of 100-hour exposure in air at elevated temperature on room temperature precracked Charpy impact energy (Ref. 8)

Alloy		Custom 455	
Form		Billet	
Condition		1500F, 1 hr, Rapid Cool + 900F, 4 hr, AC	
F _{Ty} ^a (ksi)	100 hr Air Exposure Temperature (F)	IE Precracked Charpy ^b (in-lb)	
251	Unexposed	4.8	
	600	15.5	
	700	10.7	
	800	11.5	
	900	94.3	

^a L Direction.

^b LT Orientation.

Custom 455

Table 3.2.5.2.1 Tensile and double shear strengths of bolts (Ref 49)

Alloy	Custom 455	
Form	12-Point External Wrenching Bolt with MIL-S-8879 Thread	
Condition	Forge + ST + 950F Age + Grind Shank and Thread Roll Diameters + Roll Threads and Head-To-Shank Fillet	
	F_{tu}^a (ksi)	F_{su}^b (ksi)
	240.1	139.1

^a Based on basic pitch diameter.

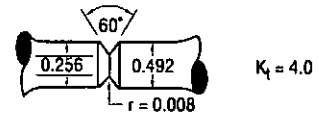
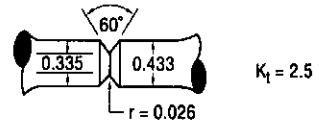
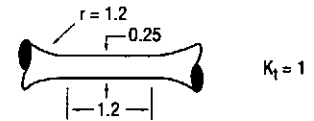
^b Based on twice the area at nominal shank diameter.

Table 3.2.7.1.8 Effect of notch acuity on mild-notch tensile strength (Ref. 22)

Alloy	Custom 455
Form	0.787-in. Bar
Condition	ST + 950F, 4 hr, AC ^a
K_t^b	NTS (ksi)
1.0	234
2.5	346
4.0	378

^a $F_{tu} = 234$ ksi.

^b Specimen configurations:



Specimens machined after heat treatment.

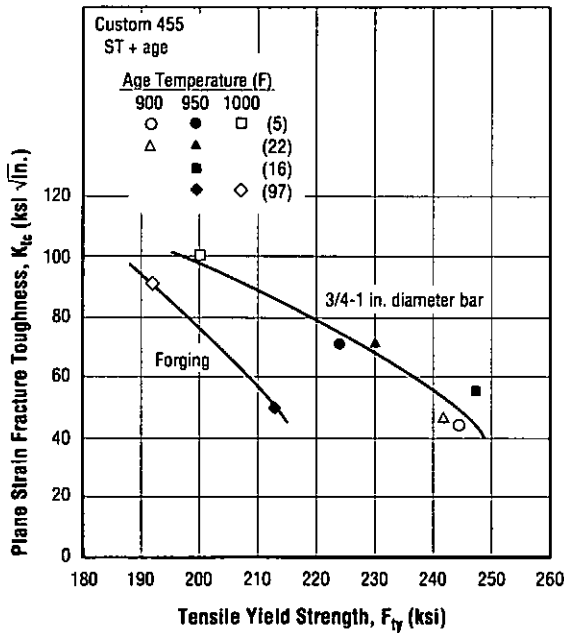


Figure 3.2.7.2.1 Relationship between yield strength and plane strain fracture toughness (Refs. 5, 16, 22, 97)

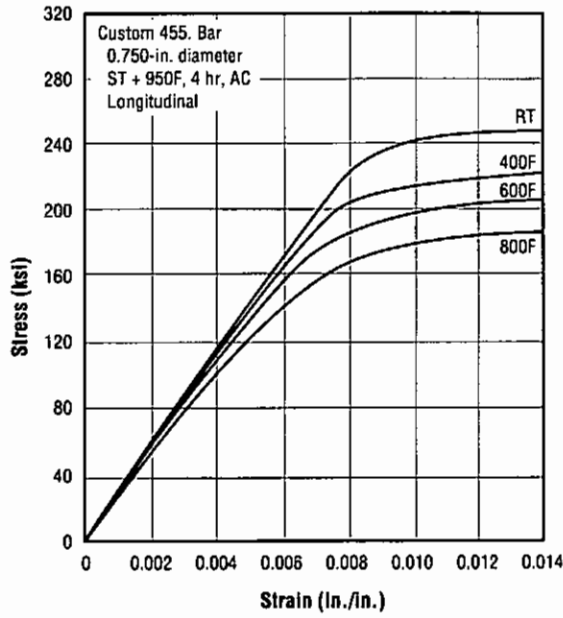


Figure 3.3.1.1 Typical stress-strain curves at room and elevated temperatures for aged bar (Ref. 16)

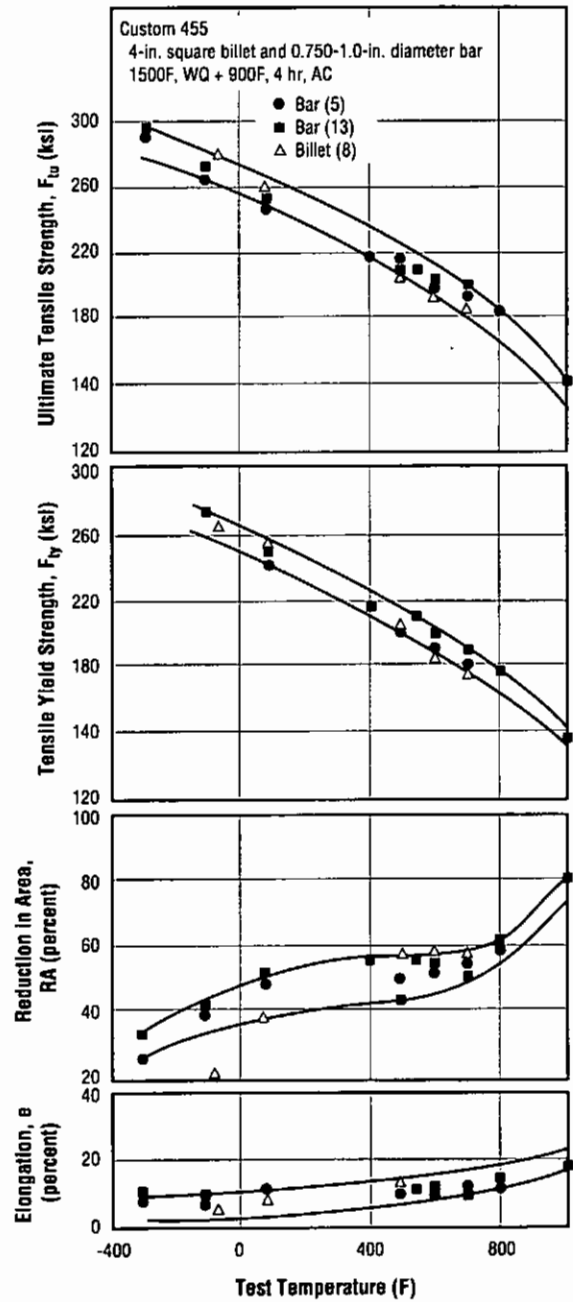


Figure 3.3.1.2 Effect of test temperature on tensile properties of billet and bar in the 900F aged condition (Refs. 5, 8, 13)

Custom 455

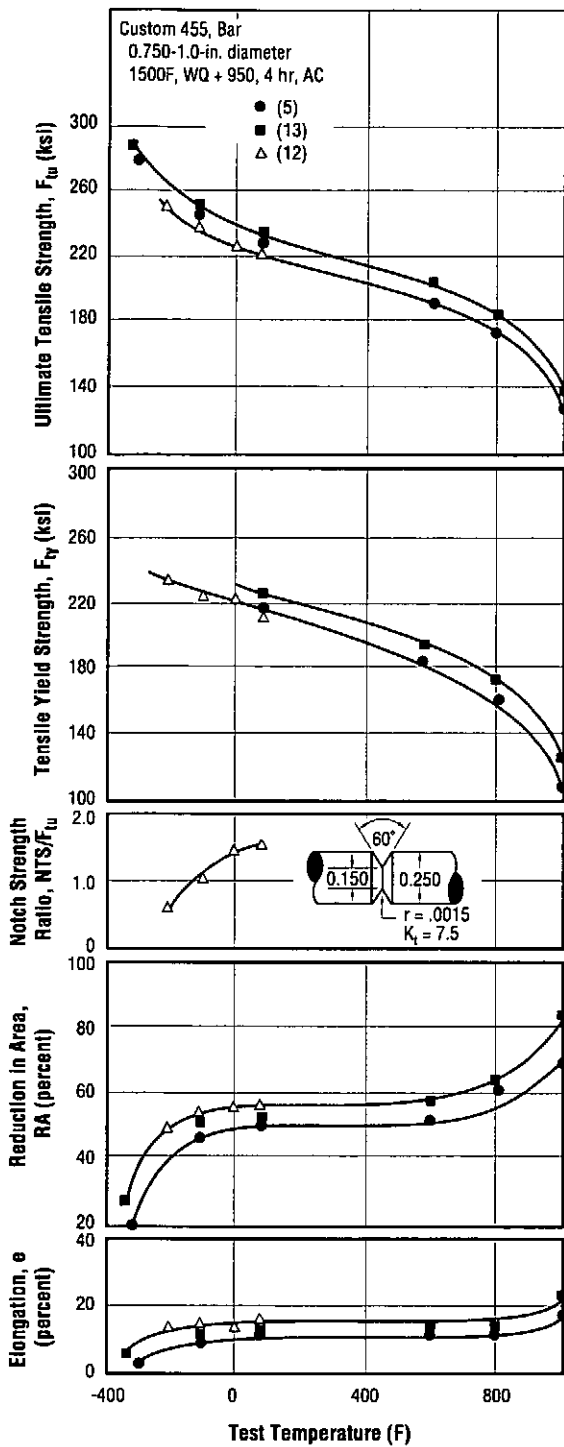


Figure 3.3.1.3 Effect of test temperature on smooth tensile properties and notch strength ratio of bar in the 950F aged condition (Refs. 5, 12, 13)

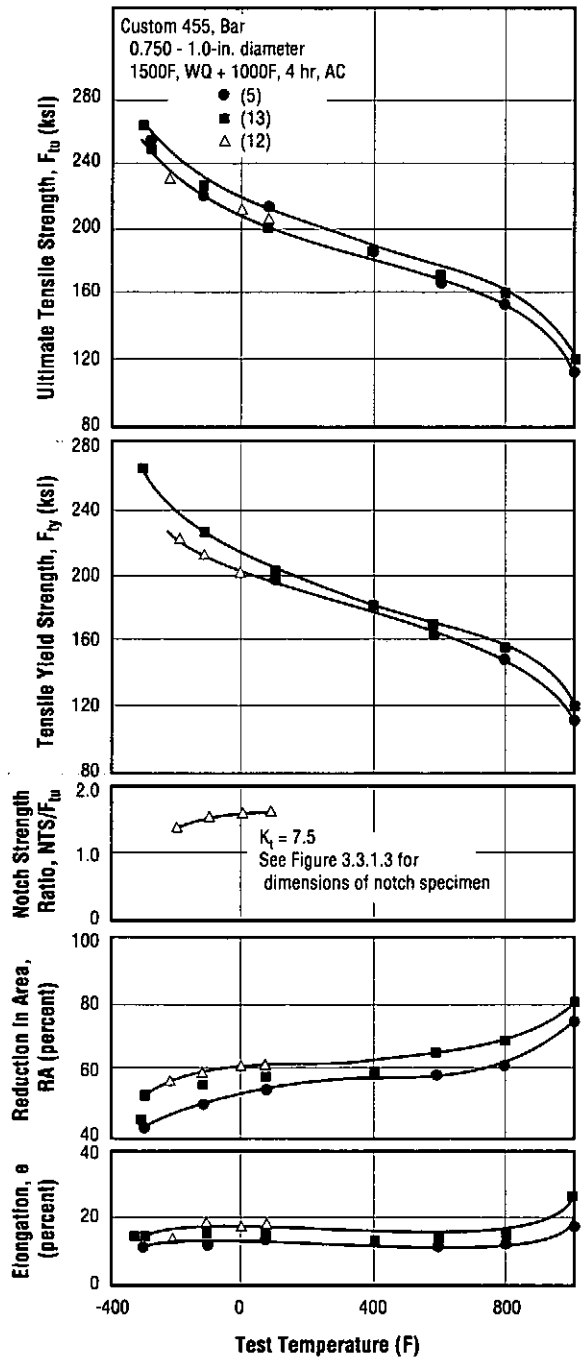


Figure 3.3.1.4 Effect of test temperature on smooth tensile properties and notch strength ratio of bar in the 1000F aged condition (Refs. 5, 12, 13)

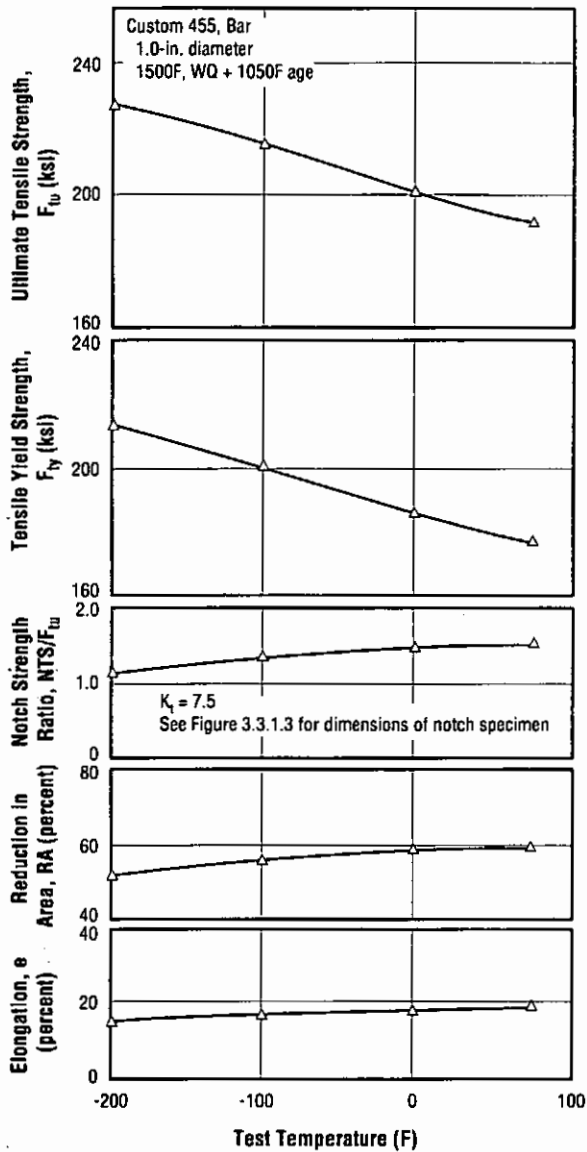


Figure 3.3.1.5 Effect of test temperature on smooth tensile properties and notch strength ratio of bar in the 1050F aged condition (Ref. 12)

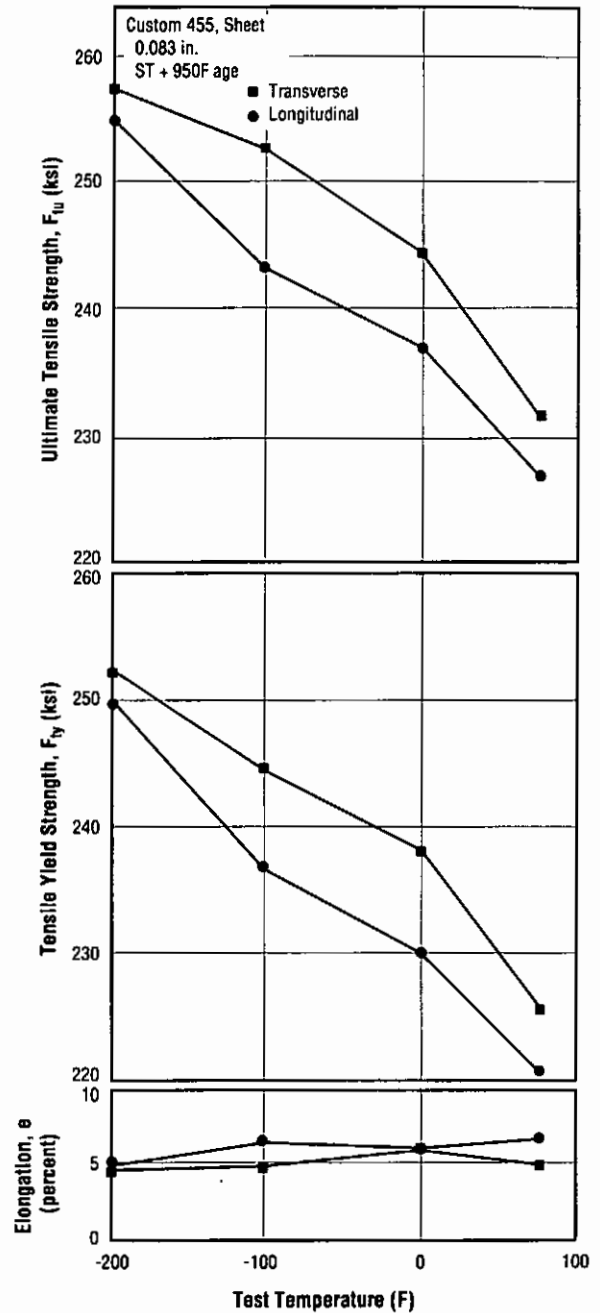


Figure 3.3.1.6 Effect of cryogenic test temperature on tensile properties of sheet in the 950F aged condition (Ref. 12)

Custom 455

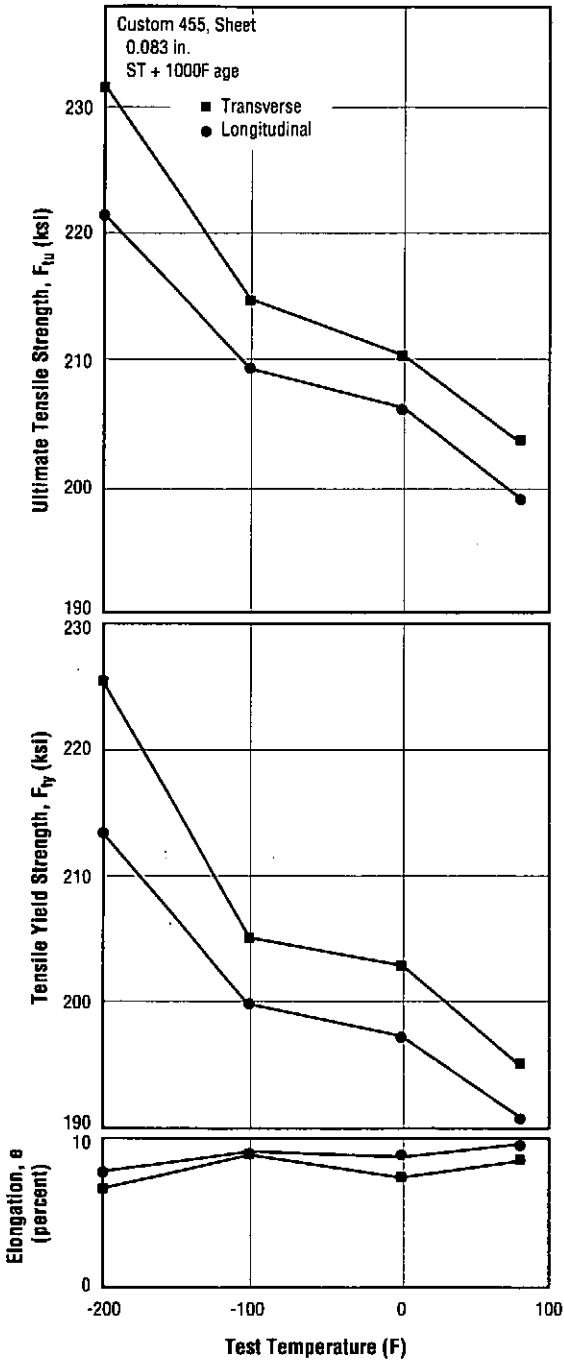


Figure 3.3.1.7 Effect of cryogenic test temperature on the tensile properties of sheet in the 1000F aged condition (Ref. 12)

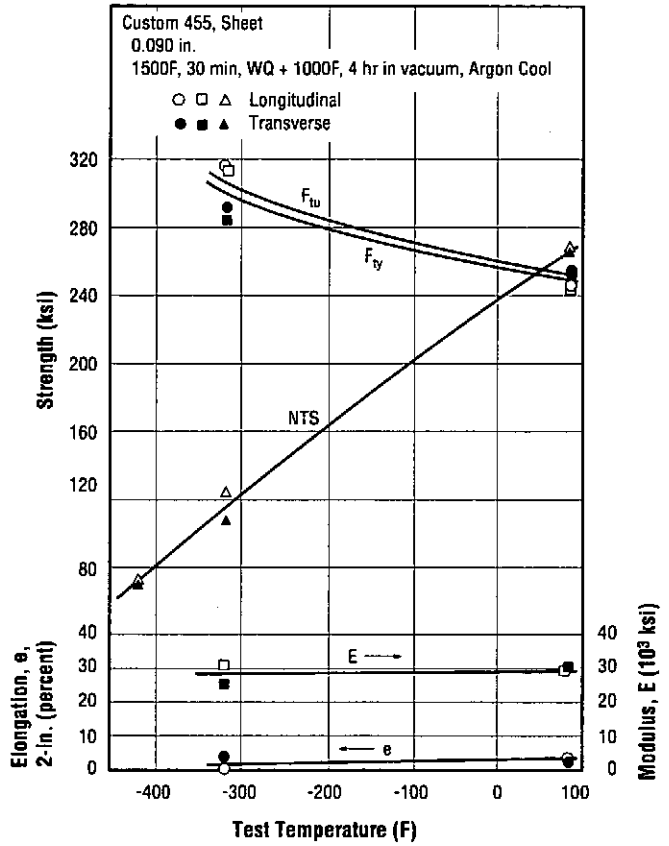


Figure 3.3.1.8 Smooth and mild-notch tensile properties at cryogenic temperatures for sheet aged at 1000F (Ref. 80)

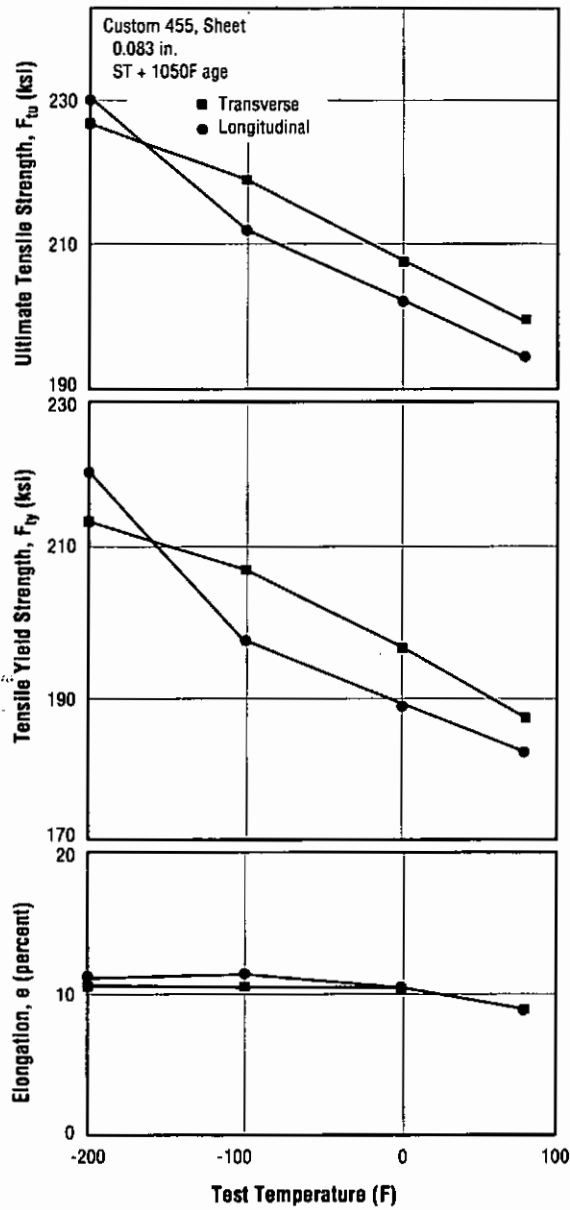


Figure 3.3.1.9 Effect of cryogenic test temperature on tensile properties of sheet in the 1050F aged condition (Ref. 12)

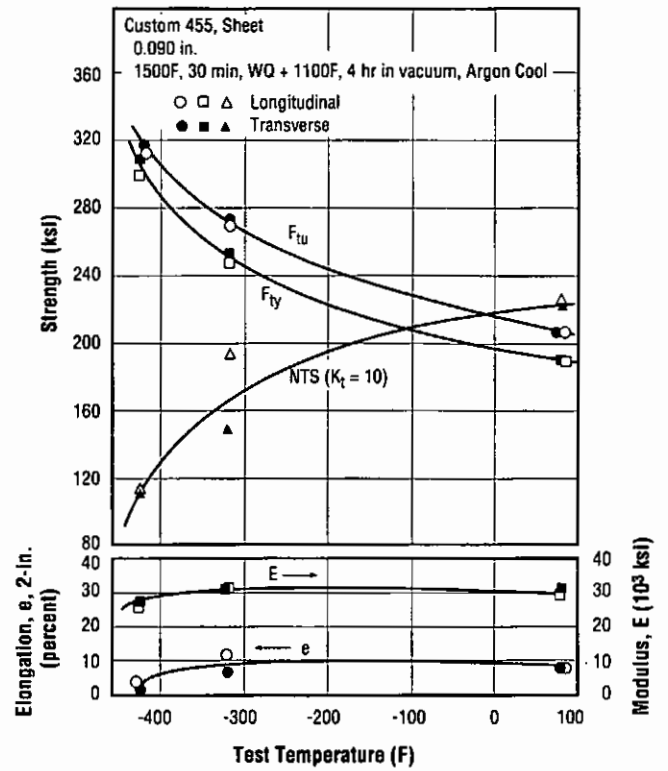


Figure 3.3.1.10 Smooth and sharp-notch tensile properties at cryogenic temperatures for sheet aged at 1100F (Ref. 80)

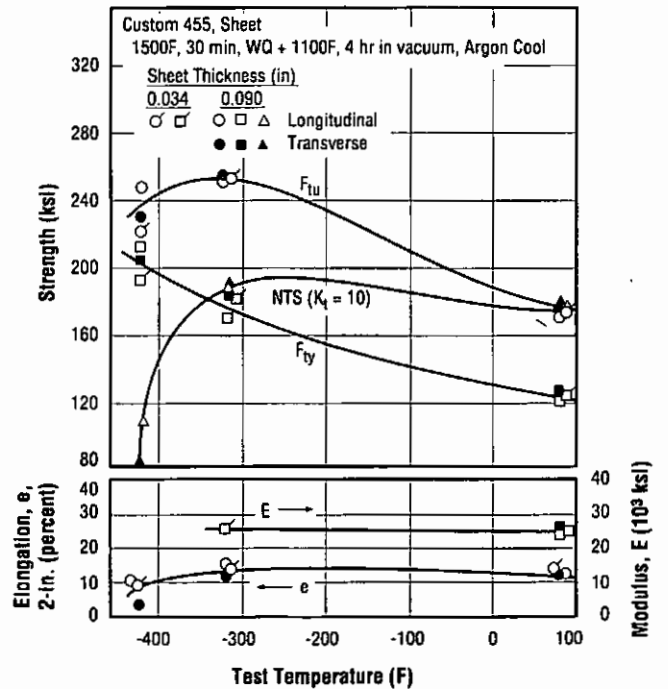


Figure 3.3.1.11 Smooth and sharp-notch tensile properties at cryogenic temperatures for sheet aged at 1150F (Ref. 80)

Custom 455

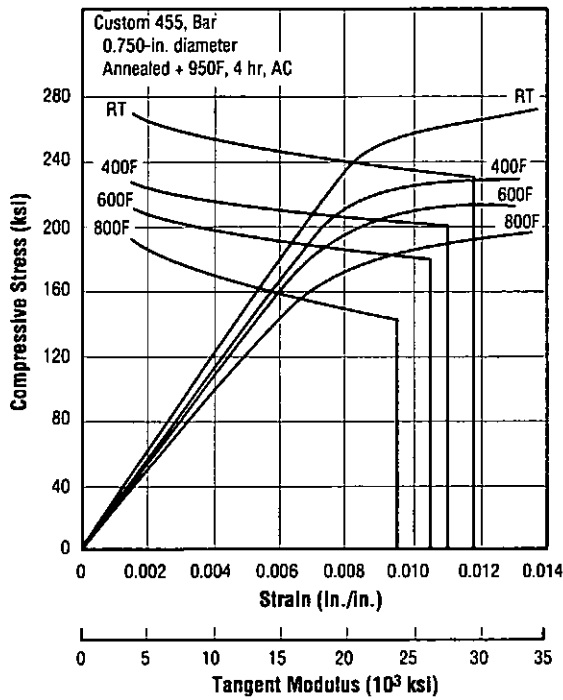


Figure 3.3.2.1 Typical compression stress-strain and tangent modulus curves for aged bar (Ref. 16)

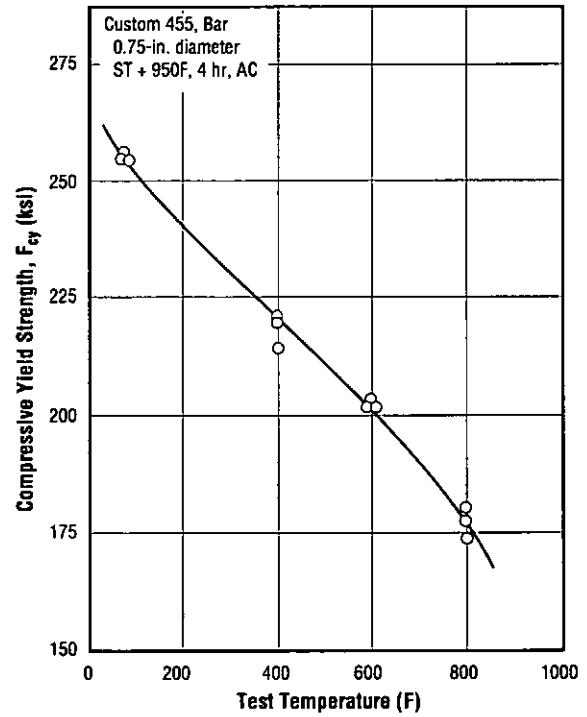


Figure 3.3.2.2 Effect of test temperature on compressive yield strength of bar aged at 950F (Ref. 16)

Table 3.3.3.1 - 70F Charpy-V impact energy for bar aged at 1050F (Ref. 47)

Alloy	Custom 455			
Form	2.5-in. Bar			
Condition	ST + 1050F, 4 hr, AC			
F_{tu} (ksi)	F_{ty} (ksi)	E (10^3 ksi)	Specimen Number	- 70F IE Charpy-V (ft-lb)
199.3	186.7	32.6	1	5
			2	4
			3	4

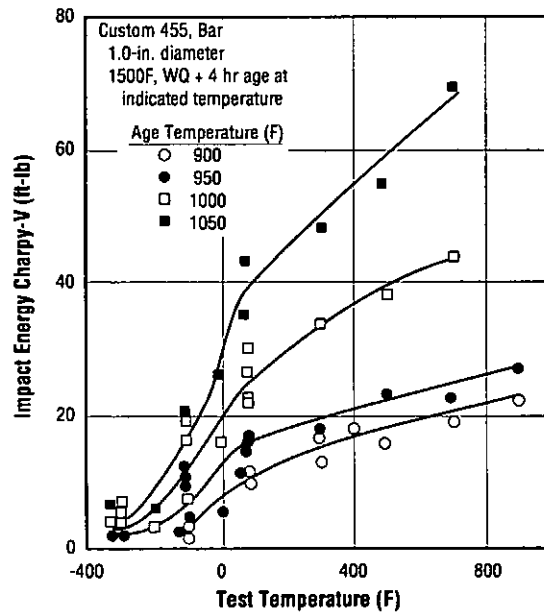


Figure 3.3.3.2 Effect of test temperature on impact energy of bar in the 900-1050F aged condition (Refs. 5, 12, 13)

Table 3.3.3.3 Charpy-V impact energy at cryogenic temperature for bar aged in 1000-1150F range (Ref. 80)

Alloy		Custom 455	
Form		13/16-in Diameter Bar	
Condition		1500F, 30 min, WQ + Age, 4 hr in Vacuum, Argon Cool	
Age Temperature (F)	Test Temperature (F)	IE Charpy-V ^a (ft-lb)	F _{ty} ^b (ksi)
1000	- 80	19 20	243.7
	- 320	2.5 3.0	317.1
1100	- 80	43.5 45.0	189.8
	- 320	6.5 8.0	247.4
1150	- 80	64.0 66.8	121.0
	- 320	15.5 16.0	176.8

^a LT Orientation.

^b Longitudinal yield strength of 0.090-inch sheet; see Figures 3.3.1.8, 3.3.1.10, and 3.3.1.11 for remainder of tensile properties.

Table 3.3.5.1 Effect of age temperature and test temperature on double restrained shear strength (Ref. 5)

Alloy		Custom 455	
Form		Annealed + Age, 4 hr, AC	
Age Temperature (F)	Test Temperature (F)	F _{TU} (ksi)	F _{SU} ^a (ksi)
900	RT	248 - 256	142 - 152
	- 100	257 - 263	157 - 166
950	RT	234 - 245	141 - 151
	400	202 - 214	122 - 129
	600	188 - 193	112 - 116
	800	168 - 172	102 - 105
1000	- 100	222 - 235	139 - 149
	RT	201 - 214	127 - 133
	400	176 - 189	111 - 118
	600	164 - 172	100 - 107
	800	145 - 154	83 - 90

^a Double restrained shear strength.

Custom 455

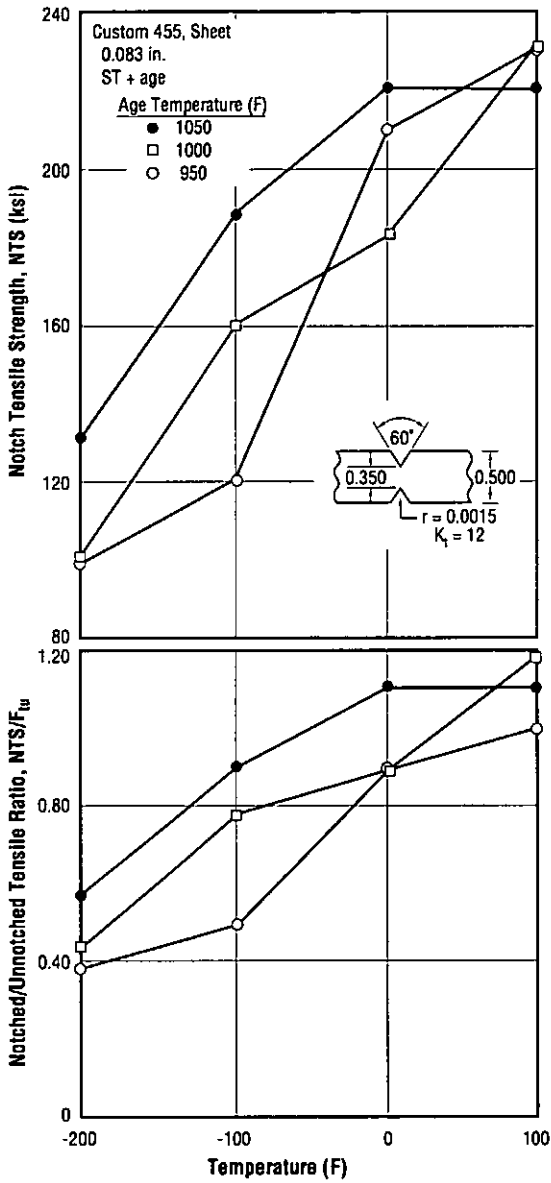


Figure 3.3.7.1.2 Effect of cryogenic test temperature on sharp-notch tensile strength and sharp-notch strength ratio of sheet in the longitudinal direction (Ref. 12)

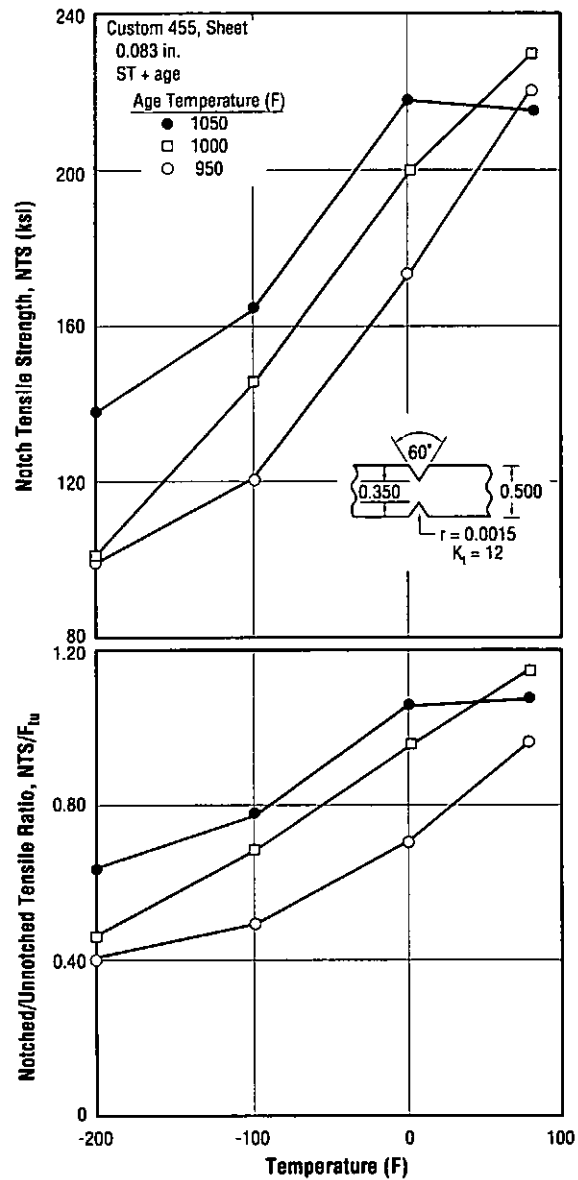


Figure 3.3.7.1.3 Effect of cryogenic test temperature on notch tensile strength of sheet in the transverse direction (Ref. 12)

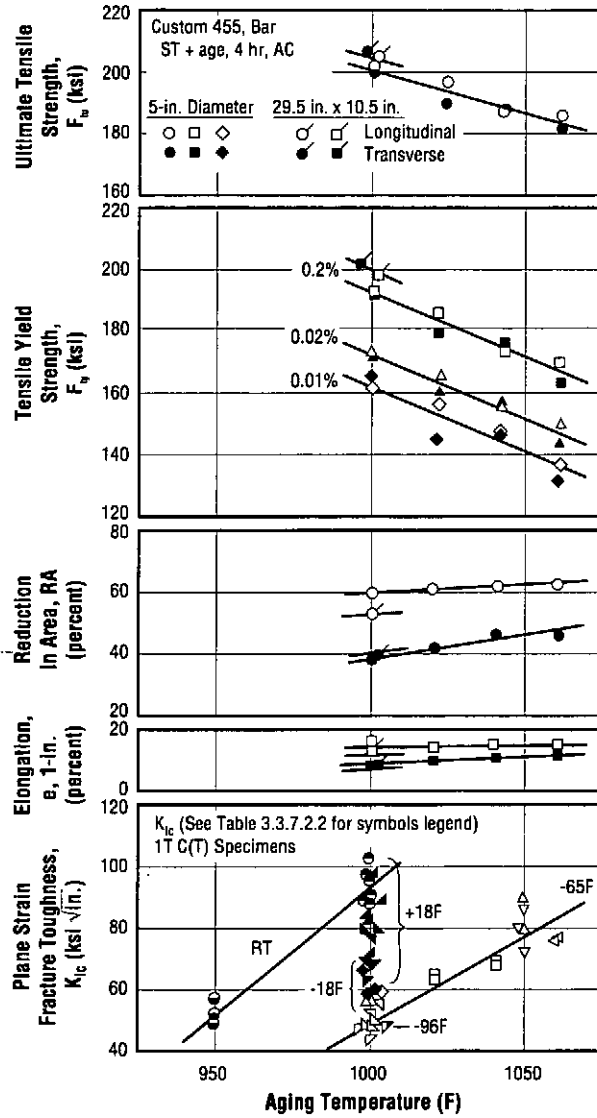


Figure 3.3.7.2.1 Effect of aging temperature on room temperature tensile properties and low temperature plane strain fracture toughness of bar in a variety of sizes and shapes from seven heats (Ref. 97)

Table 3.3.7.2.2 Symbols legend for Figure 3.3.7.2.1

Symbol	Heat Number	Bar Size (in. x in.)	Test Temperature (F)	Crack Plane Orientation
●	85284	3.5 x 3.5	RT	LT
○	96145	29.5 x 10.0	RT	LS
▲	88543	7.0 Diameter	+ 18	Unknown
▼	96145	29.5 x 10.0	+ 18	TL
◆	96145	29.5 x 10.0	+ 18	LS
◀	94189	5.0 Diameter	+18	LR
◇	88543	7.0 Diameter	- 18	Unknown
△	82125	3.0 Diameter	- 65	CR
▴	85137	8.75 x 4.75	- 65	TL
◇	94189	5.0 Diameter	- 65	LR
▽	96145	29.5 x 10.0	- 65	LS
▽	96145	29.5 x 10.0	- 65	TL
□	94189	5.0 Diameter	- 65	LR
△	82185	3.0 Diameter	- 65	CR
▽	86818	6.0 Diameter	- 65	CR
◁	94189	5.0 Diameter	- 65	LR
▽	94189	5.0 Diameter	- 96	LR

Custom 455

Table 3.3.7.2.3 Effect of quenched section size on -65F, LS orientation plane strain fracture toughness of forged block variously heat treated to a common strength level of approximately 200 ksi (Ref. 98)

Alloy		Custom 455	
Form		Forged Block	
Quenched Section Thickness (in.)	Heat Treatment	F_{tu}^a (ksi)	K_{Ic}^b (ksi $\sqrt{\text{in.}}$)
1.6	1525F, 30 min, OQ + 1525F, 2 hr, 10 min in furnace, OQ + 1000F, 8 hr, AC	198	68.8, 73.0, 61.8 ^c
1.6	1525F, 30 min, OQ + 1525F, 2 hr, 10 min in furnace, OQ + 1000F, 5 hr, AC	204	55.8, 53.5, 50.0 ^c
9 - 10	1525F, 30 min, OQ + 1000F, 5 hr, AC	203	45.5, 49.2, 47.8
9 - 10	1525F, 30 min, OQ + 980F, 12 hr, AC	201	47.8 ^c , 46.4 ^c
9 - 10	1525F, 30 min, OQ + 980F, 4 hr, AC + 995F, 5 hr, AC	203	44.9 ^c , 47.1, 46.7
9 - 10	1525F, 30 min, OQ + 800F, 8 hr, AC + 1000F, 5 hr, AC	203	48.0, 46.0, 49.3

^a Room temperature, longitudinal direction.

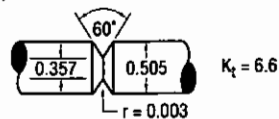
^b -65F, LS crack plane orientation, 1T C(T) specimen.

^c Not valid according to ASTM E 399.

Table 3.3.7.2.4 Room temperature, -65, and -110F smooth and mild-notch tensile strength and plane strain fracture toughness of forging (Ref. 99)

Alloy		Custom 455						
Form		Forging						
Condition		1525F, 3 hr, OQ + 1000F, 4 hr, AC						
Test Temperature (F)	Test Direction	F _{TU} (ksi)	F _{Ty} (ksi)	e, 2-in. (percent)	RA (percent)	NTS ^a (ksi)	Crack Plane Orientation	K _{IC} ^b (ksi √in.)
70	L	201.2	192.2	13.0	50.0	292.7	LT	95.1, 92.6 89.7
	T					298.3	TL	
	ST					261.7	LS	104.9, 93.2 96.2, 88.2
-65	L	212.2	203.0	12.2	44.6		LT	46.0, 50.7 46.4, 44.6 44.2, 45.7 49.2
	T	217.3	207.7	11.7	41.3		TL	47.7 47.0
	ST	212.5	205.5	7.0	15.5		LS	49.3, 48.1 44.1, 45.7 46.4, 44.0 51.3, 45.5
-110	L	217.0	207.5	11.5	44.0		LT	37.5, 42.5 38.0, 46.1 46.4
	T						TL	
	ST						LS	39.9, 43.0 44.7, 37.5 39.1, 38.6 38.1, 42.4

^a Notched cylindrical specimen:



^b CT specimen: RT tests, 1.0-inch thick, -65F and -110F tests, 0.5-inch thick.

Custom 455

Table 3.4.1 Plastic deformation in 100 and 1000 hours at 400-850F. (Refs. 14, 16)

Alloy	Custom 455		
Form	Bar		
Size	0.75-1.0-in. Diameter		
Condition	ST + 950F, 4 hr, AC		
Test Temperature (F)	400	600	850
Stress (ksi) for:			
0.2 percent plastic deformation in 100 hours	207	163	44
0.2 percent plastic deformation in 1000 hours	203	155	30

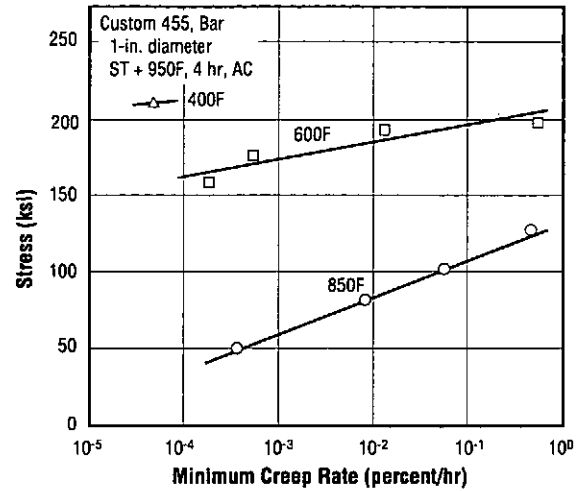


Figure 3.4.2 Minimum creep rate for bar at 400F, 600F, and 850F (Ref. 16)

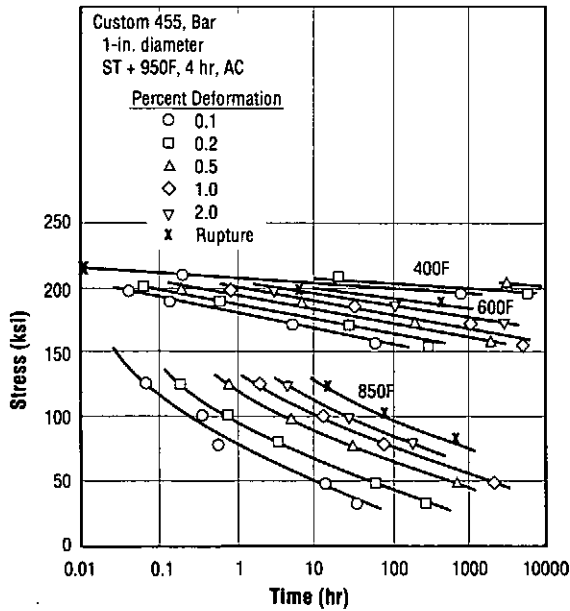


Figure 3.4.3 Stress-rupture and plastic deformation curves for bar at 400F, 600F, and 850F (Ref. 16)

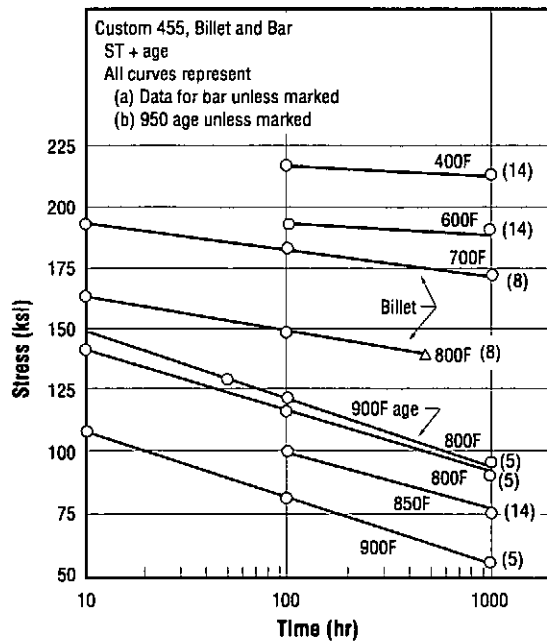


Figure 3.4.4 Creep rupture curves at 400-900F for billet and bar (Refs. 5, 8, 14)

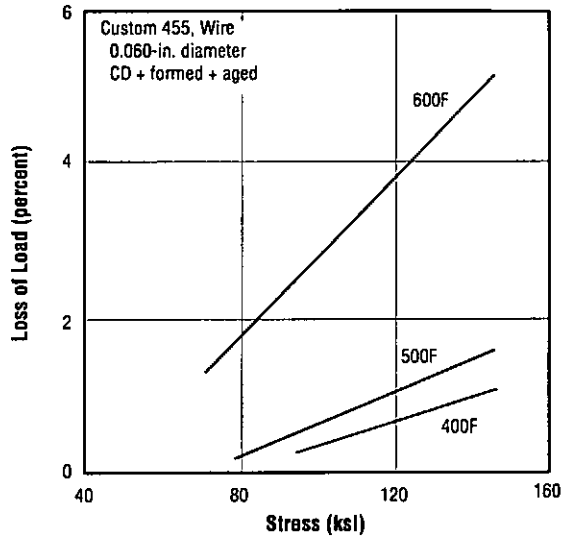


Figure 3.4.5 Loss of load in one hour at 400-600F during static loading of compression spring made from 0.060-inch wire (Ref. 5)

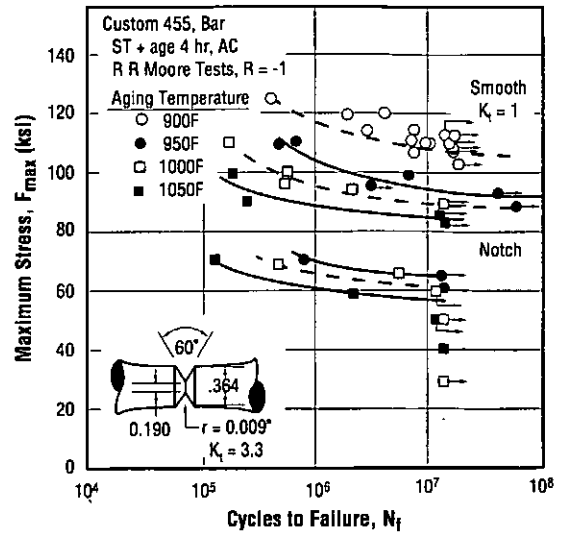


Figure 3.5.1.1 Effect of aging temperature on room temperature rotating beam smooth and mild-notch fatigue strength of bar (Refs. 5, 13)

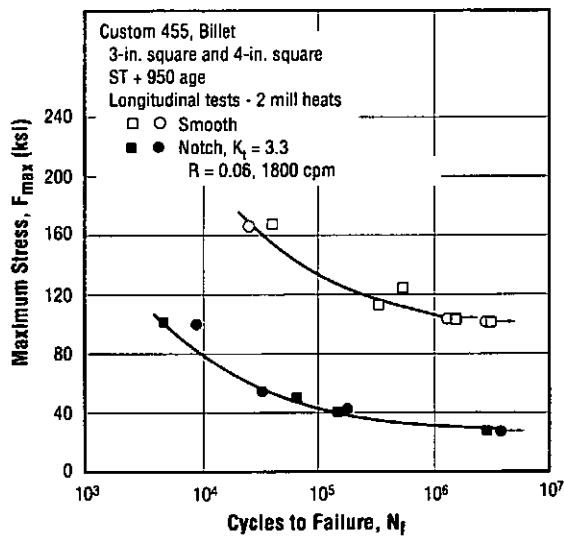


Figure 3.5.1.2 Room temperature axial-load smooth and mild-notch ($K_t = 3.3$) fatigue strength of billet aged at 950F (Ref. 8)

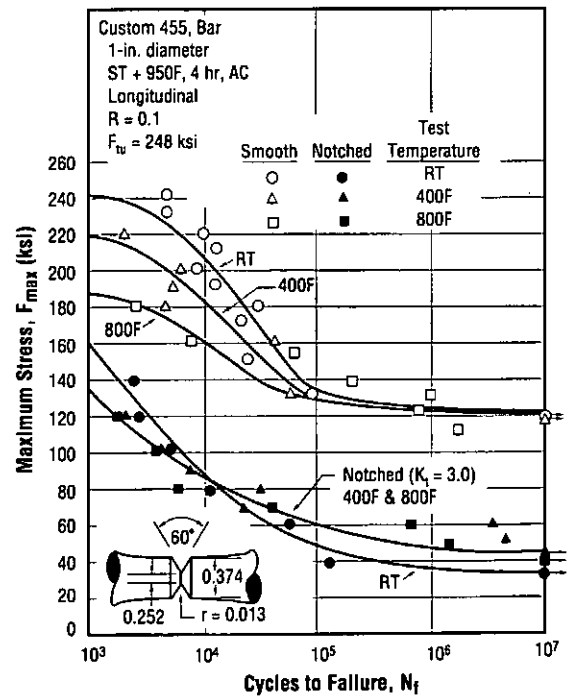


Figure 3.5.1.3 Room and elevated temperature axial-load smooth and mild-notch ($K_t = 3.0$) fatigue strength of bar aged at 950F (Ref. 16)

Custom 455

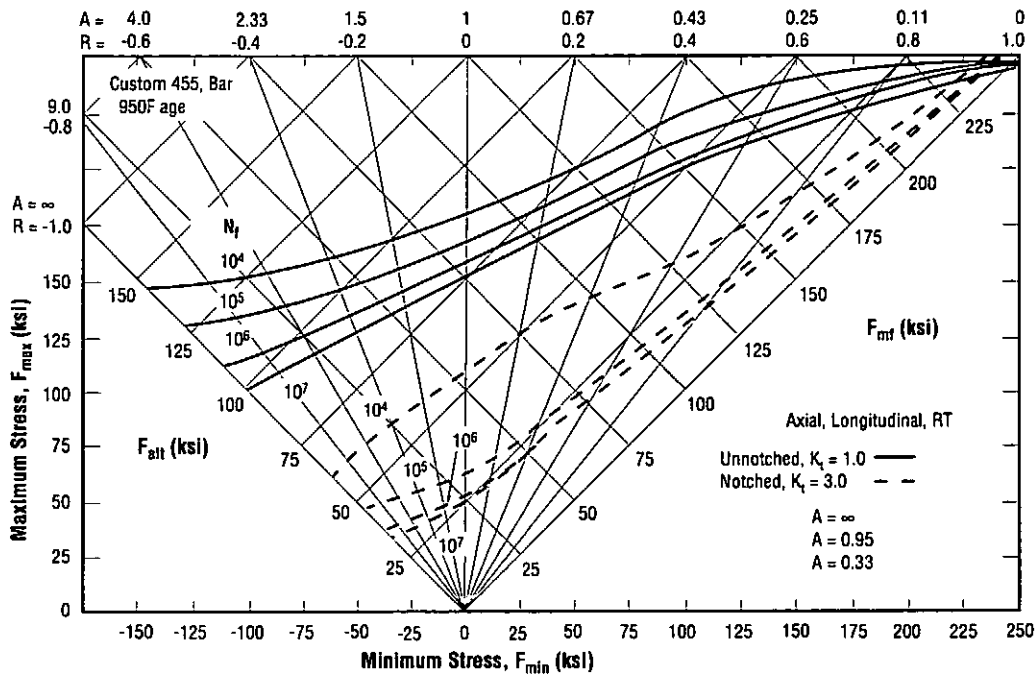


Figure 3.5.1.4 Typical axial-load smooth and mild-notch ($K_t = 3.0$) constant-life fatigue diagram for bar aged at 950F (Ref. 5)

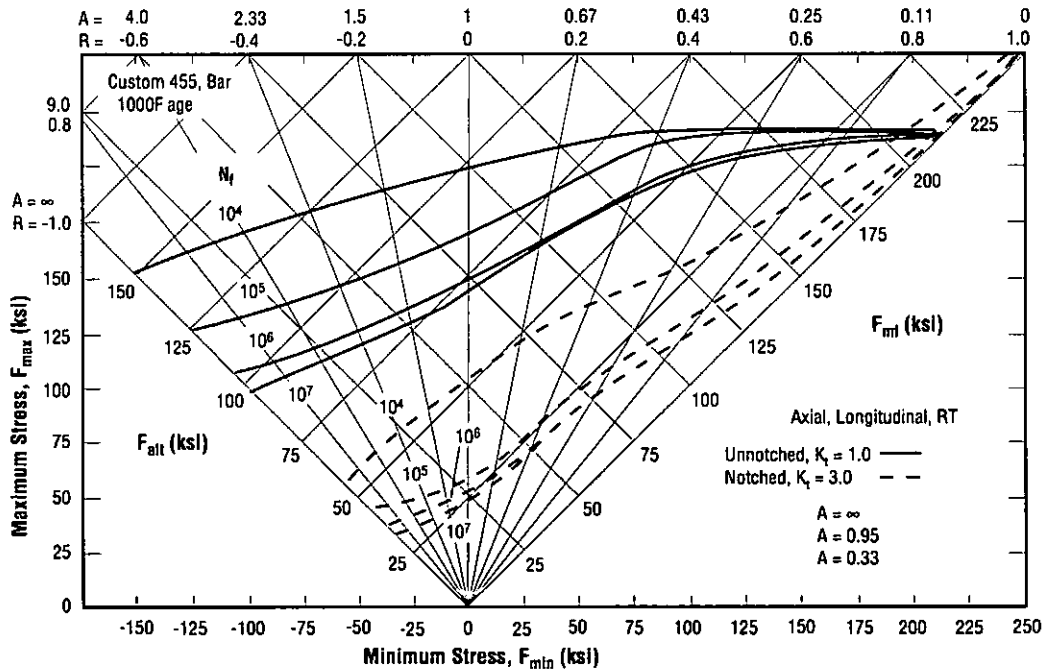


Figure 3.5.1.5 Typical axial-load smooth and mild-notch ($K_t = 3.0$) constant-life fatigue diagram for bar aged at 1000F (Ref. 5)

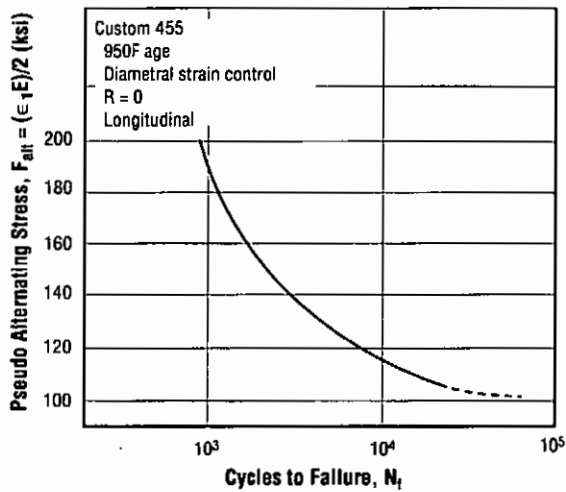


Figure 3.5.1.6 Room temperature diametral-strain-controlled low-cycle fatigue life (Ref. 5)

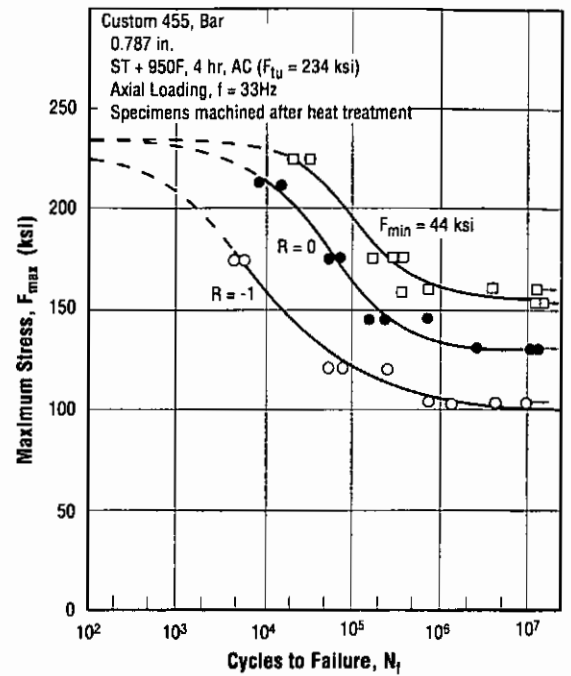


Figure 3.5.1.7 Axial-load smooth fatigue strength at several stress ratios for specimens machined from bar after 950F age treatment (Ref. 22)

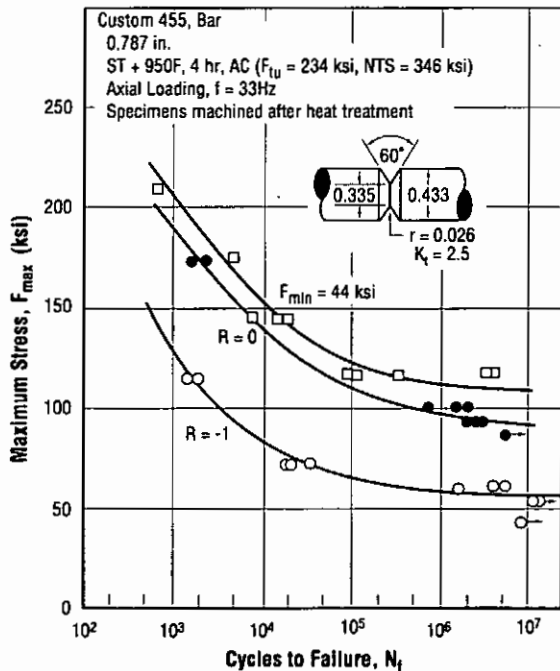


Figure 3.5.1.8 Axial-load mild-notch ($K_t = 2.5$) fatigue strength at several stress ratios for specimens machined from bar after 950F age treatment (Ref. 22)

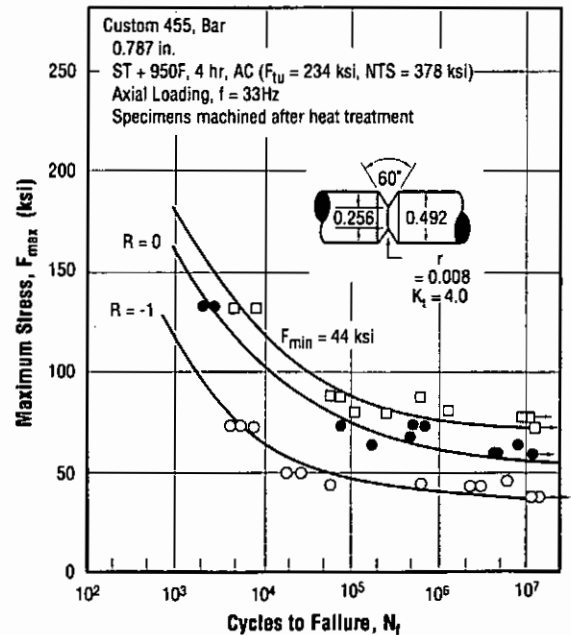


Figure 3.5.1.9 Axial-load mild-notch ($K_t = 4.0$) fatigue strength at several stress ratios for specimens machined from bar after 950F age treatment (Ref. 22)

Custom 455

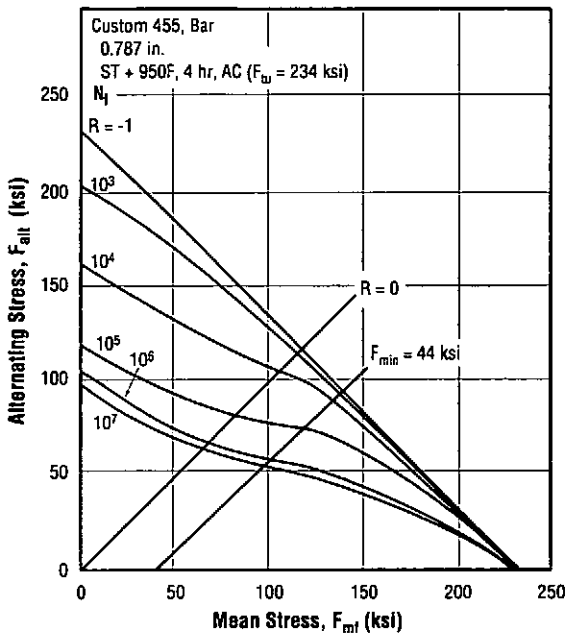


Figure 3.5.1.10 Haig diagram for axial-load smooth specimens machined from bar after 950F age treatment (Ref. 22)

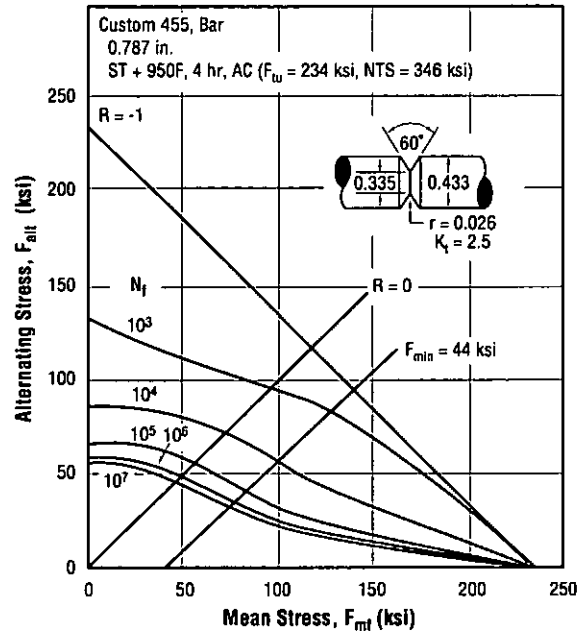


Figure 3.5.1.11 Haig diagram for axial-load mild-notch ($K_t = 2.5$) specimens machined from bar after 950F age treatment (Ref. 22)

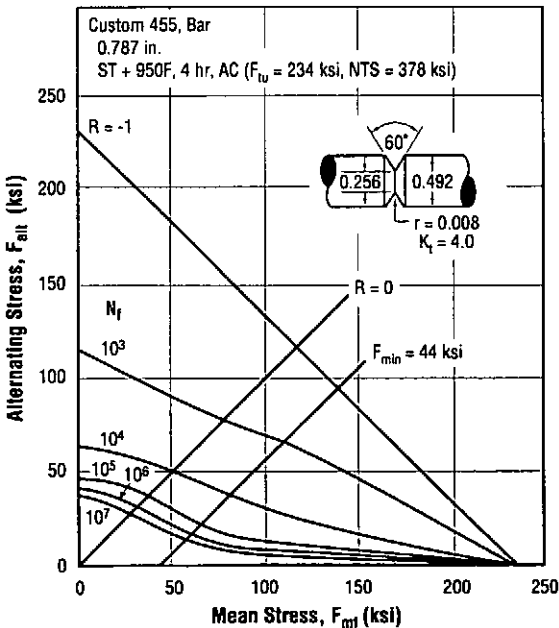


Figure 3.5.1.12 Haig diagram for axial-load mild-notch ($K_t = 4.0$) specimens machined from bar after 950F age treatment (Ref. 22)

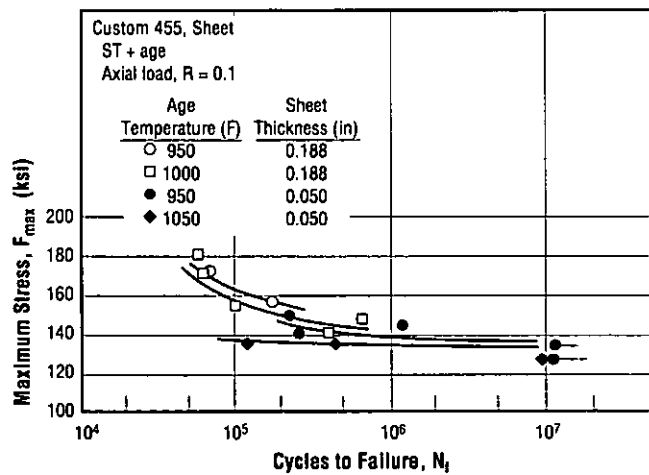


Figure 3.5.1.13 Room temperature axial-load fatigue strength of sheet (Ref. 56)

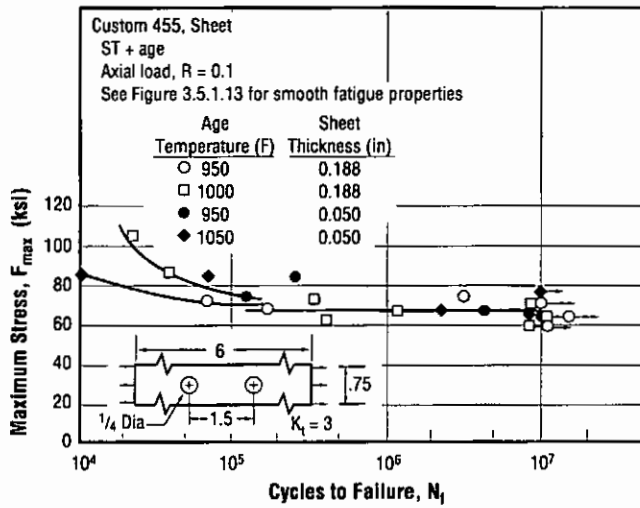


Figure 3.5.1.14 Room temperature axial-load fatigue strength of two-hole ($K_t = 3.0$) sheet specimens (Ref. 56)

Table 3.5.1.15 Room temperature axial tension fatigue strength of bolts (Ref. 49)

Alloy	Custom 455	
Form	12-Point External Wrenching Bolt with MIL-S-8879 Thread	
Condition	Forge + ST + 950F Age + Grind Shank and Thread Roll Diameters + Roll Threads and Head-To-Shank Fillet	
	F_{tu}^a (ksi)	Cycles to Failure ^b , N_f
	240.1	500,000

^a Based on basic pitch diameter.

^b $F_{max} = 99$ ksi; R = 0.1. All failures in threads.

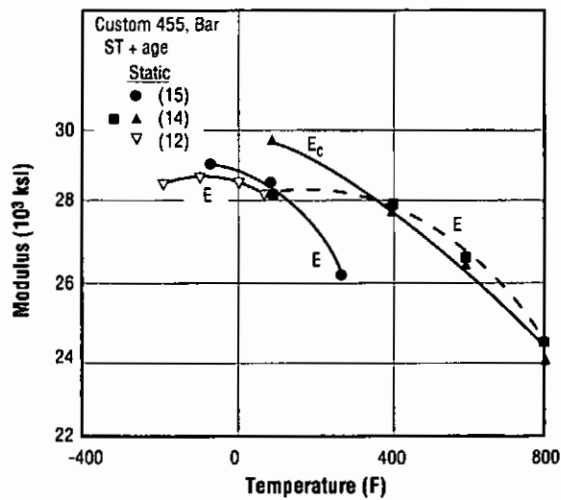


Figure 3.6.2.1 Modulus of elasticity in tension (E) and compression (E_c) at temperatures ranging from -200F to 800F (Refs. 12, 14, 15)

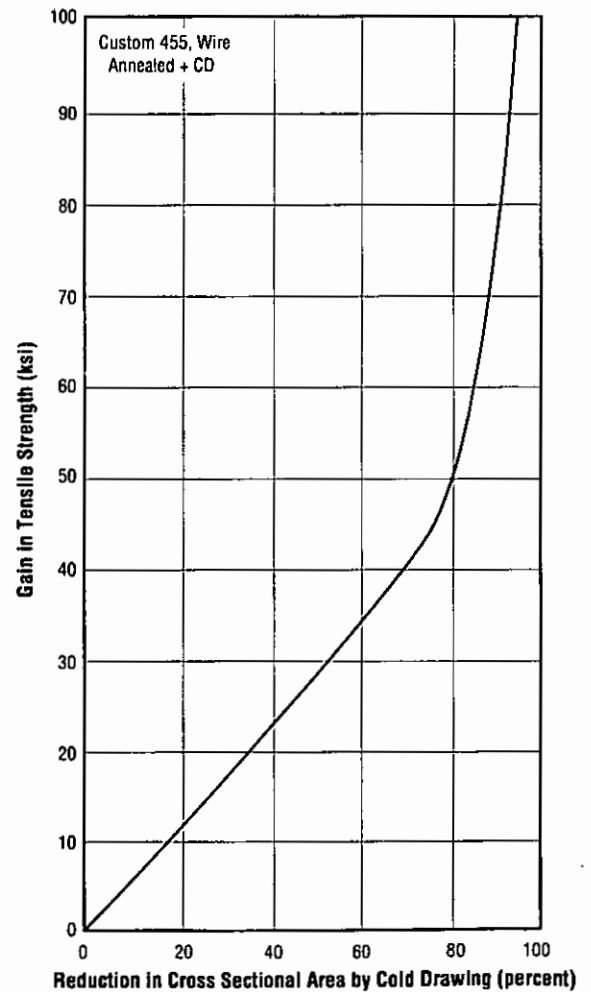


Figure 4.1.2.1 Effect of cold drawing in the annealed condition on tensile strength of wire (Ref. 5)

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