MATERIALS DATA HANDBOOK

Inconel Alloy 718

(2nd Edition)

Revised by

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PREFACE

The revised edition of the Materials Data Handbook on the Inconel Alloy 718 was prepared by Western Applied Research & Development, Inc. under contract with the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama. It is a revised and updated version of the Handbook originally prepared by the Department of Chemical Engineering and Metallurgy at Syracuse University, September 1966.

It is intended that this Handbook present, in the form of a single document, a summary of the materials property information presently available on the Inconel Alloy 718.

The Handbook is divided into twelve (12) chapters. The scope of the information presented includes physical and mechanical property data at cryogenic, ambient, and elevated temperatures, supplemented with useful information in such areas as material procurement, metallurgy of the alloy, corrosion, environmental effects, fabrication and joining techniques. Design data are presented, as available, and these data are complemented with information on the typical behavior of the alloy. The major source used for the design data is the Department of Defense document, Military Handbook-5A.

Information on the alloy is given in the form of tables and figures, supplemented with descriptive text as appropriate. Source references for the information presented are listed at the end of each chapter.

Throughout the text, tables, and figures, common engineering units (with which measurements were made) are accompanied by conversions to International (SI) Units, except in the instances where double units would over-complicate data presentation, or where SI units are impractical (e.g., machine tools and machining). In these instances, conversion factors are noted. A primary exception to the use of SI units is the conversion of 1000 pounds per square inch to kilograms per square millimeter rather than newtons, in agreement with the ASTM that this unit is of a more practical nature for worldwide use.

ACKNOWLEDGMENTS

The second edition of "Materials Data Handbook: Inconel Alloy 718" was prepared by Western Applied Research & Development, Inc. under Contract NAS8-26644 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Astronautics Laboratory, Materials Division of the George C. Marshall Space Flight Center with Mr. Wayne R. Morgan acting as Project Manager.

Sincere appreciation is tendered to the many commerical organizations and Government agencies who have assisted in the preparation of this document.

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TABULAR ABSTRACT

Inconel Alloy 718

TYPE:

Wrought, age-hardenable nickel-chromium-iron alloy

NOMINAL COMPOSITION:

Ni-19Cr-19Fe-5Cb-3Mo-0.9Ti-0.4Al

AVAILABILITY:

Sheet, plate, bar, hot-rolled shapes, machined shafts, cold drawn tube, and forgings. Castings available as Inconel Alloy 718C.

TYPICAL PHYSICAL PROPERTIES:

Density	8.19 g/cm^3 at room temperature
Thermal Conductivity	0.027 $cal/cm/cm^2/sec/^\circ C$
Av. Coeff. of Thermal Expansion	13.1 $\mu cm/cm/^\circ C$ (20–100° C)
Specific Heat	0.104 cal/g °C
Electrical Resistivity	127 microhms-cm at rm temp

TYPICAL MECHANICAL PROPERTIES: *

F_{tu}	180 ksi (127 kg/mm^2)
F_{ty}	150 ksi (105 kg/mm^2)
e(2 inch, 50.8 mm)	12 percent
E (tension)	29 x 10^3 ksi (20 x 10^3 kg/mm^2)

FABRICATION CHARACTERISTICS:

Weldability	Excellent if proper procedures are employed
Formability	Good in annealed condition
Machinability	Good in both annealed and aged conditions

COMMENTS:

A medium high temperature alloy with exceptionally high tensile and creep properties at temperatures up to about 1300° F (704° C). Alloy also has good cryogenic properties. Properties and microstructure, however, are strongly influenced by chemical composition and heat treatment.

* Aged material (see Ch. 3)

SYMBOLS

a	One-half notch section dimension
A	Area of cross section; "A" basis for mechanical property values (MIL-HDBK-5A)
Å	Angstrom unit
AC	Air cool
AMS	Aerospace Material Specifications
Ann	Annealed
ASTM	American Society for Testing Methods
Av or Avg	Average
B	"B" basis for mechanical property values (MIL-HDBK-5A)
b	Subscript "bending"
bcc	Body centered cubic
BHN	Brinell hardness number
br	Subscript "bearing"
Btu	British thermal unit(s)
°C	Degree(s) Celsius
c	Subscript "compression"
CD	Cold drawn
CF	Cold finished
cm	Centimeter
c_p	Specific heat
CR	Cold rolled
CW	Cold worked
CVM	Consumable vacuum melted
D or Dia	Diameter
DPH	Diamond pyramid hardness
e	Elongation in percent
E	Modulus of elasticity, tension
E_c	Modulus of elasticity, compression
e/D	Ratio of edge distance to hole diameter
E_s	Secant modulus
E_t	Tangent modulus
eV	Electron volt(s)
°F	Degree(s) Fahrenheit
f	Subscript "fatigue"
F_{bru}	Bearing ultimate strength
F_{bry}	Bearing yield strength

fcc	Face centered cubic
FC	Furnace cool
F_{cy}	Compressive yield strength
F_{su}	Shear stress; shear strength
F_{tu}	Ultimate tensile strength
F_{ty}	0.2% tensile yield strength (unless otherwise indicated)
g	Gram
G	Modulus of rigidity
HAZ	Heat affected zone in weldments
hcp	Hexagonal close pack
hr	Hour(s)
HT	Heat treat
IACS	International annealed copper standard
in	Inch
ipm	Inches per minute
$^{\circ}K$	Degree(s) Kelvin
K	Stress intensity factor; thermal conductivity
K_c	Measure of fracture toughness (plane stress) at point of crack growth instability
kg	Kilogram
K_{Ic}	Plane strain fracture toughness value
ksi	Thousand pounds per square inch
K_t	Theoretical elastic stress concentration factor
L	Longitudinal
lb	Pound
LT	Long transverse (same as transverse)
M	Bending moment
m	Meter
M	Subscript "mean"
Max	Maximum
ml	Milliliter
MIL	Military
Min	Minimum
mm	Millimeter
N	Cycles to failure
NSR	Notch strength ratio
NTS	Notch tensile strength
OQ	Oil quench
ppm	Parts per million
pt	Point; part

r	Radius
RA	Reduction in area; Rockwell hardness A scale
RB	Rockwell hardness B scale
RC	Rockwell hardness C scale
rpm	Revolutions per minute
RT	Room temperature
SA	Solution anneal
sec	Second
S-N	S = stress; N = number of cycles
Spec	Specifications; specimen
ST	Solution treat; short transverse
STA	Solution treated and aged
T	Transverse
t	Thickness; time
Temp	Temperature
typ	Typical
Var	Variable
VHN	Vickers hardness number
W	Width
WQ	Water quench

CONVERSION FACTORS

To Convert	To	Multiply By
angstrom units	millimeters	1×10^{-7}
Btu/lb/°F	cal/g/°C	1
Btu/ft²/sec/°F-inch	cal/g/cm²/sec/°C-cm	1.2404
circular mil	square centimeters	$5.067\ 075 \times 10^{-6}$
cubic feet	cubic meters	0.028 317
cubic feet/minute	liters/second	0.4720
cubic inches	cubic centimeters	16.387 162
feet	meters	0.304 800 609
foot-pounds	kilogram-meters	0.138 255
gallons (U.S.)	liters	3.785 411 784
inches	millimeters	25.4
ksi (thousand pounds per square inch	kilograms/square millimeter	0.70307
microns	millimeters	0.001
mils	millimeters	0.0254
ounces (avoir.)	grams	28.349 527
ounces (U.S. fluid)	milliliters	29.5729
pounds (avoir.)	kilograms	0.453 592 37
pounds/foot	kilograms/meter	1.488 16
pounds/cubic foot	grams/cubic centimeter	0.016 018 463
square feet (U.S.)	square meters	0.092 903 41
square inches (U.S.)	square centimeters	6.451 625 8

Temperature in °C = (°F – 32) (5/9)

Temperature in °K = °C + 273.15

Chapter 1

GENERAL INFORMATION

1.1 Inconel Alloy 718 (also known as Inconel 718 and Alloy 718) is a wrought, age-hardenable nickel-chromium base alloy introduced by the Huntington Division of the International Nickel Co. in 1959. This alloy was developed primarily for use at medium high temperatures up to 1300° F (704° C) to fill a need for a wrought material with good weldability. The sluggish response of the alloy to age hardening permits annealing and welding without spontaneous hardening during heating and cooling. The alloy can be readily welded in the annealed or age-hardened condition (refs. 1.1, 1.2).

1.2 Inconel Alloy 718 exhibits exceptionally high yield, tensile, creep, and creep-rupture strength at temperatures up to 1300° F (704° C). The alloy also has good properties in the cryogenic temperature range. Its slow aging response is of great benefit in fabrication processes such as forging and forming.

1.3 Typical areas of application for Inconel Alloy 718 are in lightweight welded assemblies in aircraft turbojet engines and for fuel/oxidizer injector plates, forged rings, thrust-chamber jackets, bellows and tubing for liquid-oxygen-type rocket engines (refs. 1.2, 1.4).

1.4 <u>General Precautions</u>

1.41 Optimum heat treat procedures are dependent upon the chemical composition, particularly the aluminum content.

1.42 The properties and the microstructure of the alloy are strongly influenced by heat treatment and the chemical composition.

1.43 The alloy is not recommended for gaseous-hydrogen tankage because of susceptibility to embrittlement (ref. 1.5).

Chapter 1 - References

1.1 The International Nickel Co., "Inconel Alloy 718, Age-Hardenable Nickel-Chromium Alloy," Basic Data, September 1960.

1.2 H.J. Wagner and A.M. Hall, "Physical Metallurgy of Alloy 718," DMIC Report 217, June 1965.

1.3 The International Nickel Co., "Inconel Alloy 718," February 1968.

1.4 Alloy Digest, "Inconel 718, Age-Hardenable Nickel-Chromium Alloy," (Filing Code: Ni-65), Engineering Alloys Digest, Inc., April 1961.

1.5 J.E. Campbell, "Effects of Hydrogen Gas on Metals at Ambient Temperature," DMIC Report S-31, April 1970.

1.6 Aerospace Structural Metals Handbook, J.G. Sessler and V. Weiss, Eds., AFML-TR-68-115, 1971 Edition.

Chapter 2

PROCUREMENT INFORMATION

2.1 General. Inconel Alloy 718 is available in the form of sheet, rod, bar, shapes, machined shafts, tube, plate, and forgings. Investment castings (718C) are also available in the aged condition.

2.2 Procurement Specifications

2.21 NASA Specifications. None.

2.22 Specifications that apply to Inconel Alloy 718 are listed in table 2.22 for various products.

2.23 Specifications issued for this alloy by a number of companies are listed in table 2.23.

2.3 Comparison of Specifications

Specifications for Inconel Alloy 718 have been issued by SAE and by a number of companies that intend to use the alloy for different types of applications. These applications are sometimes mentioned in the specifications as indicated in the following excerpts (ref. 2.2):

2.31 AMS 5596C. Application: Primarily for parts, such as cases and ducts, requiring high resistance to creep and creep rupture up to 1300° F (704° C) and oxidation resistance up to 1800° F (982° C), particularly those parts which are formed and then heat treated to develop required properties.

2.32 RBD 170-101 (Rocketdyne). Scope: This material is a nickel-base heat-resistant alloy intended primarily for parts requiring high short-time tensile strength up to 1000° F (538° C) and oxidation resistance to 1800° F (982° C). It has good cryogenic properties and better weldability than other age-hardenable nickel-base alloys.

2.33 EMS-581c (AiResearch). Application: Primarily for parts requiring high strength and corrosion resistance at both cryogenic and elevated temperatures, particularly those which are machined and welded and then heat treated to develop required properties. Material has good oxidation resistance up to 1800° F (982° C), but is useful at temperatures above 1200° F (649° C) only when stresses are low.

2.34 The properties of the alloy are dependent upon the specific chemical composition and heat treat procedures employed. Thus company specifications are becoming more restrictive regarding chemistry and may require widely differing heat treatments depending upon the particular application.

2.4 Major Producers of the Alloy (United States only)

2.41 Inconel Alloy 718 was developed by:

Huntington Alloy Products Division
International Nickel Company, Inc.
Huntington, West Virginia

2.42 Other producers, however, have been licensed to produce the composition under their own trade names, for example:

Allegheny Ludlum Steel Company
Allvac Metals Company
Armco Steel Corporation
Cameron Iron Works
Carpenter Technology, Inc.
Crucible Steel Company of America
Eastern Stainless Steel Company
Firth Sterling Company
Howmet Corporation
Latrobe Steel Company
Martin Metals Company
Republic Steel Corporation
Rodney Metals/Teledyne Corporation
Union Carbide Corporation
Universal-Cyclops Steel Corporation.

2.5 Available Forms, Sizes, and Conditions

2.51 This alloy is available as mill products in the form of hot rolled and cold rolled sheet, hot rolled plate, hot finished rods and bars, hot rolled shapes, machined shafts, cold drawn seamless tube, and forgings. Investment castings are available as Inconel 718C in the aged condition (ref. 2.3).

TABLE 2.22. — AMS Procurement Specifications

Source	Ref. 2.1	
Alloy	Inconel Alloy 718	
Product	Condition	Spec. No.
Investment castings	Vac. melted, sol. and prec. treated	5383
Tubing, seamless	Con. elect. or vac. melted, 1750° F sol. treated	5589
Tubing, seamless	Con. elect. or vac. melted, 1950° F sol. treated	5590
Plate, sheet, and strip	Con. elect. or vac. melted, sol. ht-treated	5596C
Plate, sheet, and strip	Con. elect. or vac. melted, sol treated 1950° F	5597A
Bars, forgings, and rings	Con. elect. or vac. melted, sol. heat-treated	5662B
Bars, forgings, and rings	Con. elect. or vac. melted, sol. and prec. ht-treated	5663B
Bars, forgings, and rings	Con. elect. or vac. melted, sol. treated 1950° F	5664A

TABLE 2.23. — Company Specifications

Source	Ref. 2.2
Alloy	Inconel Alloy 718
Company	Specification
Aerojet-General	AGC-44152
AiResearch	EMS-581C
General Electric	B50T69-S6
General Electric	C50T79 (S1)
Pratt and Whitney	PWA 1009-C
Rocketdyne	RB0170-101

Chapter 2 - References

2.1 SAE Aerospace Material Specifications, Society Automotive Eng., New York, latest Index, May 1971.

2.2 H. J. Wagner and A. M. Hall, "Physical Metallurgy of Alloy 718," DMIC Report 217, June 1, 1965.

2.3 "Handbook of Huntington Alloys," The International Nickel Co., Inc., Third Edition, January 1965.

Chapter 3

METALLURGY

3.1 Chemical Composition

3.11 Nominal chemical composition of Inconel Alloy 718, in percent (ref. 3.18)

Cr	18.6	Al	0.4
Fe	18.5	Mn	0.20
Cb	5.0	Si	0.20
Mo	3.1	C	0.04
Ti	0.9	Ni + Co	Balance

3.12 Chemical composition limits (ref. 3.1)

Ni	50.00 – 55.00	B, max	0.006
Cr	17.00 – 21.00	Co, max	1.00
Cb	4.75 – 5.50	Mn, max	0.35
Mo	2.80 – 3.30	Si, max	0.35
Ti	0.65 – 1.15	Cu, max	0.30
Al	0.20 – 0.80	P, max	0.015
C, max	- 0.08	S, max	0.015
	Fe - Balance		

3.121 The chemical composition of this alloy differs from that of other nickel-base alloys in its class by the substitution of columbium for much of the aluminum and titanium and the introduction of nearly 20 percent iron. These differences reduce the high temperature capabilities of the alloy but improve its welding characteristics (ref. 3.4).

3.122 The chemical composition and heat treatment of the alloy have a marked influence on its properties and microstructure. The complexity of the interrelationship among these factors is still being studied, and specifications for chemical composition and heat treatment have undergone many changes since the alloy was first developed. Figures 3.1 and 3.2 show the effect of aluminum content on the room temperature tensile properties of the alloy when annealed at 954° C (1750° F) and 1066° C (1950° F), and then aged at various temperatures.

3.2 Strengthening Mechanisms

3.21 General. The alloy is age-hardened by the precipitation of submicroscopic particles, the γ' (gamma prime) phase corresponding to $Ni_3(Cb, Mo, Ti)$ or $Ni_3(Cb, Mo, Al, Ti)$. The lattice parameter of the precipitated phase is about 0.8 percent larger than the lattice parameter of the fcc matrix. The resulting coherency strains account for most of the strengthening which occurs. Aging for long times or at higher temperatures transforms the metastable γ' to the orthorhombic Ni_3Cb, which is stable. Conditions for formation of these phases are shown in the isothermal transformation diagram presented in figure 3.3, with double aging treatment superimposed.

Recent studies by Cometto (see reference 3.4) have indicated that this alloy precipitates a metastable γ' phase based on the Ni_3Cb composition, but with a body-centered tetragonal Ni_3V structure. Upon aging at 1400°F (760°C) for 10 hours, furnace cooling at 100°F/hour (38°C/hr) to 1200°F (649°C), holding 8 hours, and air cooling, the lattice constants of the γ' phase were found to be:

$$a_0 = 3.624 \times 10^{-7} \text{ mm}$$

$$C_0 = 7.406 \times 10^{-7} \text{ mm}$$

$$a_0 / C_0 = 2.044$$

Both the metastable Ni_3Cb γ' and the orthorhombic Ni_3Cb are made up of the same type of atom layers, though apparently they differ in stacking sequence. The transformation to γ' occurs by a simple rearrangement of atoms on existing lattice sites, and occurs rapidly and uniformly because it is not necessary to nucleate a new lattice. The individual γ' particles are disc-shaped or in the form of platelets (see figure 3.4) and lie on the [100] matrix planes. The C_0 axis of the γ' structure is perpendicular to the plane of the discs. This relationship results in three orientations of γ' particles delineating three [100]-type γ planes (ref. 3.4).

This analysis can be used to explain the reason why double-aging results in higher strength than single aging. Apparently, to get maximum strengthening, it is necessary to precipitate as much γ' as possible without overaging, that is, without transforming from the bcc tetragonal γ' to the orthorhombic Ni_3Cb. High temperatures and long times favor the latter situation.

A detailed discussion of this subject may be found in references 3.4, 3.6, and 3.19. It is indicated that more investigations of the complex interreactions in the alloy need to be conducted before a full understanding of the mechanisms involved can be obtained.

3.22 Heat Treatment. High strength in the alloy is developed by a high-temperature annealing treatment, followed by a lower temperature aging treatment. The prescribed heat treatments to develop desired characteristics of the material have been modified considerably since its introduction. When first introduced, an annealing temperature of 954°C (1750°F) was recommended. Users were cautioned not to use annealing temperatures exceeding 982°C (1800°F). Since then, controversy has developed on what constitutes the best heat treatment. Now, annealing temperatures from 954°C to 1066°C (1750° to 1950°F) are commonly used.

It appears that optimum heat treatment procedures are dependent upon the chemical composition and on the specific properties desired. The response of Inconel Alloy 718 to heat treatment and the optimization of heat treatments for improved properties of wrought and cast alloy have been investigated extensively by Rocketdyne (ref. 3.17). The heat treatments recommended by the International Nickel Company (ref. 3.2) are given below.

3.221 For Optimum Tensile Properties (where stress rupture notch ductility is not required). All product forms:

Anneal at 1900° – 1950° F (1038°-1066° C) plus aging at 1325°F (718° C) for 10 hours; furnace cool to 1200° F (593° C) and hold for total aging time of 20 hours; air cool.

3.222 For Optimum Creep-Rupture Properties. All product forms:

Anneal at 1700° – 1850° F (927°-1010° C) plus aging at 1325° F (718° C) for 8 hours; furnace cool to 1150° F (621° C) and hold for 18 hours; air cool.

3.223 Typical heat treatments according to AMS and several company specifications, table 3.1.

3.224 The alloy contracts slightly during the aging process at a linear contraction rate of about 0.001 inch per inch (or cm per cm) (ref. 3.9).

3.225 The alloy is susceptible to sulfur embrittlement or attack by elements such as lead, bismuth, etc. It is therefore essential that all foreign material such as grease, oils, paints, etc. be removed by suitable solvents prior to heat treatment (ref. 3.9).

3.3 Critical Temperatures

3.31 Melting range. Melting begins at approximately 2250° F (1232°C) (ref. 3.4).

3.4 Crystal Structure. The crystallographic structure of Inconel Alloy 718 is quite complex due to the various interactions that take place in this alloy during its production and heat treatment. The meta-stable γ' strengthening phase is similar in many ways to the face-centered-cubic matrix γ phase from which it forms. It is reported (ref. 3.4) that this precipitated γ' phase is based on the ortho-rhombic Ni_3Cb composition, but has a body-centered tetragonal Ni_3V structure. Carbides (Cb, Ti) have been identified and also a Laves phase (cast material) which has been found to be isomorphous with Fe_2(Cb, Ti) (ref. 3.12).

3.5 Microstructure. The microstructure of Inconel Alloy 718 is strongly influenced by composition and heat treatment. The cast structure contains a Laves phase in addition to dendrites in the matrix. The Laves phase in the cast structure has been identified with the phenomenon of "freckles," a condition which apparently is detrimental to yield strength and ductility. Studies by Barker (ref. 3.13) have indicated that this phase in the cast structure is not affected by solution treatment at temperatures below 2100° F (1149° C). It appears that it can be dissolved at 2100° F (1149° C) or above. Eiselstein (ref. 3.11) has indicated that the Laves phase will also appear after long time exposure to relatively high temperatures. A typical "as-cast" structure, showing the Laves phase, is given in figure 3.5

Wrought bar has a microstructure typical of wrought nickel base alloys. Aging of the annealed structure at temperatures from 1300° to 1400°F (704° to 760°C) precipitates the γ' phase which is not visible in the optical microscope. After overaging, this phase transforms to the stable orthorhombic Ni_3Cb (ref. 3.4), which precipitates at the grain boundaries. The microstructure of Inconel Alloy 718 is discussed in greater detail in reference 3.4.

3.6 Metallographic Procedures

3.61 Macro-specimens. The degree of surface preparation is largely dependent upon the nature of the examination and the type of etchant to be employed. Rough grinding on an abrasive wheel is usually adequate for small samples. Large specimens may be prepared on a surface grinder. Recommended solutions for macro-etching are given in table 3.2. Macro-etching can be hastened by warming the sample with hot water prior to etching. Large samples may be conveniently handled by making a raised rim or dam around the edges with plastic tape and then flooding the surface with the etchant (ref. 3.15).

3.62 Micro-specimens. A suitable specimen, either unmounted or mounted in plastic with a flat surface is prepared as follows (ref. 3.15):

A. Grinding. Hand- or power-driven disk grinders carried through a series of emery papers of successively increasing fineness. Commonly used papers are Nos. 3, 2, 1, 0, 00, 000. Each successive grind should be at right angles to the preceding cut and should remove all scratches left by the preceding (coarser) grit.

B. Rough Polishing. Specimens ground through No. 000 paper may be wet polished on a broadcloth-covered wheel, using levigated alumina (particle size about 5 µm) suspended in water. A much faster method utilizes a silk or nylon covered wheel impregnated with diamond dust paste (particle size about 3 µm). If this method is employed, preparation need only consist of grinding through No. 1 paper, thereby eliminating three grinding steps.

C. Final Polishing. Fine scratches are removed on a microcloth or duracloth covered wheel using gamma alumina powder (less than 0.1 µm size) suspended in water (ref. 3.15).

D. Etching. The recommended solution for microetching of Inconel Alloy 718 samples is given in table 3.2.

TABLE 3.1. — Typical Heat Treatments

Source	Refs. 3.1, 3.4, 3.10							
Alloy	Inconel Alloy 718							
Specification Identification	Company	Annealing temp, °F	Annealing temp, °C	1st Aging temp °F	1st Aging temp °C	2nd Aging temp, °F	2nd Aging temp, °C	Aging Method (a)
AMS 5596C	Society of Automotive Engineers	1775	966	1325	718	1150	621	I or II
AMS 5597A		1950	1066	1400	760	1200	649	I or II
B50T69-S6	General Electric Company	1700	927	1325	718	1150	621	I
C50T79(S1)	General Electric Company	1800	982	1325	718	1150	621	I
PWA 1009-C	Pratt & Whitney Aircraft	1750	966	1325	718	1150	621	I or II
EMS-581c	AiResearch	1950	1066	1350[a]	718	1200	649	I
RB0170-101	Rocketdyne	1950	1066	1400	760	1200	649	III
AGC-44152	Aerojet-General	1950	1066	1350	732	1200	649	IV

(a) I: Hold 8 hours at first aging temperature, furnace cool at 100° F (38° C) per hour to second aging temperature. Hold 8 hours, air cool.

II: Hold 8 hours at first aging temperature, furnace cool to second aging temperature. Hold at second aging temperature until total time elapsed since the beginning of the first aging is 18 hours.

III: Hold 10 hours at first aging temperature, furnace cool to second aging temperature. Hold at second aging temperature until total time elapsed since the beginning of the first aging is 20 hours.

IV: Same as II, but first aging time may be 8 to 10 hours.

[a] 1400° F (760° C) on certain heavy forgings.

TABLE 3.2. – Etching Solutions for Revealing Structure

Source	Ref. 3.15	
Alloy	Inconel Alloy 718	
Use	Solution - Composition(a)	Remarks
Macrostructure	Lepito's: 15 g $(NH_4)_2SO_4$ in 75 ml H_2O 250 g $FeCl_3$ in 100 ml HCl, mix and add 30 ml HNO_3	Etching time 30-120 seconds. Macro-etch for general surface and weld structure.
	Hydrochloric-Peroxide: H_2O_2 (30%) 1 part HCl 2 parts H_2O 3 parts	Must be freshly mixed. Use hot water to speed reaction. Any stains formed may be removed with 50% HNO_3. Macro-etch for revealing grain structure.
Microstructure	Chromic Acid: CrO_3 5 g H_2O 100 ml	Electrolytic micro-etch for grain boundaries. Use 0.2 to 0.5 amps/cm^2 for 30 to 50 seconds. Specimen is anode a platinum or Inconel 600 cathode.

(a) Use concentrated acids.

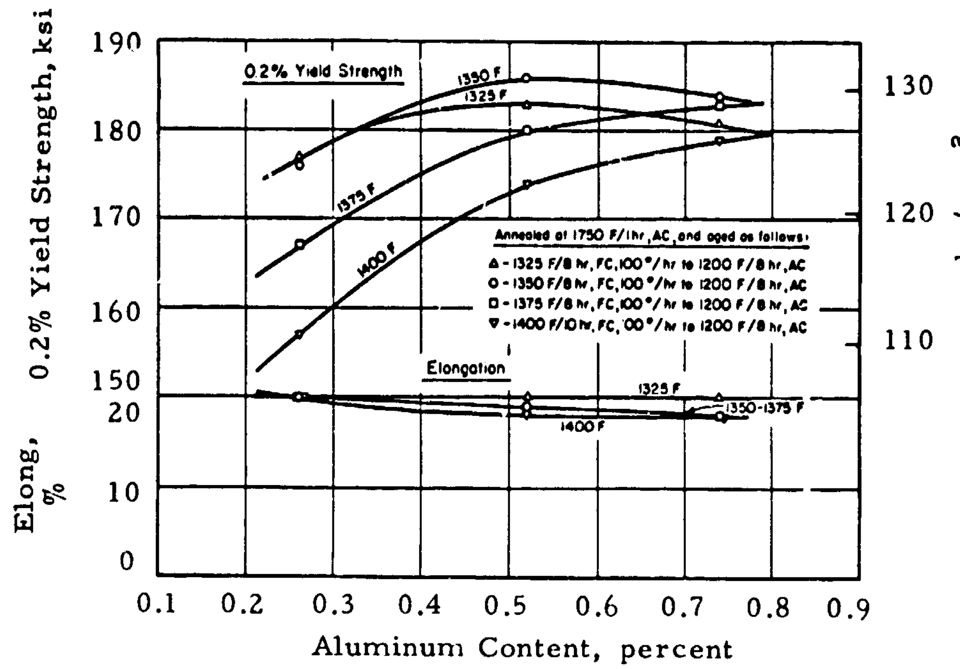


FIGURE 3.1. – Effect of aluminum content on room temperature yield strength of hot rolled bar stock annealed at 1750° F (954° C). (Ref. 3.4)

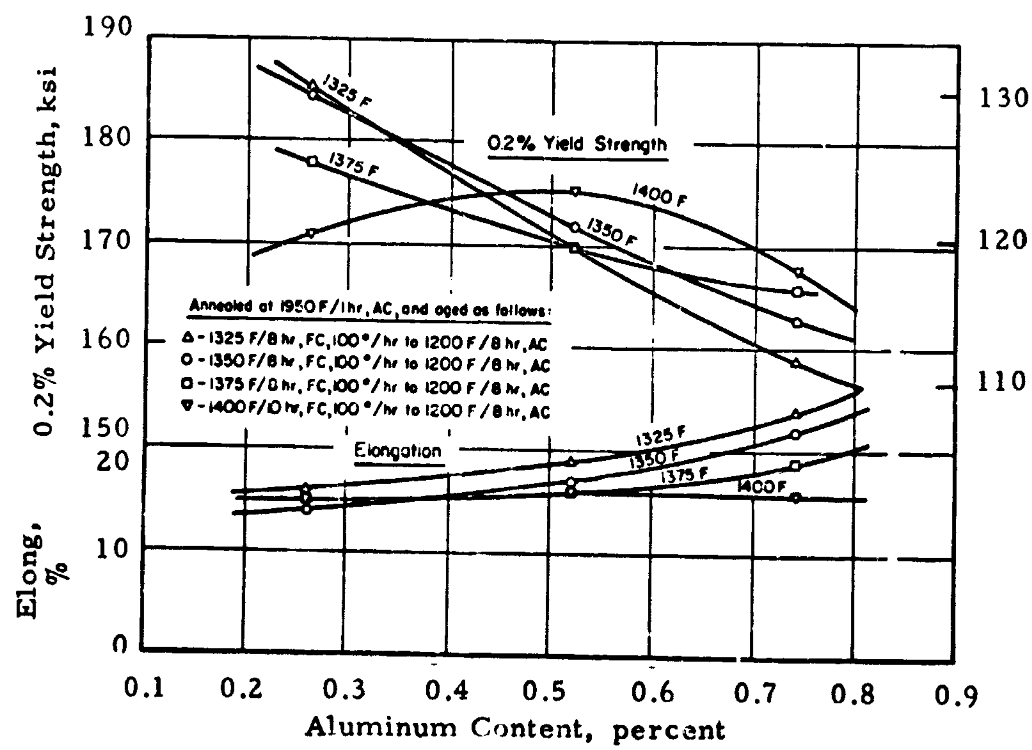


FIGURE 3.2. – Effect of aluminum content on room temperature yield strength of hot rolled bar stock annealed at 1950° F (1066° C). (Ref. 3.4)

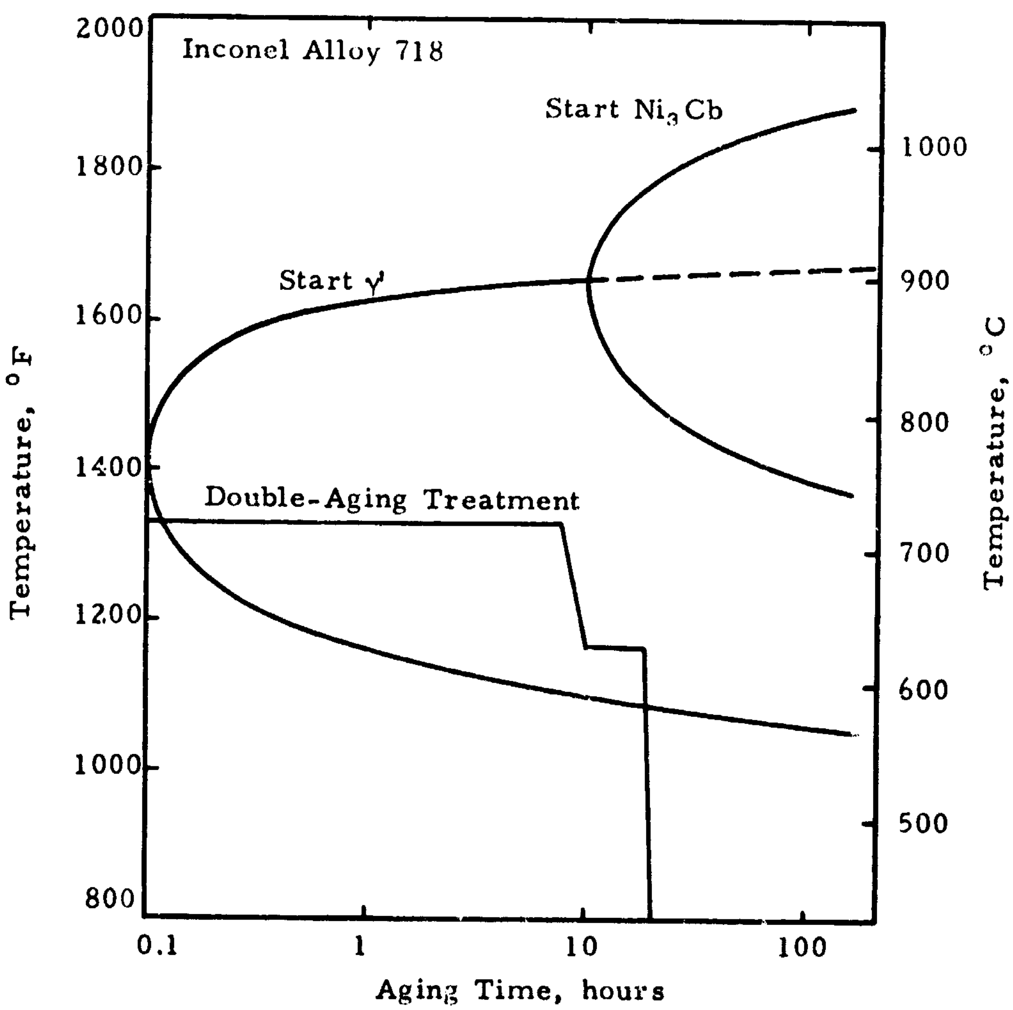
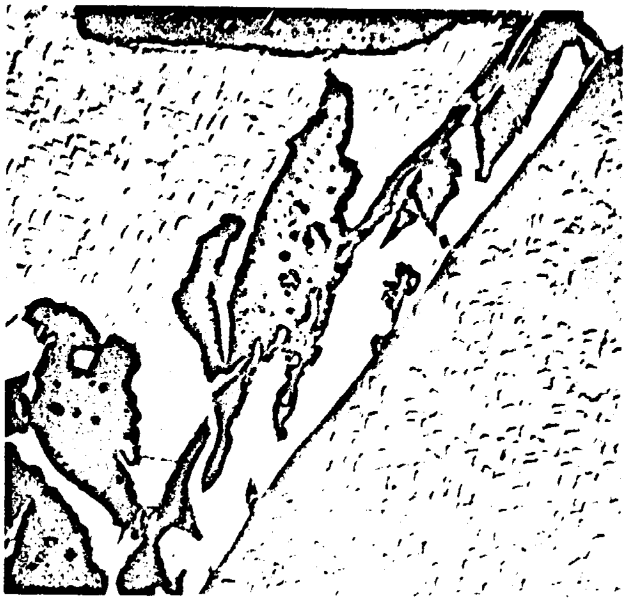


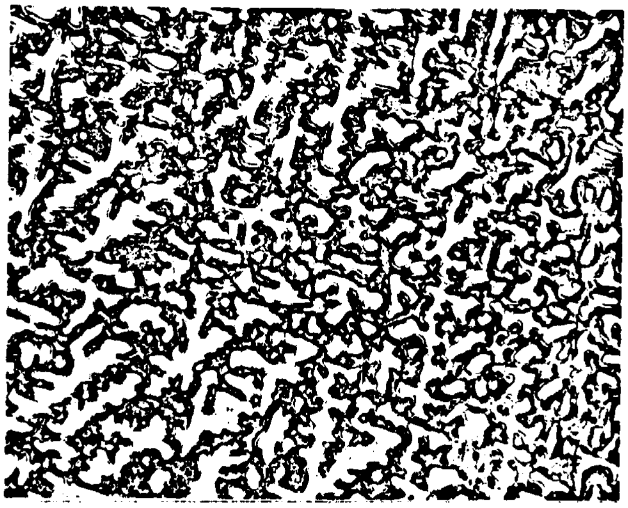
FIGURE 3.3 – Isothermal transformation diagram for γ' and Ni_3Cb phases, with double-aging treatment superimposed.

(Ref. 3.11)



17,500 X (reduced approximately 20% in printing)

FIGURE 3.4. – Alloy 718 annealed at 2200°F (927°C) for 1 hr, cooled to 1400°F (760°C), held 4 hr, and water quenched. (Ref. 3.4)



100X; overetched in chromic acid (reduced approximately 20% in printing)

FIGURE 3.5. – Structure of toe of cast 718 ingot with 5.4% Cb + Ta. (Ref. 3.4)

Chapter 3 - References

3.1 SAE Aerospace Materials Specification, AMS 5596C, Society Automotive Engineers, revised Nov. 1, 1968.

3.2 The International Nickel Co., Huntington Div., "Inconel Alloy 718," February 1968.

3.3 General Electric Co. (Large Jet Engine Dept.), Materials Specification B50T69-S6, Inconel 718, December 1964.

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3.9 E.H. Schmidt, "Correlation of Experimental Data for Fabrication of Inconel 718," Rocketdyne/North American, Lab. Report No. RD-62-10, July 1962.

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3.12 M. Kaufman and A.E. Palty, "Phase Structure of Inconel 718 and 702 Alloys," Trans. AIME, 221, 1253 (1961).

3.13 J.F. Barker, Inconel 718 Phase Study Review," General Electric Co., DM-61-183, July 1961.

3.14 E.H. Schmidt and C.S. Shira, "Correlation of Experimental Data for Fabrication of Inconel 718," Lab. Report No. RD 62-10, Rocketdyne/North American, July 1962.

3.15 The International Nickel Co., Huntington Div., "Handbook of Huntington Alloys," Third Edition, January 1965.

3.16 A.M. Sabroff et al., "A Manual on Fundamentals of Forging Practice," Suppl. to ML-TDR-64-95, December 1964.

3.17 Rocketdyne/North American, MFS-18285, MFS-18502, and MFS-90756 in "Metallurgy: A Compilation," NASA SP-5940 (01), 1970.

3.18 1971 SAE Handbook, Society of Automotive Engineers, New York.

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Chapter 4

PRODUCTION PRACTICES

4.1 General. Production practices that are considered to be conventional for heat-resistant alloys are used in the production of Inconel Alloy 718 mill products. These practices are very similar to those used for the production of stainless steel products in wrought forms. Primary deformation processes such as rolling, forging, extrusion and drawing are employed to reduce an ingot or billet to a standard mill product (e.g., sheet, plate, bar, tube, etc.). Hot working temperatures are generally higher than the temperatures used for steel because the nickel-base alloys retain their strength to higher temperatures (refs. 4.2, 4.6).

4.2 Manufacture of Wrought Products

4.21 Melting. An important factor in the production of high quality wrought products is the making of a good casting in the form of an ingot. The ingot will not be sound unless the melting procedures are carefully controlled. The Inconel Alloy 718 is always vacuum melted. Procedures employed include (a) induction melting in air followed by consumable arc remelting, (b) vacuum induction melting (sometimes followed by consumable arc remelting or double-vacuum induction melting). Vacuum-induction melting prevents uncontrolled losses of easily oxidized elements (such as Ti and Al), removes gaseous impurities, and permits stricter control of final composition. All of these factors result in more consistent properties than are obtained by air melting. Also, consistently better 100-hour creep-rupture strength is usually obtained over the entire temperature range of importance by employing vacuum melting techniques.

Consumable electrode, vacuum-arc melting volatilizes impurities and also breaks down and disperses nonmetallic inclusions. Segregation and unsoundness at the center of the ingot are reduced, which results in improved hot working characteristics, particularly when vacuum-induction-melted ingots are employed as electrodes for remelting by the consumable electrode process in vacuum (refs. 4.1, 4.2, 4.3).

4.22 After solidification, the cast ingots are converted to wrought products by conventional methods that are normally used for the working of nickel-base alloys. The high-temperature strength of these alloys, however, requires that equipment for hot working must be more powerful than for equivalent sections of carbon steel. The lower temperature limit of the hot working range is usually determined by the limitations of the equipment and the upper limit must be safely below the melting point. The hot working range is very narrow so that frequent reheating is necessary during the ingot breakdown.

Ingots are conventionally reduced to blooms, billets, or large bars by the use of steam-driven cogging hammers, vertical presses, or blooming mills. Extrusion is also being used to a limited extent. After the cogging operation and prior to further work or finishing, the billet is "conditioned" to remove surface defects. Common conditioning methods are swing-frame grinding, scarfing (gouging with a burning oxygen stream), or machining. Heat-resistant alloys are relatively difficult to scarf unless a flux is added to the oxygen stream since the metal does not burn out spontaneously as in the case of carbon steel. Sometimes, grinding or scarfing is done "hot" while the billet is being cogged. Cracks may develop which would prevent further working unless they are removed immediately. Conditioning by machine is faster than grinding, but has the disadvantage that sound metal is also removed along with the defective areas, whereas in swing-frame grinding a skillful operator can confine his efforts primarily to the areas that need attention (refs. 4.1, 4.2, 4.6).

4.23 Many types of finishing processes are employed in the production of heat-resistant alloys. After conditioning, blooms and billets are reduced to bars, rounds, squares, or flats on hot rolling mills. Subsequent to the rolling process, bar sections are usually stress relieved or heat treated and given a final processing by pickling, cold drawing, centerless grinding, or a combination of these processes. Plate, sheet, and strip are produced in a conventional manner, usually on "hand" mills where the work is passed through the rolls and then back over the rolls by hand. A great deal of flexibility is inherent in this process (ref. 4.1). The primary deformation processes (rolling, extrusion, forging, and drawing) used for the production of nickel-base alloy mill product forms are discussed in considerable detail in references 4.5 and 4.6.

4.3 Cast Products. Although Inconel Alloy 718 is used primarily in wrought forms, the alloy is also used in the form of castings (e.g., engine frames). The casting composition is essentially the same as that of the wrought alloy and it is usually vacuum melted to maintain cleanliness (ref. 4.4).

Chapter 4 - References

4.1 C. T. Evans, Jr., "Production and Fabrication of Heat Resistant Alloys from the Producers' Standpoint," Symposium on Utilization of Heat-Resistant Alloys, American Society for Metals, 1954.

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4.6 Metals Handbook, Vol. 4, "Forming," 8th Edition, American Society for Metals, Metals Park, Ohio, 1969.

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Chapter 5

MANUFACTURING PRACTICES

5.1 General. The slow aging response of Inconel Alloy 718 is beneficial in the fabrication of the alloy. Distortion of fabricated assemblies is kept at a minimum and formability is maintained at a high level because low annealed hardness can be obtained by air cooling from the annealing temperatures. It is reported (ref. 5.1) that strain-age cracking is practically nonexistent in this alloy because of its sluggish aging response. Forgeability of the alloy is reported to be as good as that of V-57 for blades and of Waspaloy for wheels (ref. 5.1).

5.2 Forming. Nickel-base alloys have been fabricated both by primary and secondary forming techniques that are similar to those used for the forming of stainless steels. Primary deformation processes are those designed to reduce ingots or billets to standard mill product forms and these include processes such as rolling, forging, extrusion, and drawing. Mill products may be converted to more useful shapes by secondary deformation processes. All of the conventional techniques used for this purpose have been applied successfully to nickel-base alloys, including the following:

Brake bending	Tube forming
Deep drawing	Roll forming and bending
Spinning and shear forming	Dimpling
Drop hammer forming	Joggling
Trapped-rubber forming	Blanking
Stretch forming	Sizing

Most nickel-base alloys can be worked at both room and elevated temperatures. The hot working temperatures are generally higher than those used for steel because these alloys retain their strengths to higher temperatures. The ductility of most nickel-base alloys compares with that of stainless steels at room temperature. Thus, secondary working can usually be performed with conventional processing techniques. References 5.4 and 5.11 are recommended as excellent state-of-the-art summaries of the present status of deformation processing of nickel-base alloys.

Studies at McDonnell Aircraft Corp. (ref. 5.2) have indicated that the alloy has good formability characteristics in the annealed condition, using standard production rubber forming methods. These studies included measurements of total elongation, uniform elongation, and bend tests. Also, Guerin rubber forming and impact rubber forming methods were used to form 0.048-inch specimens on a stretch flange radius of 6.05 inches and a shrink flange radius of 9.95 inches. These specimens were formed around a 0.090-inch bend radius. (Note: 1 inch=25.4 mm.) Various flange lengths were formed to determine the amount of flange distortion that would result from each configuration. It was found that both forming methods resulted in formed parts with very nearly the required production tolerances. A minimum amount of restriking and hand would be necessary to smooth out any deformities to produce parts to production tolerances. Typical results of the forming tests are given in table 5.1.

Bend tests on 0.048-inch annealed sheet indicated a minimum bend radius of 0.031 inch for specimens bent perpendicular to the rolling direction and 0.047 inch for specimens bent parallel to the rolling direction of the sheet (ref. 5.2).

Examples of the types of failures usually encountered in various sheet forming processes are shown in table 5.2.

5.3 Forging. Hot working of Inconel Alloy 718 is performed in the range of temperatures from 2100° F down to 1800° F (1149° to 982° C). In this range, the alloy has high strength (F_{ty} = 16 ksi (11.2 kg/mm²)) and offers considerable resistance to deformation during hot working. Thus, the forces required for forging of the alloy are somewhat higher than those required for most other nickel-base alloys. In the last operation, the metal should be worked uniformly with a gradually decreasing temperature, finishing with some reduction in the 1800°-1850° F (982° to 1010° C). This hot-cold work helps to improve the strength of the forging (ref. 5.3).

Care should be taken to avoid overheating the metal by heat buildup due to working. The piece should be reheated when any portion has cooled below 1800° F (982° C). Air cooling is preferred to water quenching after forging (ref. 5.3).

All tools and dies should be preheated to about 400° to 500° F (204° to 260° C) to avoid chilling the metal. The stock should be charged into a furnace controlled at 2025° to 2075° F (1117° to 1134° C). The metal should be placed on clean steel rails or in a sulfur-free refractory and should be protected against contamination from foreign materials. Fuels used should be low in sulfur content.

The forging stock is brought up to temperature and soaked long enough to insure uniformity, then pulled from the furnace. Prolonged soaking, while not too harmful, is not preferred. To avoid duplex or germinated grain structure, the material should be uniformly reduced. If possible, a final reduction of 20 percent minimum should be used for open die work and 10 percent for closed die practices.

If ruptures appear on the surface during forging, they must be removed at once, either by hot grinding or cooling the work and cold overhauling. When upsetting rod stock, the edges should be given a 1/4-inch (6.35mm) chamfer or radius to prevent localized chilling. This also avoids the formation of a ring-like impression on the faces of the upset disc (ref. 5.3).

During forging of nickel-base alloys, a lubricant is necessary between the part and die to reduce their natural tendency to seize and gall. Lubricants containing sulfur are undesirable. Commonly used lubricants are mixtures of graphite and oil, but materials such as glass, mica, sawdust, and asbestos have also been used with varying degrees of success (ref. 5.4).

5.4 Machining. The alloy is readily machined in the annealed or the age-hardened condition. The aged material gives better chip action on chip-breaker tools and produces a better finish. The annealed condition, however, will give a slightly longer tool life and requires slightly less power than is required for Inconel Alloy X-750.

Typical lathe turning tool dimensions are presented in table 5.3. Recommended parameters for machining the alloy with high speed steel tools are given in table 5.4.

Drills should be ground with 130° to 135° included point angle. For reaming, narrow land reamers ground to a 30° angle chamfer and a 5° to 10° face rake are recommended. Standard milling cutters with a 5° (primary) and 10° (secondary) relief back of the cutting edges, to prevent drag, may be used. For thread tapping, standard taps ground to a hook angle of about 7° to 10° have been used successfully. Threads can be chased with tangent, milled, or hobbed type insert thread chasers ground to 15° rake, 5° relief, and 20° throat angle.

Chlorinated sulfurized oils should not be used when drilling, form cutting, or reaming. For general turning, a water-base chemical coolant is recommended. Oils and coolants should be removed completely prior to any heating operations (ref. 5.3).

TABLE 5.1. – Forming Tests on 0.048-Inch (1.22-mm) Sheet

Source	Ref. 5.2	
Alloy	Inconel Alloy 718 (Annealed)	
Operation	Flange Length	Remarks
7000-ton Hydropress	1.40 stretch flange 0.86 shrink flange	Three wrinkles in shrink flange, diagonal buckle in stretch flange ends
7000-ton Hydropress 1/2-inch hard lead overlay with 5 soft lead straps (a)	1.40 stretch flange 0.86 shrink flange	No wrinkles in either flange; slight web warpage
Impact rubber formed 1/2-inch hard lead overlay	1.40 stretch flange 0.86 shrink flange	Slight web warpage; slight wrinkling of shrink flange and at ends of stretch flange
Impact rubber formed Soft lead strip overlay at shrink flange Restrike without overlay	1.60 stretch flange 1.06 shrink flange	Slight web warpage Small wrinkles present in shrink flange Slight warpage at one end of stretch flange
Impact rubber formed 1/2-inch hard lead overlay Reduced heavy shrink flange wrinkles by hand forming with soft lead straps Restrike 2 times Repeat above	1.60 stretch flange 1.06 shrink flange	Slight wrinkles not completely removed by hand working and restriking operations

(a) The hard lead overlay consisted of lead alloyed with 6% antimony.

(b) Note: 1 inch = 25.4 mm.

TABLE 5.2 – Types of Failure in Sheet-Forming Processes

Source	Ref. 5.6	
Alloy	Inconel Alloy 718	
Process	Cause of Failure: Splitting	Cause of Failure: Buckling
Brake forming	X	
Dimpling	X	
Beading		
Drop hammer	X	
Rubber press	X	
Sheet stretching	X	
Joggling	X	X
Liner stretching	X	X
Trapped rubber, stretching	X	X
Trapped rubber, shrinking		X
Roll forming		X
Spinning		X
Deep drawing		X

TABLE 5.3. – Typical Lathe Turning Tool Dimensions

Source	Ref. 5.8	
Alloy	Inconel Alloy 718	
Type of Tool	High Speed Steel	Cemented Carbide
Back rake angle	0 to 8 degrees	0 to 8 degrees positive
Side rake angle	8 to 15 degrees	8 to 15 degrees positive
End relief angle	5 to 7 degrees	5 to 7 degrees (P) 8 to 10 degrees (S)
Side relief angle	5 to 7 degrees	5 to 7 degrees (P) 8 to 10 degrees (S)
End cutting edge angle	10 to 20 degrees	8 to 10 degrees
Side cutting edge angle	15 to 25 degrees	15 to 30 degrees
Nose radius	1/32 inch	1/32 inch

(P) Primary
(S) Secondary
1/32 inch = 0.8 mm.

TABLE 5.4. – Recommended Parameters for Machining with HSS Tools

Source	Refs. 5.7, 5.9			
Alloy	Inconel Alloy 718			
Operation	Condition (Hardness)	Speed sfm	Feed ipr	HSS Tool
Turning, single point	0.250 in depth of cut (Rb = 85)	12-18	0.010	T-5
	0.050 in depth of cut (Rc = 45)	15-20	0.008	M-36
Drilling	Unaged	10-12	0.004-0.007	M-36
	Aged	8-10	0.006-0.010	M-36
Threading	-	3.0-3.5	-	M-2, M-10
Tapping (50% thread engagement)	Unaged, aged	5-10	-	M-2, M-10
Reaming	-	6-8	-	M-2, M-10
Broaching	8°–10° rake angle	6	-	T-1, T-4, M-4

Note: 1 inch = 25.4 mm.

Chapter 5 - References

5.1 J.F. Barker, "A Superalloy for Medium Temperatures," Metal Progress, 81 (5), May 1962.

5.2 McDonnell Aircraft Corp., "Evaluation of Inconel 718, Age Hardenable Nickel-Chromium Alloy," Report A250, Ser. No. 1, December 1963.

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5.4 D.E. Strohecker et al., "Deformation Processing of Nickel-Base and Cobalt-Base Alloys," NASA TM X-53439, April 1966.

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5.12 International Nickel Company, "Fabricating Huntington Alloys," November 1967.

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Chapter 6

SPACE ENVIRONMENT EFFECTS

6.1 General. Nickel-base alloys are used successfully in both structural and nonstructural applications for launch vehicles and spacecraft. In general, these alloys are relatively insensitive to degradation under typical space environment conditions. The vapor pressures of these alloys are sufficiently high (table 6.1) so that the combined temperature—vacuum effects are negligible. Nuclear and space indigenous radiation induced defects do not appear to significanlty affect mechanical and physical properties, at room ambient and elevated temperatures, below accumulated doses of about 1×10^{19} neutrons/cm^2 or greater (ref. 6.2). At these high doses, slight embrittlement takes place, resulting in increases in hardness and in some physical properties and a decrease in creep rate. Fatigue properties do not appear to be affected significantly. When irradiated at cryogenic temperatures, the dose threshold may be lowered by one or two decades, but the probabilities of encountering doses on this order of magnitude are extremely remote except in the vicinity of nuclear reactors.

Elevated temperatures, hard vacuums, high energy radiations, and micrometeoroids can individually and collectively influence the surface characteristics of nickel-base alloys by desorption processes and erosion. These phenomena are of importance if optical properties, lubrication, certain electrical properties, etc. are critical design parameters . Sputtering of the surface by atomic or molecular particles can deteriorate surface finishes in a relatively short period. The sputtering process is associated with a minimum threshold energy value for atomic or molecular particles striking a material surface. Loss of metal by this mechanism can vary over a wide range and the greatest loss ($<100 \times 10^{-7}$ mm) may be expected during solar storms (ref. 6.4). However, loss of metal by sputtering has little structural significance, although it may seriously affect optical and emissive properties of the material surface.

Micrometeoroids can produce surface erosion similar to sputtering but on a more macroscopic scale, and may also produce punctures. They vary widely in mass, composition, velocity and flux; generalizations about rates of erosion and penetration, therefore, must be used with care. The predicted frequency of impact as a function of meteoroid mass is given in figure 6.1.

The surface erosion of nickel-base alloys due to corpuscular radiation is probably insignificant, amounting to something of the order of 250 nm per year. Indigenous space radiation, however, will tend to accelerate the removal of surface films on these alloys. The removal of such films might result in loss of lubricity and an increased propensity to "cold weld." The interaction of indigenous radiation with desorption gases might cause some spurious, transient electrical conditions if the alloy is used for electrical applications.

TABLE 6.1. – Evaporation Rates in Vacuum of Typical Elements Used in Aerospace Alloys (a, b)

Source	Ref. 6.14				
Element	Evaporation Rate, $g/cm^2/sec$				
	–100° C	0° C	100° C	250° C	500°C
Aluminum	1.2×10^{-81}	1.1×10^{-48}	2.0×10^{-33}	1.7×10^{-21}	6.5×10^{-12}
Titanium	$<10^{-99}$	2.5×10^{-60}	4.1×10^{-42}	7.4×10^{-28}	2.0×10^{-16}
Iron	$<10^{-99}$	6.8×10^{-64}	2.4×10^{-44}	4.8×10^{-29}	9.1×10^{-17}
Nickel	$<10^{-99}$	5.7×10^{-70}	1.3×10^{-48}	6.7×10^{-32}	1.7×10^{-18}
Copper	1.2×10^{-94}	1.4×10^{-56}	6.2×10^{-39}	4.0×10^{-25}	4.7×10^{-14}
Chromium	9.5×10^{-92}	1.0×10^{-54}	1.4×10^{-37}	3.8×10^{-24}	2.2×10^{-13}
Vanadium	$<10^{-99}$	1.9×10^{-87}	2.1×10^{-61}	5.0×10^{-41}	1.2×10^{-24}
Manganese	2.2×10^{-72}	1.1×10^{-42}	6.5×10^{-28}	3.8×10^{-18}	1.6×10^{-9}
Silicon	$<10^{-99}$	1.9×10^{-62}	3.6×10^{-43}	4.3×10^{-28}	5.5×10^{-16}
Magnesium	2.9×10^{-36}	5.3×10^{-20}	1.8×10^{-12}	1.3×10^{-6}	6.6×10^{-2}
Zinc	3.5×10^{-30}	5.1×10^{-16}	1.8×10^{-9}	2.3×10^{-4}	2.80

(a) The actual evaporation rate of each element in combination with others will be lower.

(b) The values may be in error by several orders of magnitude as they have been extrapolated from high-temperature data. The rates at low tempeatures will be considerably less than the values given in the table.

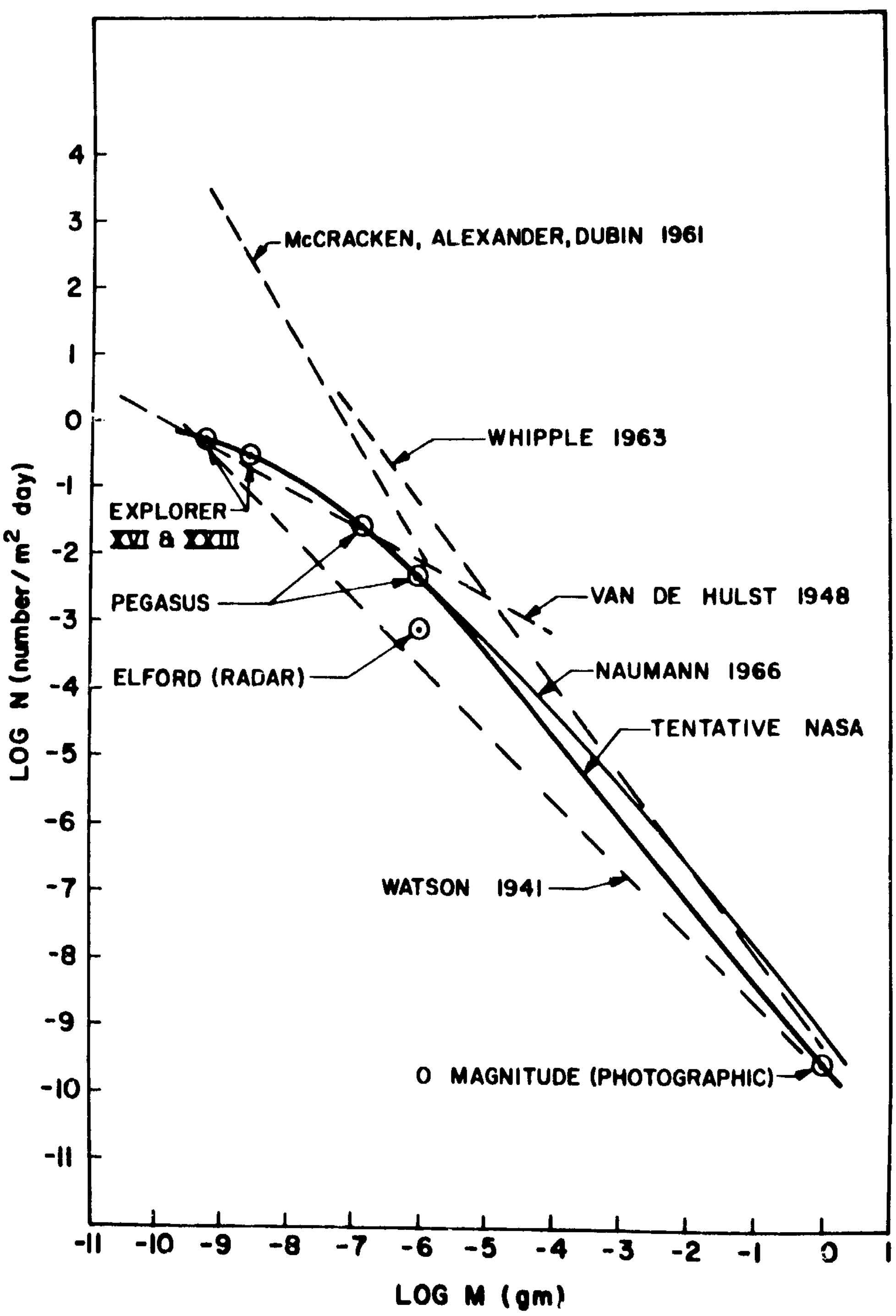

FIGURE 6.1. — Various estimates of meteoroid mass influx. (Ref. 6.3)

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Chapter 7

STATIC MECHANICAL PROPERTIES

7.1 Specified Properties

7.11 NASA Specified Properties. None.
7.12 AMS Specified Properties (ref. 7.1)
7.121 AMS minimum tensile requirements for alloy after 1750° F (954°C) anneal plus aging, table 7.121.
7.122 AMS minimum tensile requirements for alloy after 1950° F (1066° C) anneal plus aging, table 7.122.
7.123 AMS minimum tensile requirements for alloy investment castings, table 7.123.
7.124 AMS specified bend factors for annealed sheet, strip, and plate:

Thickness		Bend Factor	
≤0.050 inch	≤1.27 mm	1t	
0.050–0.187	1.27–4.75	2t	(ref. 7.1)

7.13 Military Specified Properties
7.14 Federal Specified Properties
7.15 ASTM Specified Properties

7.2 Elastic Properties and Moduli

7.21 Poisson's ratio at various temperatures, figure 7.21.
7.22 Young's modulus of elasticity, E.
7.221 Design value of E (ref. 7.16), 29.6×10^3 ksi (20.8×10^3 kg/mm²).
7.222 Typical values of E (ref. 7.13) –

70° F (21° C) 29.0×10^3 ksi (20.4×10^3 kg/mm²).
1400° F (760° C) 23.3×10^3 ksi (16.4×10^3 kg/mm²).

7.223 Effect of temperature on E of STA alloys, figure 7.223.
7.23 Compression modulus, E_c.
7.24 Modulus of rigidity (shear modulus), G
7.241 Typical value of G at various temperatures, figure 7.241.
7.25 Tangent modulus
7.26 Secant modulus

7.3 Hardness

7.31 AMS specified hardness for 1750° F(954° C) annealed plus aged products, see table 7.121.
7.32 AMS specified hardness for 1950° F(1066° C) annealed plus aged products, see table 7.122.
7.33 AMS specified hardness for investment castings, see table 7.123.

7.4 Strength Properties (see also Section 7.1)

7.41 Tension (see also tables 7.121, 7.122, and 7.123).
7.411 Design tensile properties
7.4111 Design tensile properties for all forms, table 7.4111.

7.4112 Effect of age hardening on yield strength, figure 7.4112.
7.4113 Effect of final aging temperature on room temperature properties of sheet, figure 7.4113.
7.4114 Typical tensile and impact properties for annealed and aged pancake forgings, table 7.4114.
7.4115 Effect of annealing temperature on room temperature tensile properties, figure 7.4115.
7.4116 Effect of cold work on room temperature tensile properties of sheet and strip, figure 7.4116.
7.412 Stress-strain diagrams (tension)
7.4121 Typical stress-strain curves (tension) at various temperatures for aged alloy, figure 7.4121.
7.413 Effect of low temperature on tensile properties.
7.4131 Effect of low temperatures on tensile properties of aged sheet, figure 7.4131.
7.4132 Effect of low temperatures on tensile properties of cold reduced and aged sheet, figure 7.4132.
7.414 Effect of elevated temperatures on tensile properties.
7.4141 Effect of temperature on ultimate yields strength of STA alloy, figure 7.4141.
7.4142 Effect of temperature on tensile yield strength of STA alloy, figure 7.4142.
7.4143 Effect of test temperature on tensile properties of cold rolled and aged sheet, figure 7.4143.
7.4144 Effect of room and elevated temperature on tensile properties of wrought sheet and bar, figure 7.4144.
7.4145 Effect of test temperature on tensile properties of hot rolled bar, figure 7.4145.
7.4146 Tensile properties of forgings at various temperatures for three different heat treatments, figure 7.4146.
7.4147 Effect of test temperature on tensile properties of investment castings, figure 7.4147.
7.4148 Effect of room and elevated temperatures on tensile properties of cast test bars, figure 7.4148.
7.415 Effect of irradiation on tensile properties (see reference 7.15).
7.42 Compression
7.43 Bending
7.44 Shear and torsion
7.45 Bearing
7.46 Fracture
7.461 Notch properties
7.4611 Notch strength of aged sheet at low temperatures, figure 7.4611.
7.4612 Notch strength of cold reduced and aged sheet at low temperatures, figure 7.4612.
7.4613 Net section strength of center notch fatigue cracked specimens compared to round notch fatigue cracked specimens, figure 7.4613.
7.4614 Sharp notch data for sheet at elevated temperatures, figure 7.4614.
7.462 Fracture toughness
7.4621 Net section strength and fracture toughness of aged forgings, figure 7.4621.

TABLE 7.121. – AMS Minimum Tensile Requirements for Alloy after 1750° F (954° C) Anneal plus Aging

Source	Ref. 7.1			
Alloy	Inconel Alloy 718			
Product/ Specification	Property	Room Temp.	1200° F (649° C) ≤0.025 in	1200° F (649° C) ≥0.025 in
Sheet, strip, and plate (c) AMS 5596	F_{tu}, ksi (kg/mm^2)	180 (127)	140 (98.4)	145 (102)
	F_{ty} (0.2% offset), ksi (kg/mm^2)	150 (105)	115 (80.9)	120 (71.7)
	e (2 in), %	12	5	
	Hardness, [illegible] (a)	36	-	
Bars, forgings, and rings AMS 5662B AMS 5663B	F_{tu}, ksi (k[illegible]mm^2) - L	185 (130)	145 (102)	
	(forgings) - LT	[illegible]	140 (98.4)	
	(bar) - T	180 (127)	140 (98.4)	
	F_{ty} (0.2% offset), ksi (kg/mm^2)	150 (105)	125 (87.9)	
	e (2 in), % - L	12	12	
	(forgings) - LT	10	10	
	(bar) - T	6	6	
	Hardness, BHN (a)	331	-	
Seamless tubing (b) AMS 5589	F_{tu}, ksi (kg/mm^2)	185 (130)	-	
	F_{ty} (0.2% offset), ksi (kg/mm^2)	150 (105)	-	
	e (2 in), %	12	-	
	Hardness, RC (a)	36		

(a) Or equivalent.

(b) Properties apply only for O.D. ≥0.125 in (3.17 cm), and wall thickness ≥0.015 in (0.038 cm).

(c) 0.025 in = 0.635 mm.

TABLE 7.1222. — AMS Minimum Requirements for Alloy after 1950° F (1066° C) Anneal plus Aging

Source	Ref. 7.1		
Alloy	Inconel Alloy 718		
Specification	AMS 5664A	AMS 5597A	AMS 5590 (d)
Property	Bars, forgings, rings	Sheet, strip, plate	Seamless tubing
F_{tu}, ksi (kg/mm²)	180 (127)	180 (127)	170 (120)
F_{ty} (0.2% offset), ksi (kg/mm²)	150 (105)	150 (105)	145 (102)
e (2 in), %	10 (a) 12 (b)	15	15
Hardness (c)	341 BHN	38 Rc	

(a) bars (b) forgings, rings (c) or equivalent
(d) O.D. ≥0.125 in (3.17 cm) and wall thickness ≥0.015 in (0.038 cm).

TABLE 7.123. — AMS Minimum Requirements for Alloy Investment Castings

Source	Ref. 7.1
Alloy	Inconel Alloy 718C, Annealed and Aged
Specification	AMS 5383
Property	**Value**
F_{tu}, ksi (kg/mm²)	125 (87.9)
F_{ty} (0.2% offset), ksi (kg/mm²)	110 (77.3)
e (1 in or 4D), %	5
Hardness, Rc	34-44

TABLE 7.4111. – Design Tensile Properties for Alloy 718

Specification	AMS 5383	AMS 5589	AMS 5590	AMS 5596, and 5597	AMS 5662, and 5663	AMS 5664
Form	Castings	Seamless tubing		Sheet, plate	Bars, forgings	
Condition	Solution-treated and aged per indicated specification					
Thickness or diameter, in.		O.D. ≥ 0.125 wail ≤ 0.015				
Basis	S[g]	S	S	S	S	S
Mechanical properties:						
F_{tu}, ksi:						
L	125	185	170		185	180
T				180[a]	180	180[d]
F_{ty}, ksi:						
L	110	150	145		150	150
T				150[a]	150	150
F_{cy}, ksi:						
L						
T						
F_{su}, ksi						
F_{bru}, ksi:						
(e/D = 1.5)						
(e/D = 2.0)						
F_{bry}, ksi:						
(e/D = 1.5)						
(e/D = 2.0)						
e, percent:						
L	5	12	15		12	10[c]
T				15[a,b]	6[e]	10[d,e]

[a] Test direction longitudinal for widths < 9 in.
[b] Thickness > 0.025 inch.
[c] For tranverse dimensions ≥ 2½ inches. For long tranverse in forgings use 10%.
[d] Apply to transverse dimensions ≥ 2½ inches.
[e] Apply to bars only. For forgings use 12%.
[f] Dynamic modulus.
[g] For cast test bars. Specimens machined from larger castings may have lower properties.

1 inch = 25.4 mm
1 ksi = 0.70307 kg/mm^2

(Ref. 7.16)

TABLE 7.4114. — Typical Tensile and Impact Properties for Annealed and Aged Pancake Forgings

Source	Ref. 7.8				
Alloy	Inconel Alloy 718				
Thickness	8 in (20.32 cm) diam				
Test Orientation	Radial Center			Tangential	
	Top Edge	Center	Bottom Edge	Top Edge	Bottom Edge
F_{tu}, ksi (a)	180 (c)	188	177	193	196
(b)	182	196	186.5	209	210
F_{ty}, ksi (a)	146.5	147.5	145.5	156	160
(b)	159	160	159.5	181	179
e (2 in), % (a)	20	24	14	21	20
(b)	10	24	16	19	18
RA, % (a)	22	34	16	32	36
(b)	10.5	33	19	27.5	29.5
Impact, ft-lb (a)	28 (d)	22-25	28	17-22	21-23
(b)	-	-	-	17-21	21-21

(a) 1800° F, 1 hr + 1325° F, 8 hr, FC 100° F/hr to 1150° F, +1150° F, 8 hr. (982° C, 1 hr + 718° C, 8 hr, FC 38° C/hr to 621° C, + 621° C, 8 hr.)

(b) 1800° F, 1 hr + 1325°F, 16 hr. (982° C, 1 hr + 718° C, 16 hr.)

(c) 1 ksi = 0.70307 kg/mm²

(d) 1 ft-lb = 0.13826 kg-m

Strain rate 0.005 in/in/minute through 0.2% yield strength, then 0.050 in/in/minute.

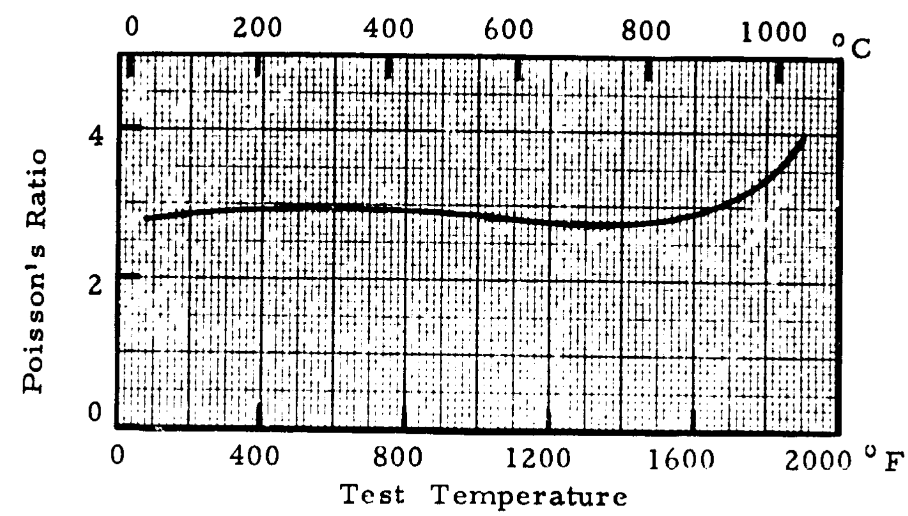


FIGURE 7.21. — Poisson's ratio at various temperatures for Alloy 718. (Ref. 7.6)

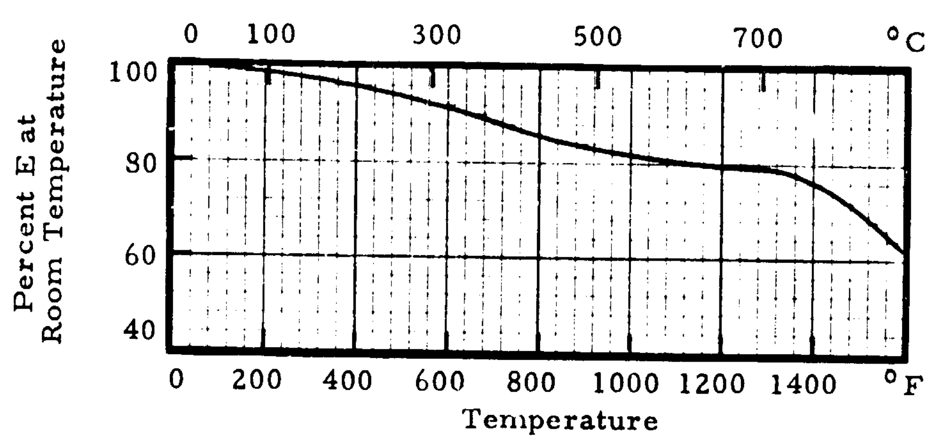


FIGURE 7.223. — Effect of temperature on the tensile modulus (E) of solution-treated and aged Alloy 718. (Ref. 7.16)

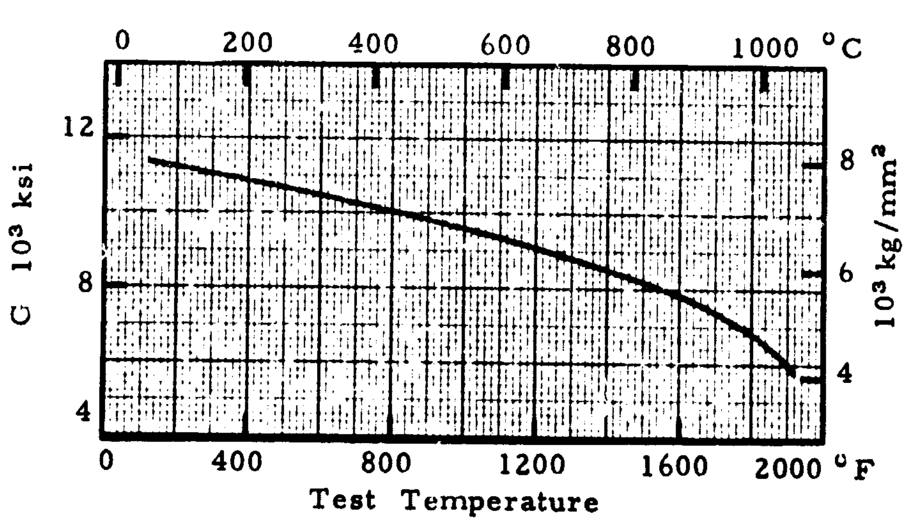


FIGURE 7.241. — Typical value of G at various temperatures for Alloy 718. (Ref. 7.6)

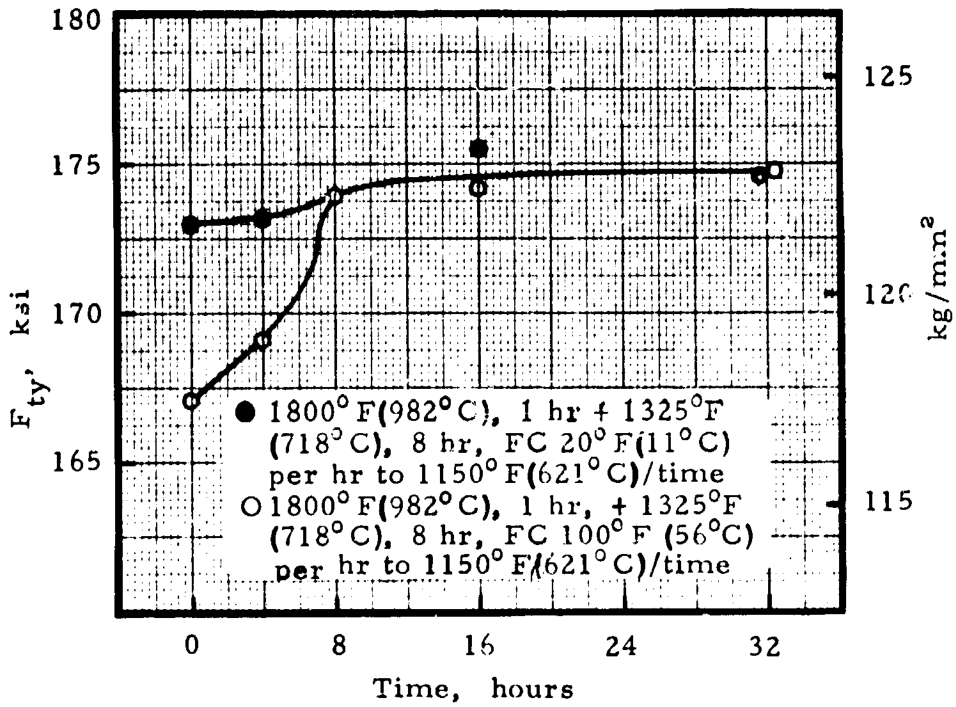


FIGURE 7.4112. – Effect of age hardening on yield strength of Alloy 718.

(Ref. 7.8)

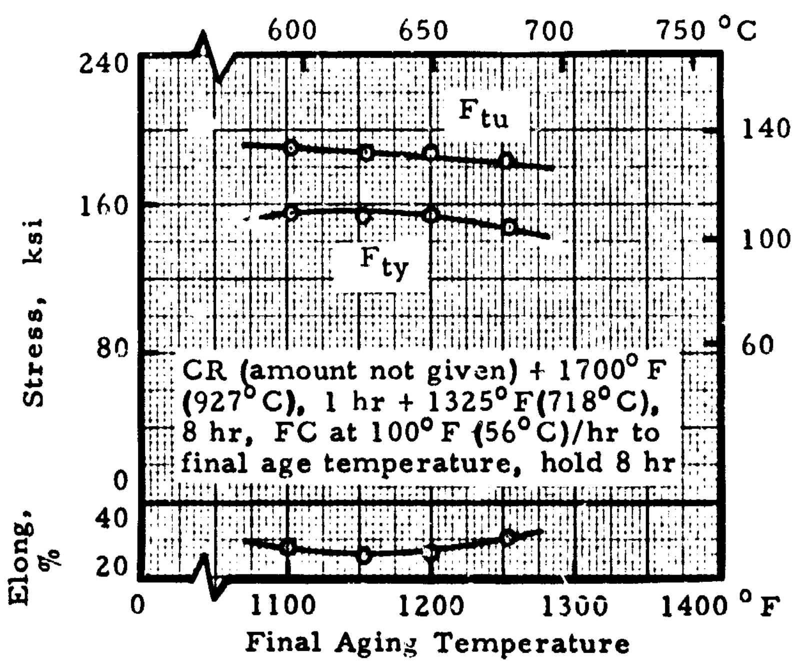


FIGURE 7.4113. – Effect of final age temperature on room temperature properties of Alloy 718 sheet; thickness, 0.060 inch (1.52 mm).

(Ref. 7.8)

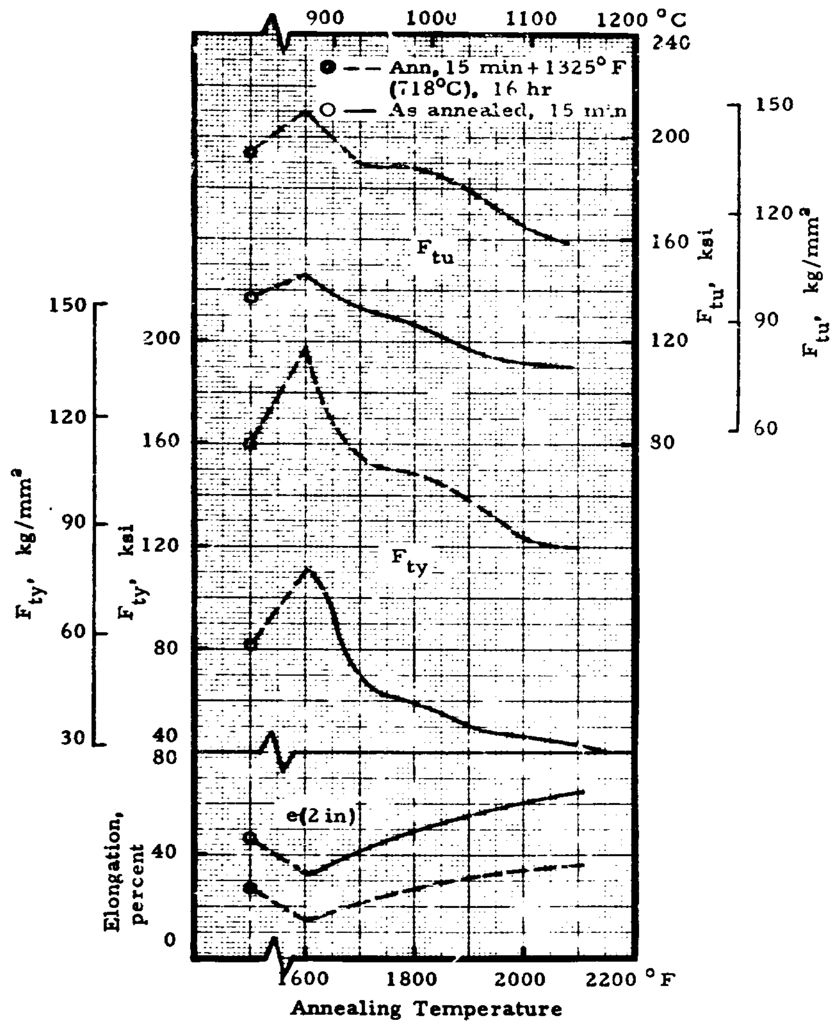


FIGURE 7.4115. – Effect of annealing temperature on room temperature tensile properties of Alloy 718 sheet and bar. (Ref. 7.3)

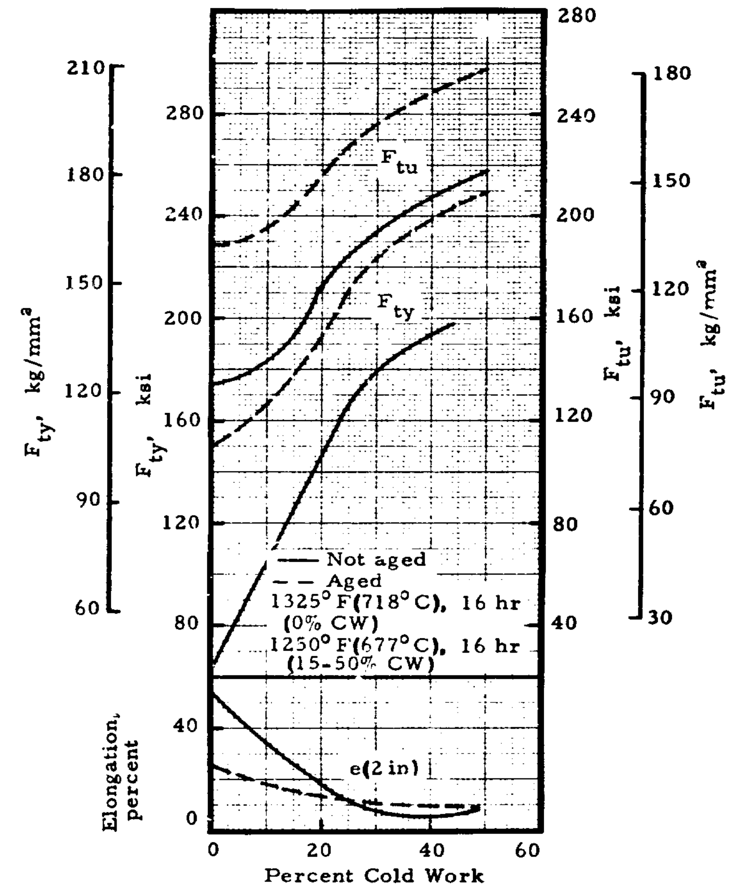


FIGURE 7.4116. – Effect of cold work on room temperature tensile properties of Alloy 718 sheet and strip.
(Ref. 7.3)

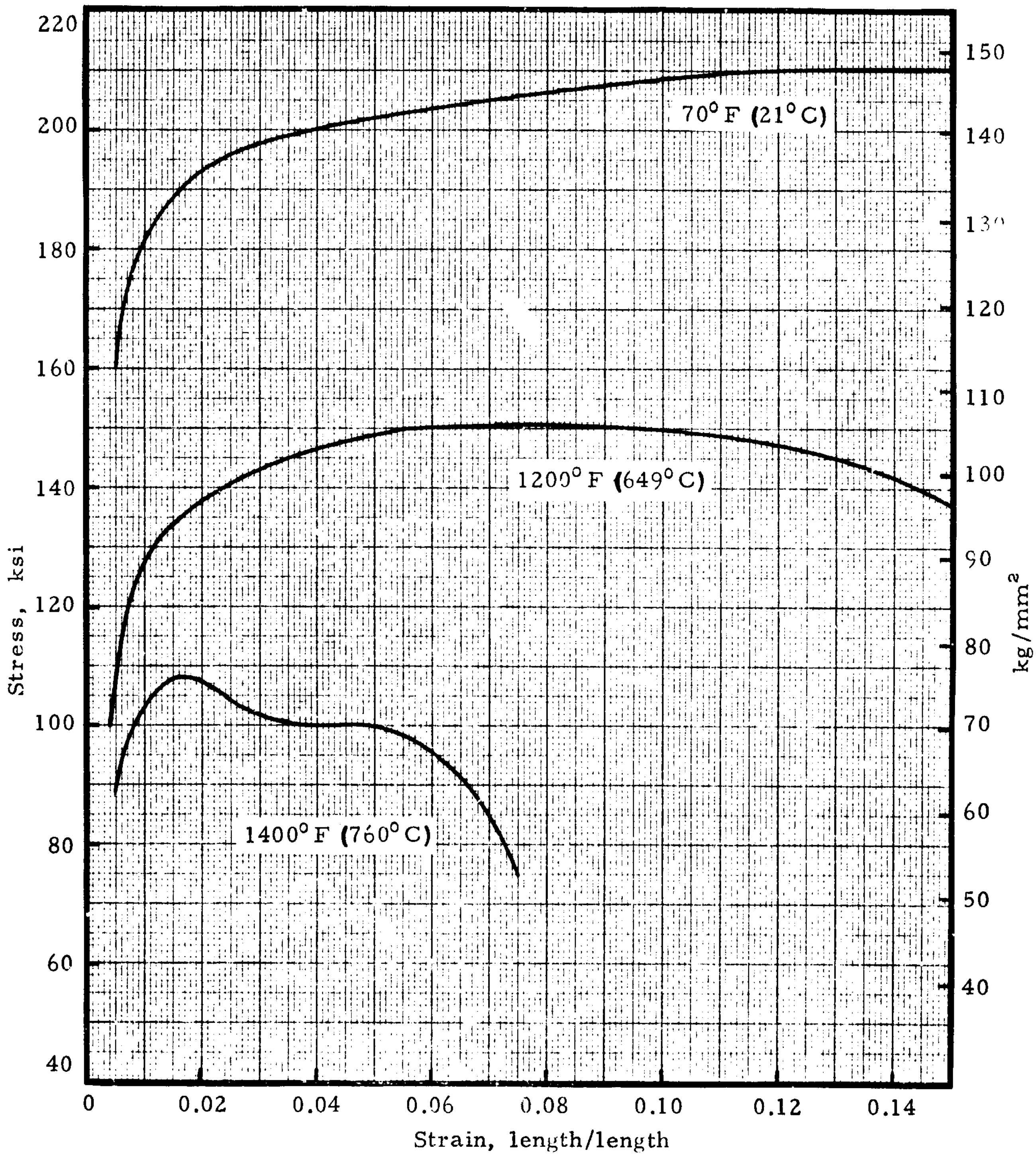


FIGURE 7.4121. – Typical stress-strain curves (tension) at various temperatures for aged Alloy 718. (Ref. 7.7)

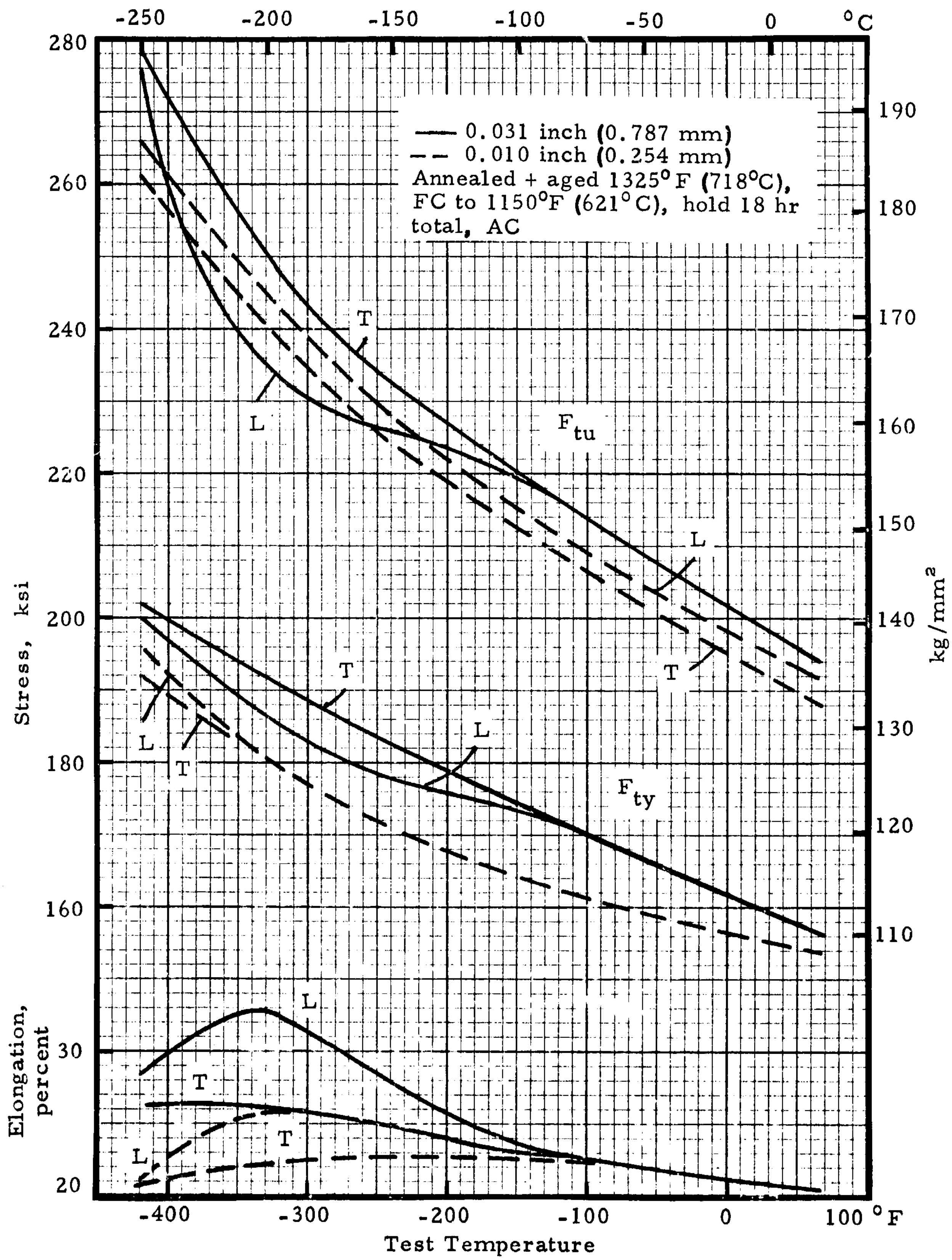


FIGURE 7.4131. — Effect of low temperatures on tensile properties of aged Alloy 718 sheet.

(Ref. 7.5)

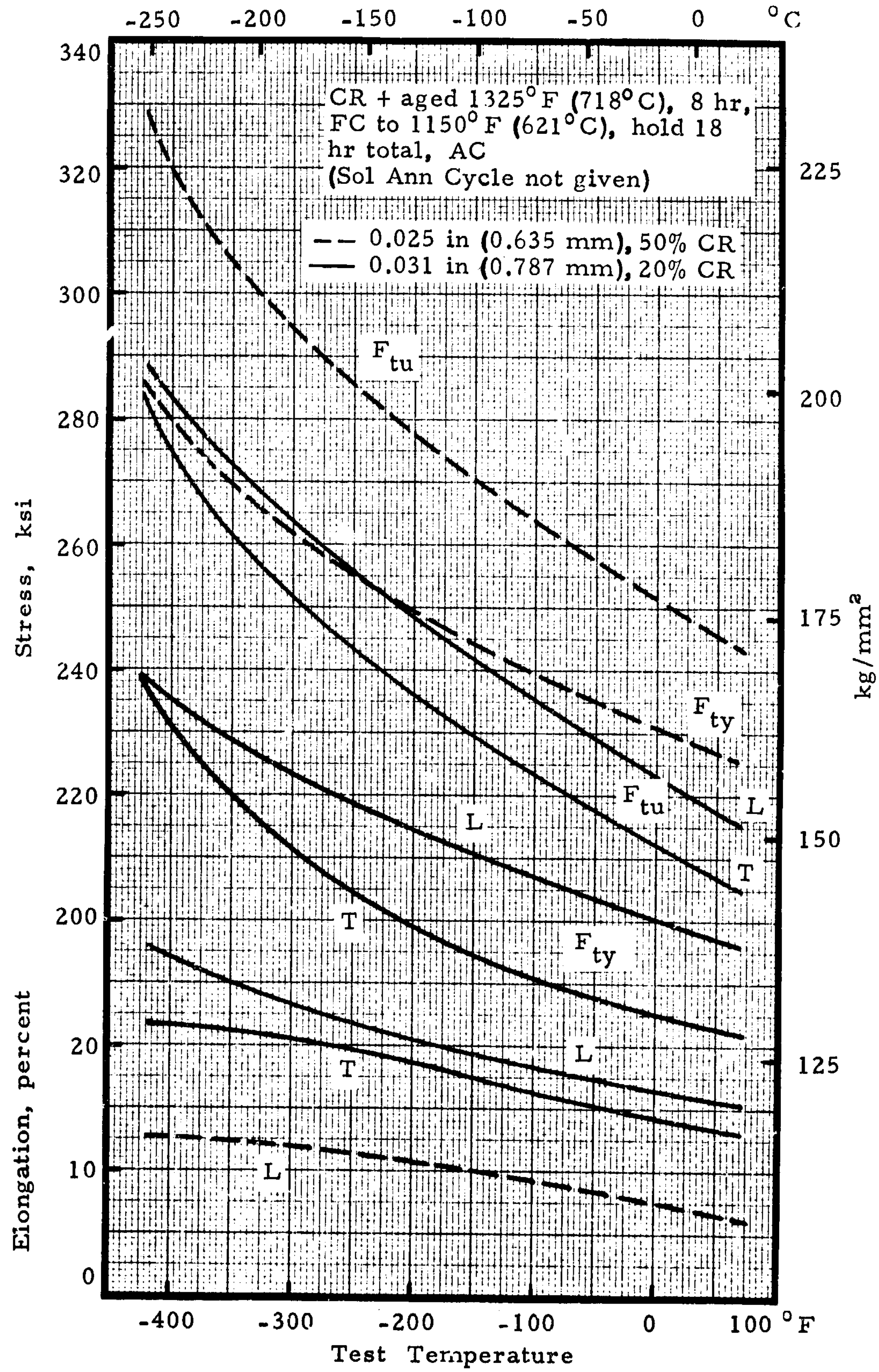


FIGURE 7.4132. — Effect of low temperature on tensile properties of cold reduced and aged Alloy 718 sheet. (Ref. 7.5)

FIGURE 7.4141. – Effect of temperature on the ultimate tensile strength of solution-treated and aged Alloy 718.

(Ref. 7.16)

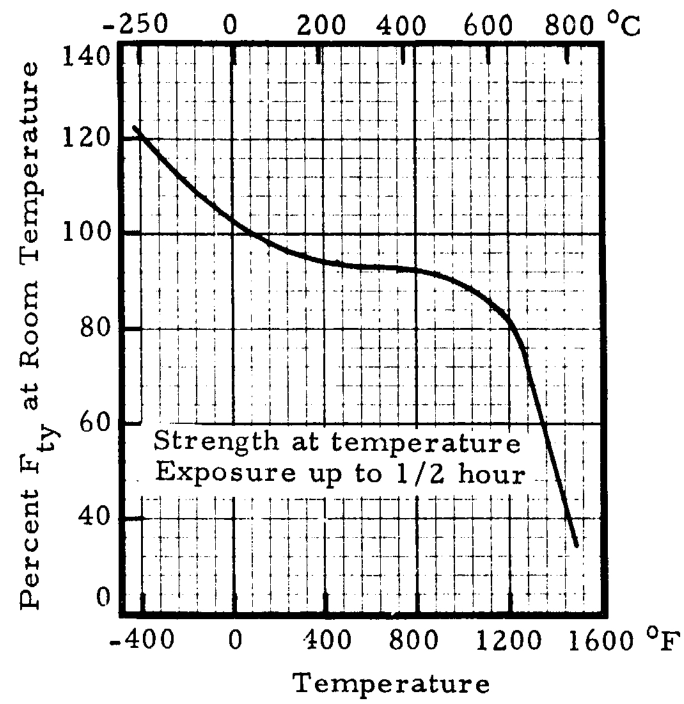
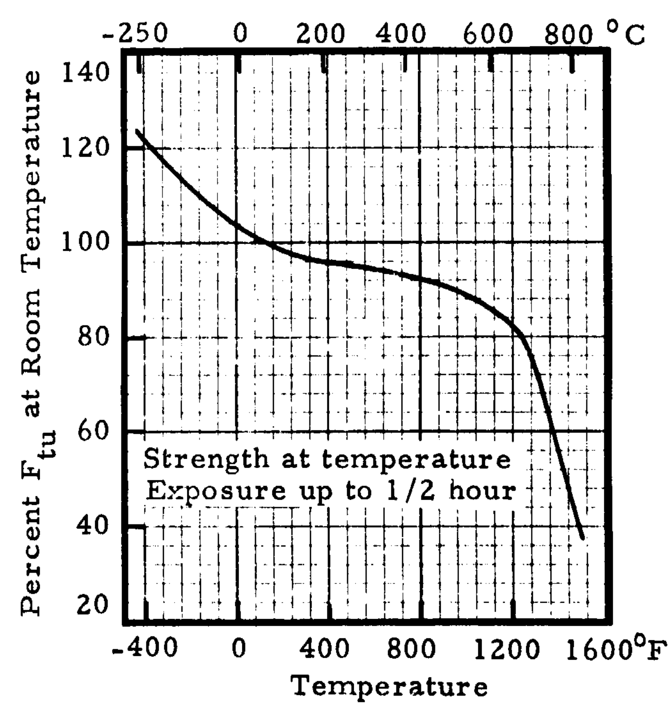


FIGURE 7.4142. – Effect of temperature on the tensile yield strength of solution-treated and aged Alloy 718.

(Ref. 7.16)



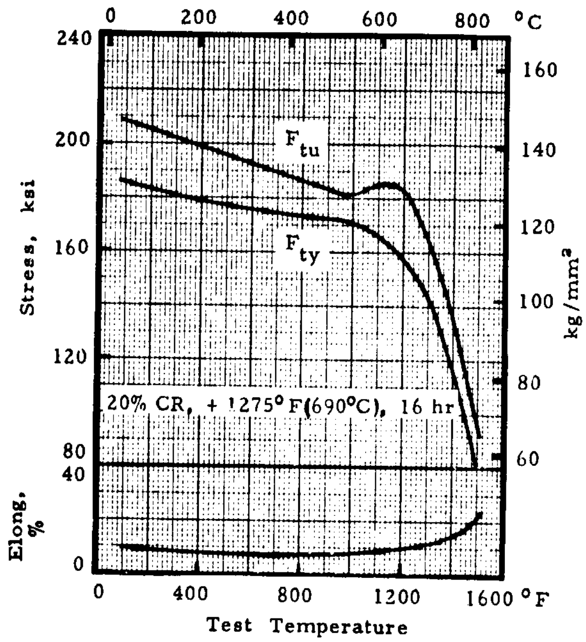


FIGURE 7.4143. – Effect of test temperature on tensile properties of cold rolled and aged Alloy 718 sheet.
(Ref. 7.3)

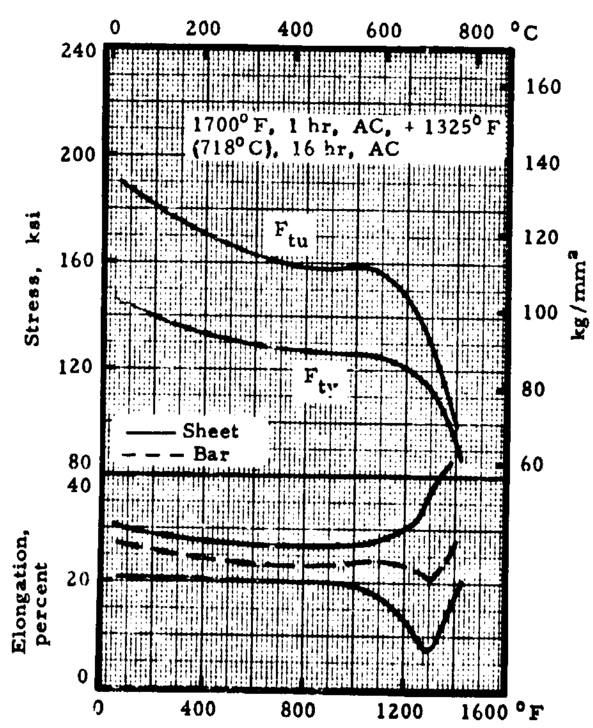


FIGURE 7.4144. – Effect of room and elevated temperature on tensile properties of Alloy 718 wrought sheet and bar (mill annealed).
(Ref. 7.11)

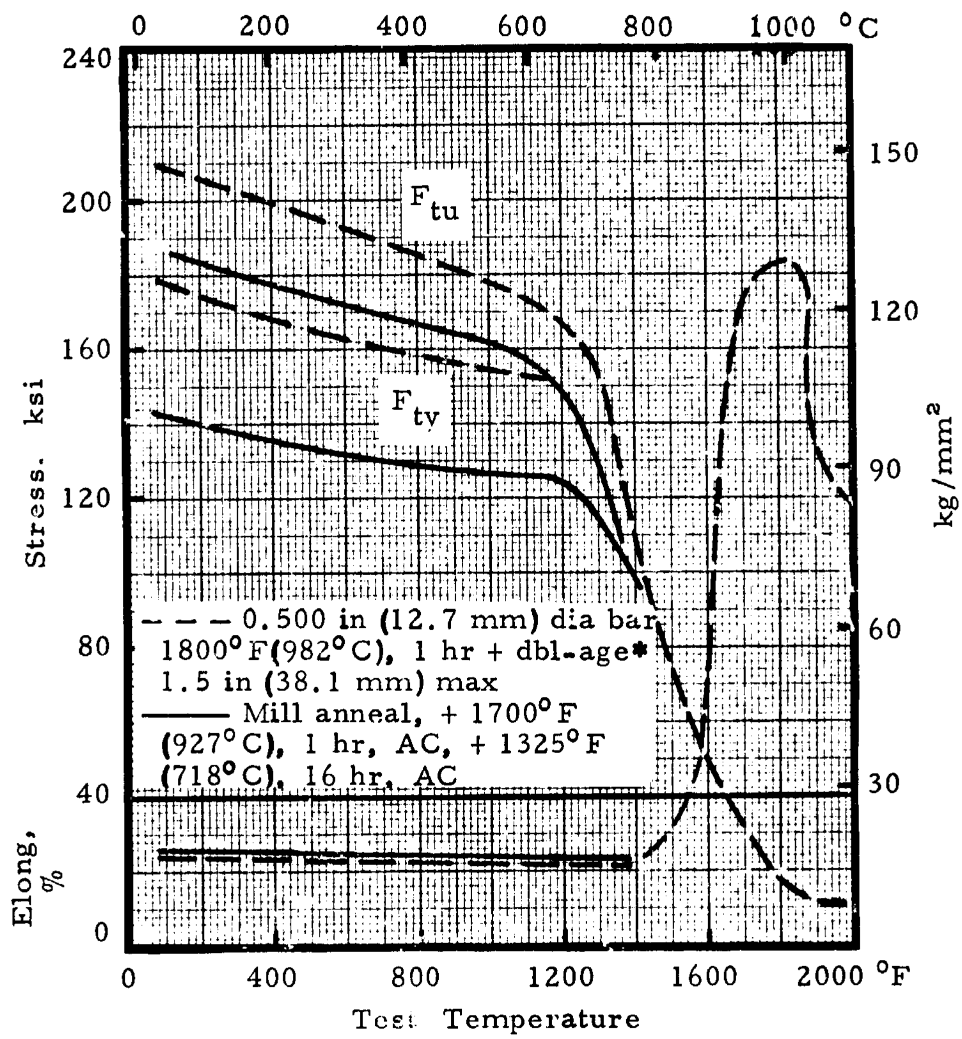


FIGURE 7.4145. – Effect of test temperature on tensile properties of hot rolled Alloy 718 bar.

[*1325° F (718° C), 8 hr, FC 100° F (560° C)/hr to 1150° F (621° C) + 1150° F, 8 hr]

(Refs. 7.8, 7.10)

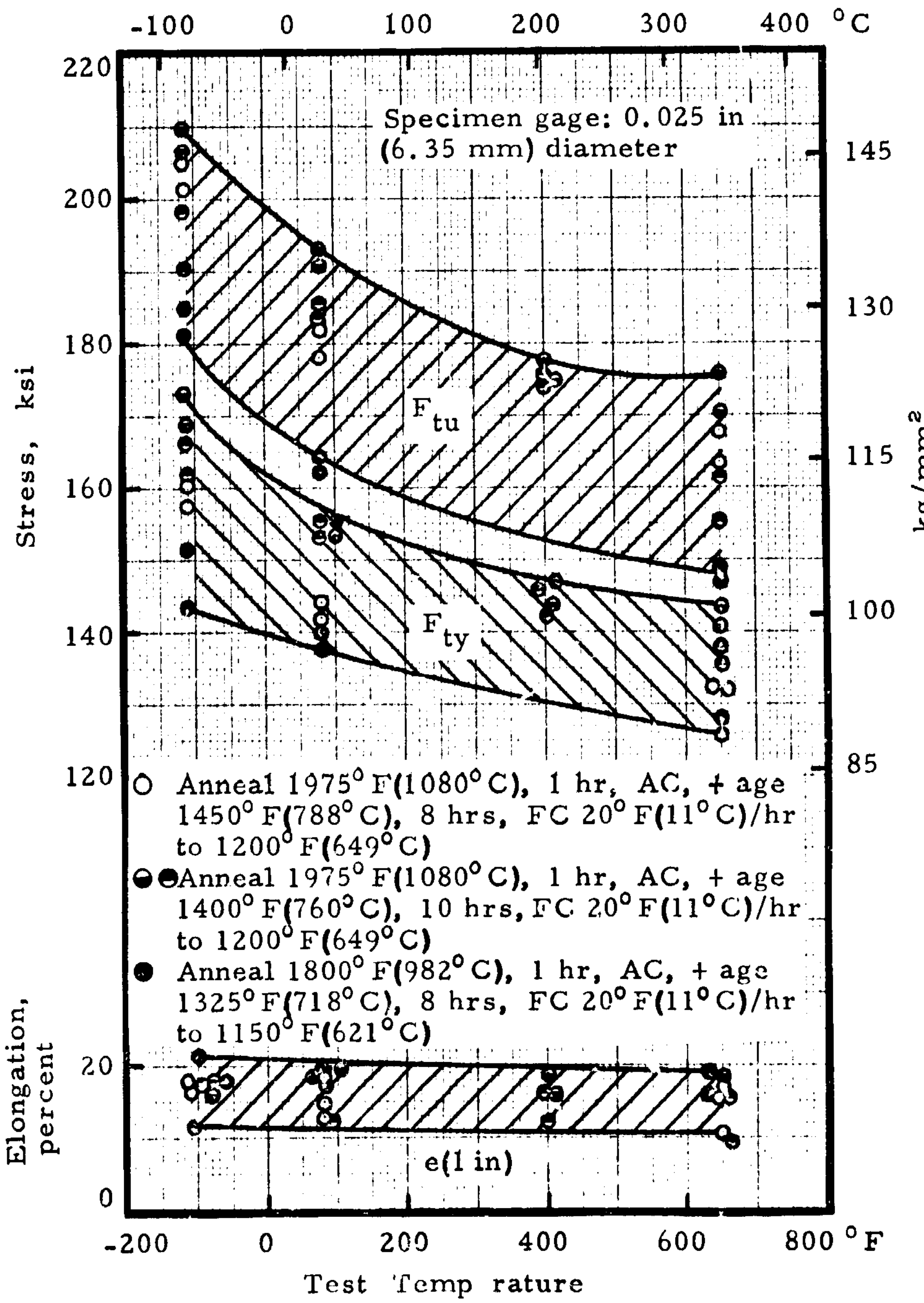


FIGURE 7.4146. – Tensile properties of Alloy 718 forgings (consumable electrode vacuum remelt) at various temperatures for three different heat treatments.

(Ref. 7.4)

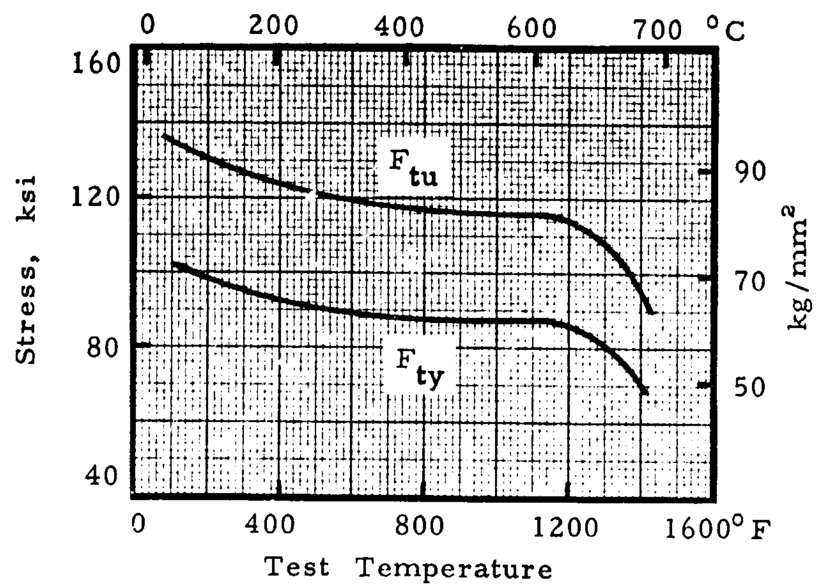


FIGURE 7.4147. – Effect of test temperature on tensile properties of Alloy 718 investment castings.

[1700° F(927° C), 1 hr, AC + 1325° F(718° C), 16 hrs, AC]

(Ref. 7.12)

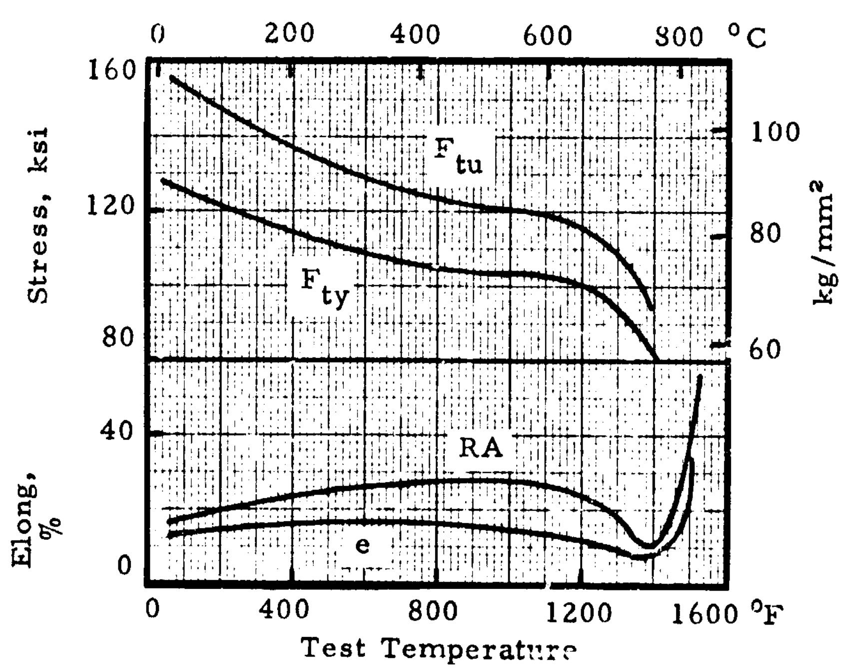


FIGURE 7.4148. – Effect of room and elevated temperature on tensile properties of cast Alloy 718 test bars.

[Ann 2000° F(1093° C), 1 hr, AC, stress relief 1800° F (982° C), 1 hr, AC + age 1325° F(718° C), 16 hrs, AC]

(Ref. 7.11)

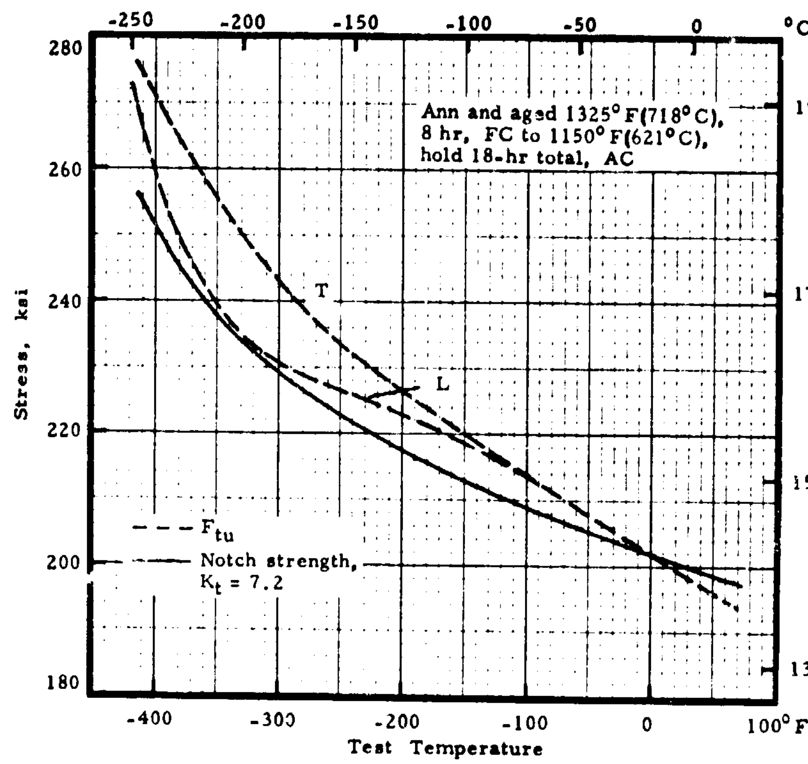


FIGURE 7.4611. — Notch strength of aged Alloy 718 sheet at low temperatures; thickness, 0.031 inch (0.787 mm).

(Ref. 7.5)

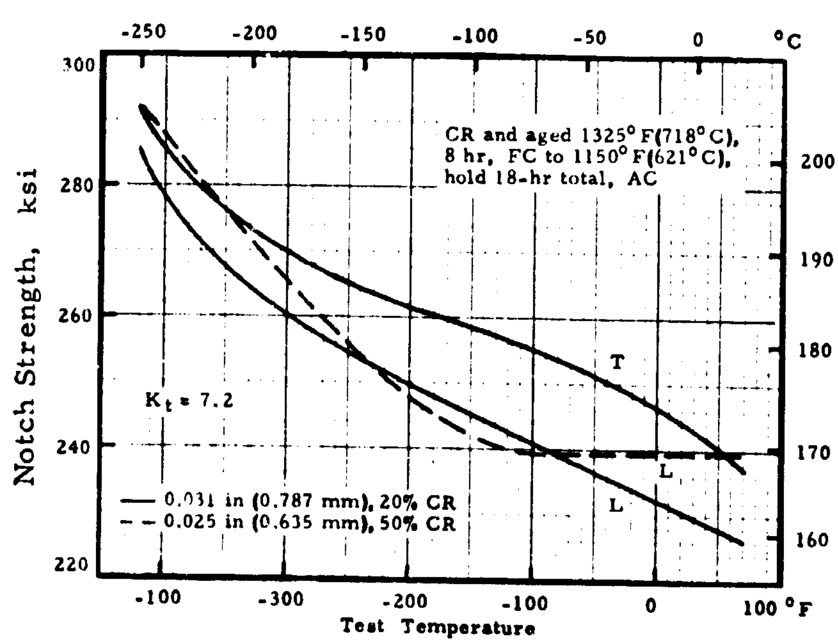
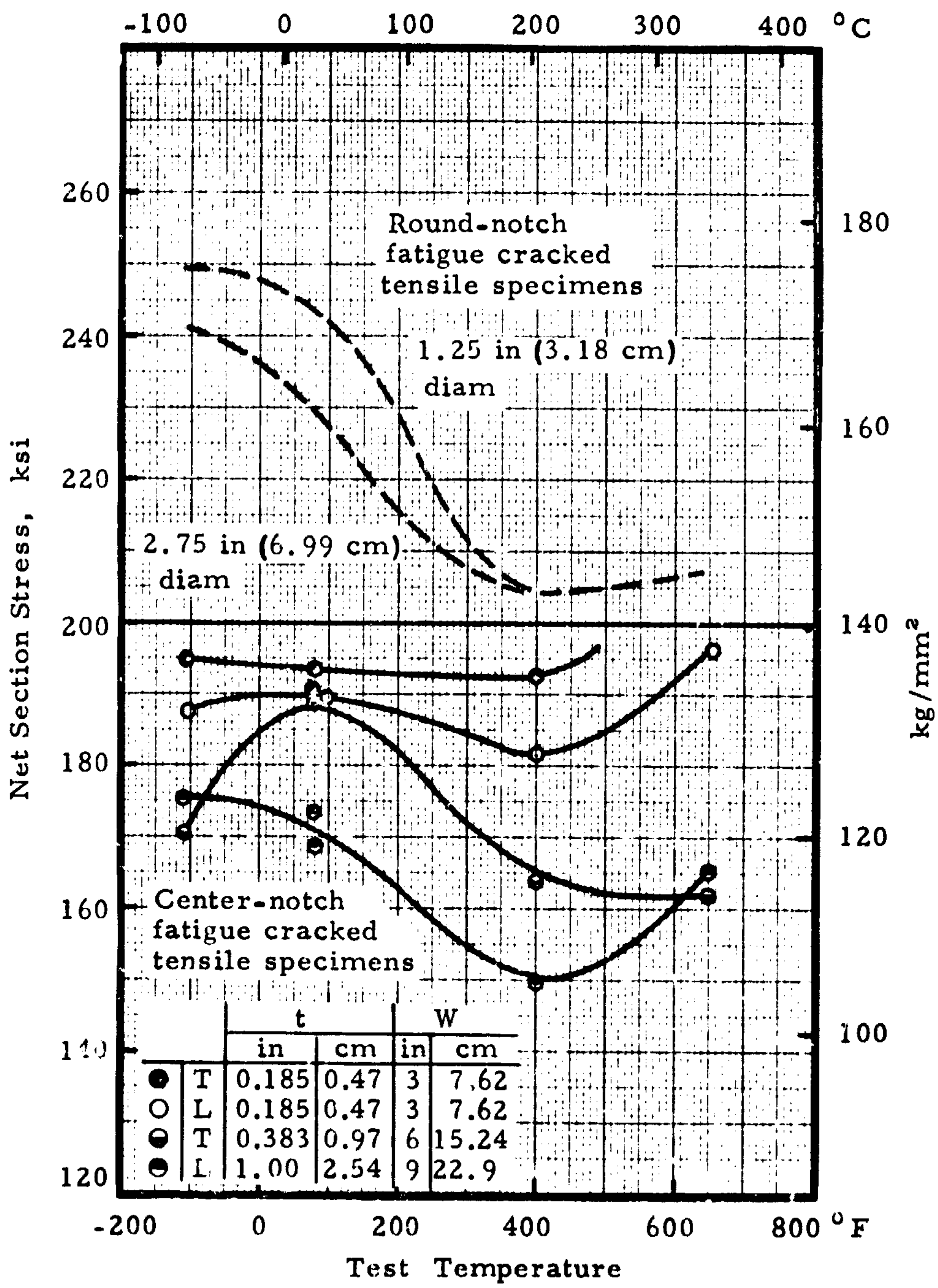


FIGURE 7.4612. — Notch strength of cold reduced and aged Alloy 718 sheet at low temperatures.

(Ref. 7.5)



		t		W	
		in	cm	in	cm
●	T	0.185	0.47	3	7.62
○	L	0.185	0.47	3	7.62
◒	T	0.383	0.97	6	15.24
◓	L	1.00	2.54	9	22.9

FIGURE 7.4613. – Net section strength of center-notch fatigue cracked specimens of Alloy 718 forged billets compared to round-notch fatigue cracked specimens.

[1975° F(1080° C), 1 hr, AC + 1400° F(760° C), 10 hrs, FC 20° F(11° C)/hr to 1200° F(649° C)]

(Ref. 7.4)

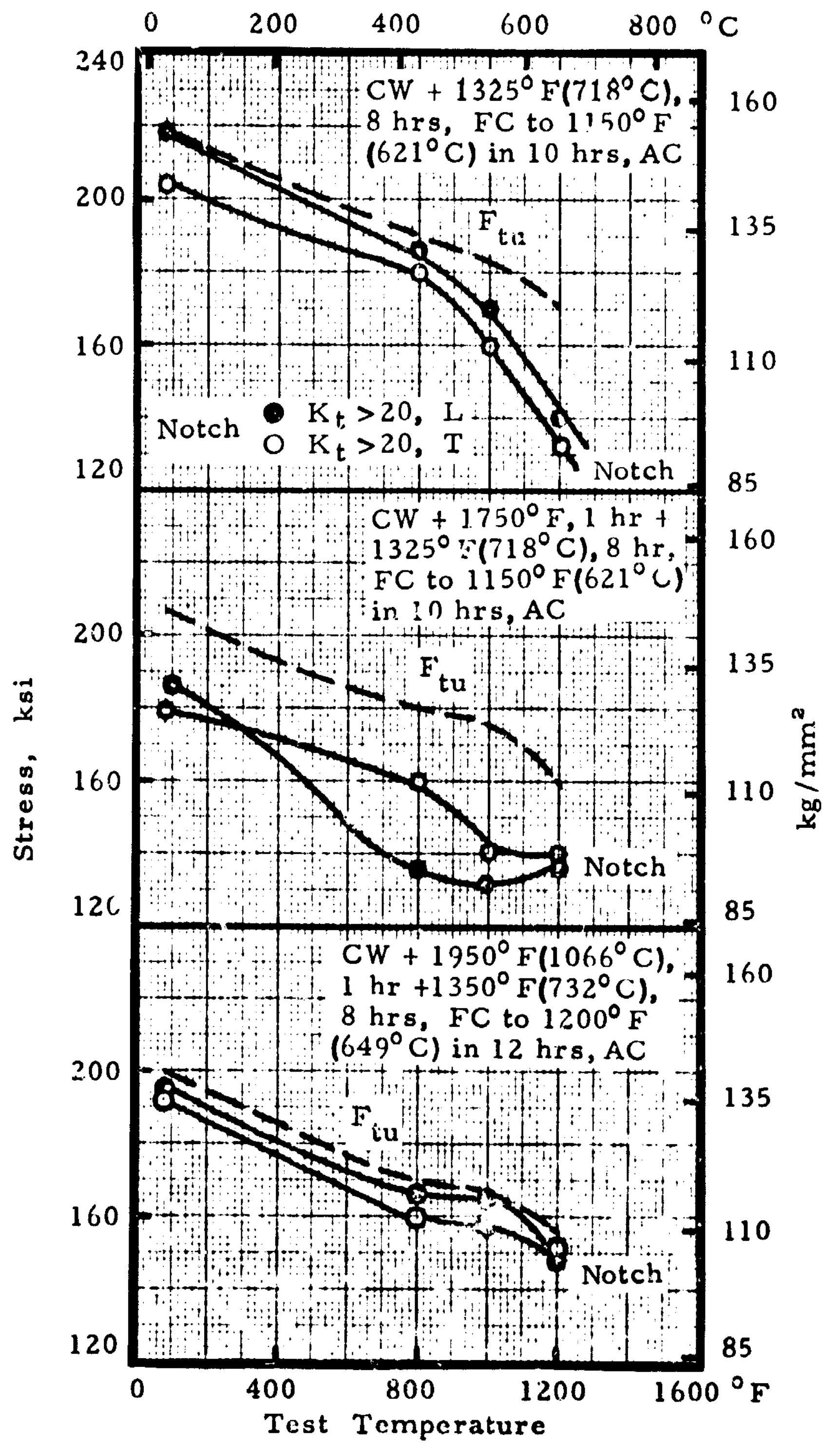


FIGURE 7.4614. – Sharp notch data for Alloy 718 sheet at elevated temperatures; 0.025-in (0.635-mm) sheet, CW 24 percent plus heat as shown.

(Ref. 7.14)

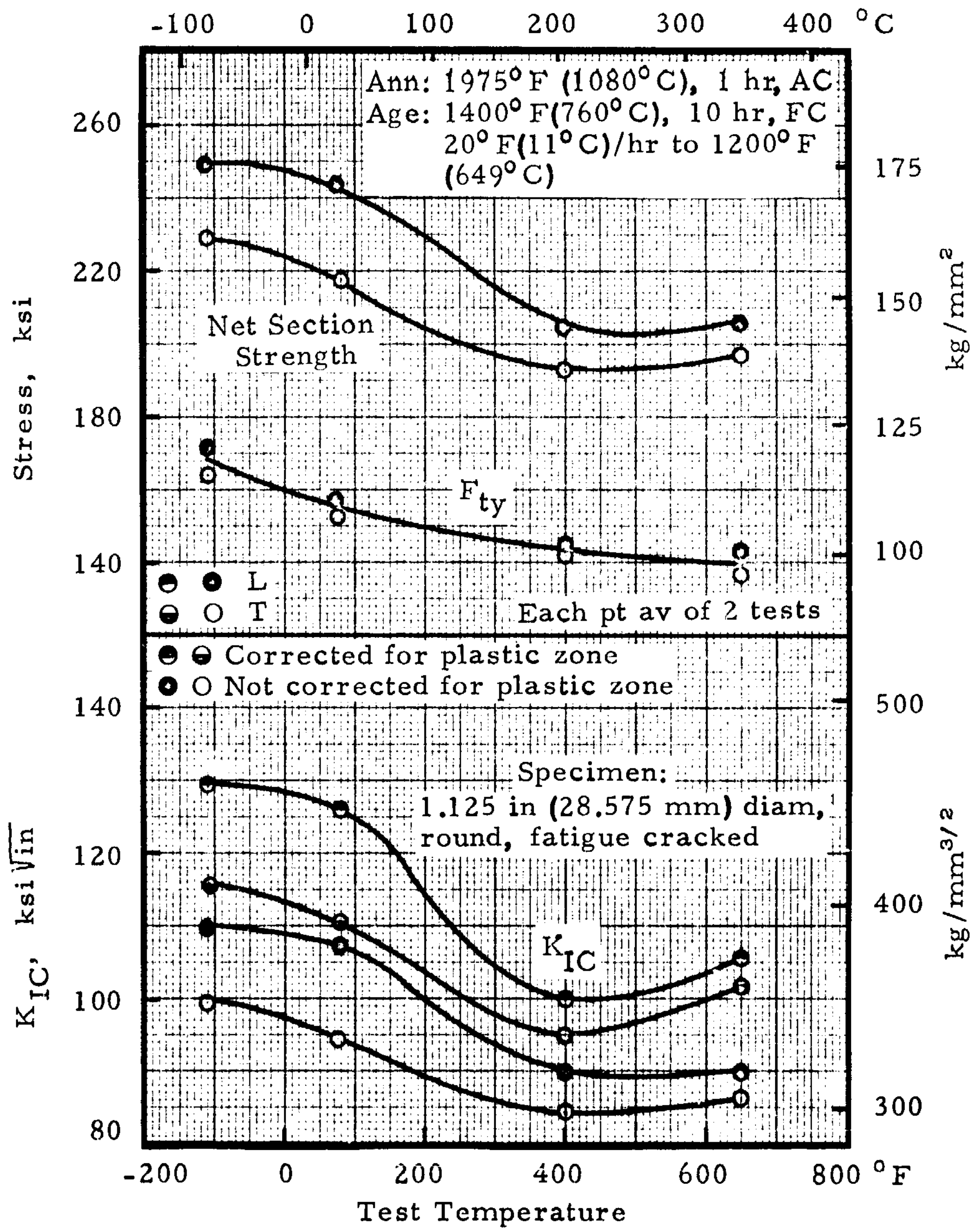


FIGURE 7.4621. — Net section strength and fracture toughness of Alloy 718 aged forgings.

(Ref. 7.4)

C-2

Chapter 7 - References

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Chapter 8

DYNAMIC AND TIME DEPENDENT PROPERTIES

8.1 General. The creep and creep-rupture properties of Inconel Alloy 718 are influenced by chemical composition and the heat treatment employed. The recommended heat treatment has undergone considerable change since the introduction of the alloy in 1950. For creep-rupture applications, the heat treatment currently recommended for all product forms by the major producer of the alloy is given in Chapter 3, Section 3.222.

In general, the alloy exhibits excellent creep and creep-rupture properties up to temperatures of about 1150° F (621° C) and good oxidation resistance up to 1800° F (982° C). Sheet, annealed at 1750° F (954° C) and aged at 1325° F (718° C) exhibits good sharp notch stress-rupture properties.

An extensive study of the fatigue behavior of thin sheet at temperatures up to 650° F (343° C) has been conducted and the results are reported in detail in references 8.8 and 8.9.

8.2 Specified Properties

8.21 AMS minimum stress-rupture requirements, table 8.21.

8.3 Impact

8.31 Izod impact strength at room temperature. 21 ft-lbs (0.29 kg-m) (ref. 8.4).

8.4 Creep

8.41 Creep and creep rupture data.

8.411 Effect of annealing temperature on rupture life of sheet, figure 8.411.

8.412 Creep rupture data for smooth and sharp notch sheet specimens at temperatures of 800°, 1000°, and 1200° F, figure 8.412.

8.413 Creep and creep rupture curves for annealed and aged sheet at 1100° to 1400° F, figure 8.413.

8.414 Creep and creep rupture curves for cold rolled and aged sheet at 1100° and 1300° F, figure 8.414.

8.415 Creep and creep rupture curves for cold rolled and aged sheet at 1200° and 1400°F, figure 8.415.

8.416 Total plastic creep curves at 1100° to 1400° F for bar stock, figure 8.416.

8.417 Minimum creep rate for sheet at 800°, 1000°, and 1200° F, figure 8.417

8.42 Linear parameter master curves

8.421 Master curve for creep and creep rupture of aged sheet, figure 8.421.

8.422 Linear parameter master curves for creep and creep rupture of aged sheet, figure 8.422.

8.423 Linear parameter master curves for creep and creep rupture of cold rolled sheet, figure 8.423.

8.424 Linear parameter master curve for hot rolled bar, figure 8.424.

8.43 Stress relaxation data

8.431 Effect of time and temperature on stress relaxation of hot rolled, annealed, and aged bar, figure 8.431.

8.432 Residual stress at various temperatures and times for bar, figure 8.432.

8.5 Stability

8.51 Effect of stressed exposure at 800° F on room temperature tensile properties, table 8.51.

8.52 Effect of prior exposure at elevated temperatures under stress on tensile properties of sheet, figure 8.52.

8.6 Fatigue

8.61 Comparison of S-N curves for unnotched and notched sheet at room temperature, figure 8.61.

8.62 Stress range fatigue diagram for unnotched sheet at room temperature, 400° F, and 650° F, figure 8.62.

8.63 Effect of prior soak at elevated temperatures on S-N fatigue curves at room temperature for unnotched sheet, figure 8.63.

8.64 Bending fatigue strength of 10% CR sheet at 10^7 cycles (ref. 8.6):

Condition	(a)		(b)		(c)	
Stress Ratio	R = −1	R = 0	R = −1	R = 0	R = −1	R = 0
Max stress, ksi (d)	43.0	70.0	40.0	69.0	43.0	68.0
Mean stress, ksi	0	35.0	0	34.5	0	34.0

(a) as rolled
(b) + aged 1300° F (704° C), 16 hrs
(c) + annealed + aged 1300° F (704° C), 16 hrs
(d) 1 ksi = 0.70307 kg/mm^2.

8.65 Typical constant-life fatigue diagram for sheet at room temperature, figure 8.65.

8.66 Typical constant life fatigue diagram for sheet at 1000° F, figure 8.66.

8.67 Typical constant-life fatigue diagram for sheet at 1200° F, figure 8.67.

8.68 Typical constant-life fatigue diagram for sheet at 1400° F, figure 8.68.

TABLE 8.21. — AMS Minimum Requirements for Stress-Rupture

Source	Ref. 8.2			
Alloy	Inconel Alloy 718			
Specification	Axial Stress Load ksi	(kg/mm^2)	Test Time, hours	e(in 4D) after test, min %
Test at 1200° F (649° C)				
AMS 5596C	95(a)	(66.8)	23	4
Sheet, strip, plate	100(b)	(70.3)	23	4
AMS 5662B and 5663B Bars, forgings, rings	100	(70.3)	23	4 (c)
Test at 1300° F (704° C)				
AMS 5589 Seamless tubing (d)	72.5	(51.0)	23	5
AMS 5383 Investment castings	65	(45.7)	23	3

(a) $\leq$0.025 inch (0.635 mm)

(b) >0.025 inch (0.635 mm)

(c) $\geq$5-inch (127-mm) diameter or thickness

(d) Properties only for wall thickness $\geq$0.015 inch (0.381 mm) and O.D. $\geq$0.125 inch (3.175 mm).

TABLE 8.51. – Effect of Stressed Exposure at 800° F (427° C) on Tensile Properties Tested at Room Temperature

Source	Ref. 8.7					
Alloy	Inconel Alloy 718					
Form	0.025-inch (0.635 mm) sheet					
Heat Treatment	L or T	Exposure Conditions: Stress, ksi (a)	Exposure Conditions: Time, hrs	F_{tu}, ksi	F_{ty}, ksi	e(2 in), %
A	L	0	0	218	207	9.5
	L	184	1000	224	222	7.0
	L	180	1300	219	205	8.5
	T	0	0	217	204	7.5
	T	188	1100	225	225	8.5
	T	185	1300	221	220	4.5
B	L	0	0	208	173	17.3
	L	170	4463	210	204	15.3
	L	165	1000	208	196	17.3
	L	160	1000	209	191	18.0
	T	0	0	206	173	18.0
	T	175	5180	212	212	14.8
	T	170	3280	208	197	17.5
	T	165	1000	209	202	16.3
C	L	0	0	204	177	20.5
	L	165	4340	200	194	15.8
	L	160	1000	198	189	20.8
	T	0	0	199	168	21.0
	T	160	4340	196	189	18.5
	T	155	1000	194	183	20.0

A: CW (24%) + 1325° F (718° C), 8 hr, FC to 1150° F (621° C) in 10 hr, AC

B: CW (24%) + 1750° F (954° C), 1 hr + 1325° F (718° C), 8 hr, FC to 1150° F (621° C) in 10 hr, AC

C: CW (24%) + 1950° F (1066° C), 1 hr + 1350° F (732° C), 8 hr, FC to 1200° F (649° C) in 12 hr, AC

(a) 1 ksi = 0.70307 kg/mm^2

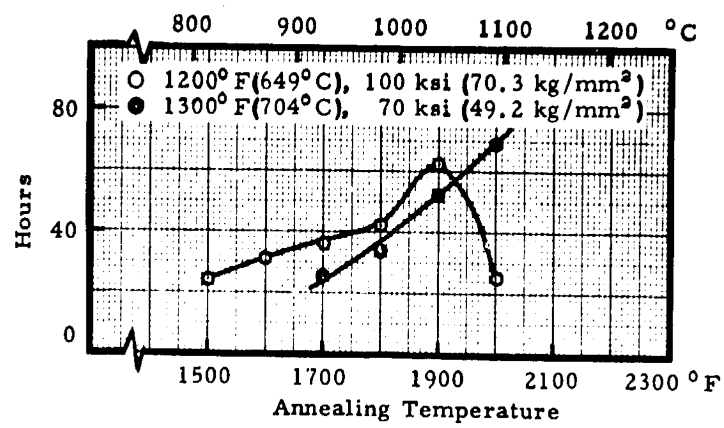

FIGURE 8.411. – Effect of annealing temperature on rupture life of CR Alloy 718 sheet; annealed 1 hr + 1325°F (718°C), 16 hrs.

(Ref. 8.3)

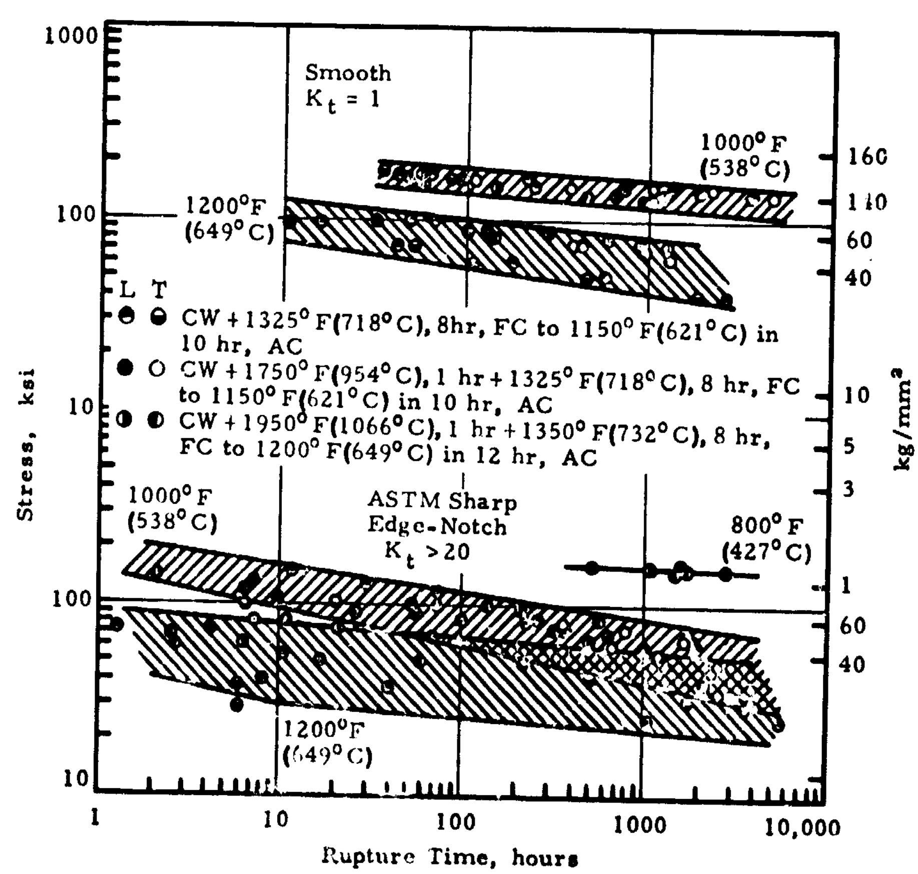

FIGURE 8.412. – Creep rupture data for smooth and sharp notch sheet specimens of Alloy 718 at elevated temperatures; 0.025-in (0.635-mm) sheet, CR 24% plus heat as shown.

(Ref. 8.7)

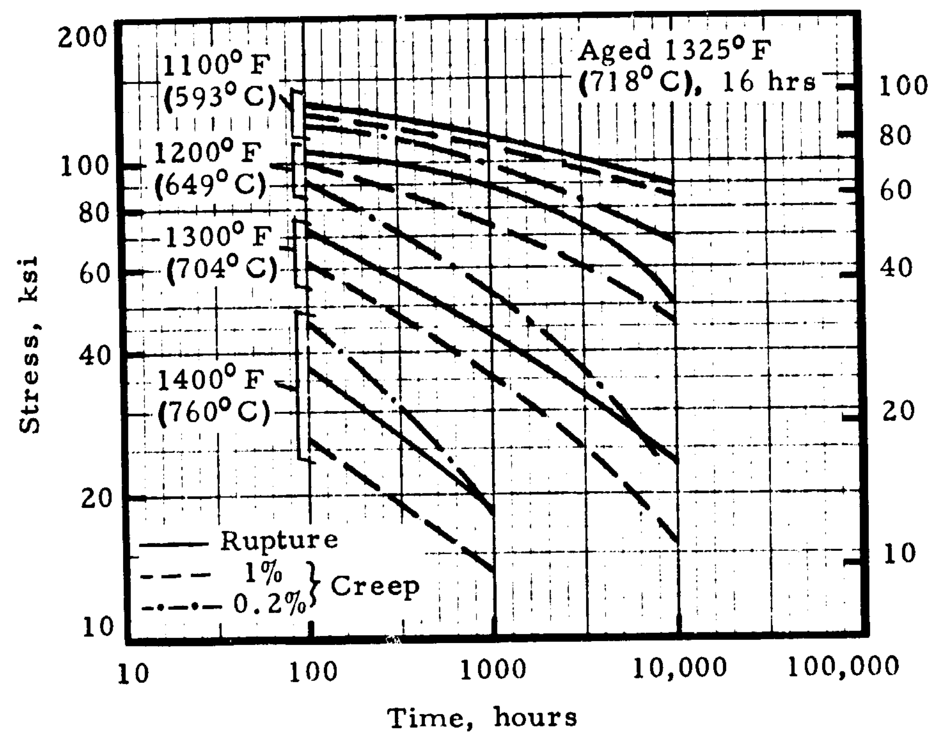

FIGURE 8.413. – Creep and creep rupture curves for annealed and aged Alloy 718 sheet at elevated temperatures (derived from Larson-Miller parameter). (Ref. 8.5)

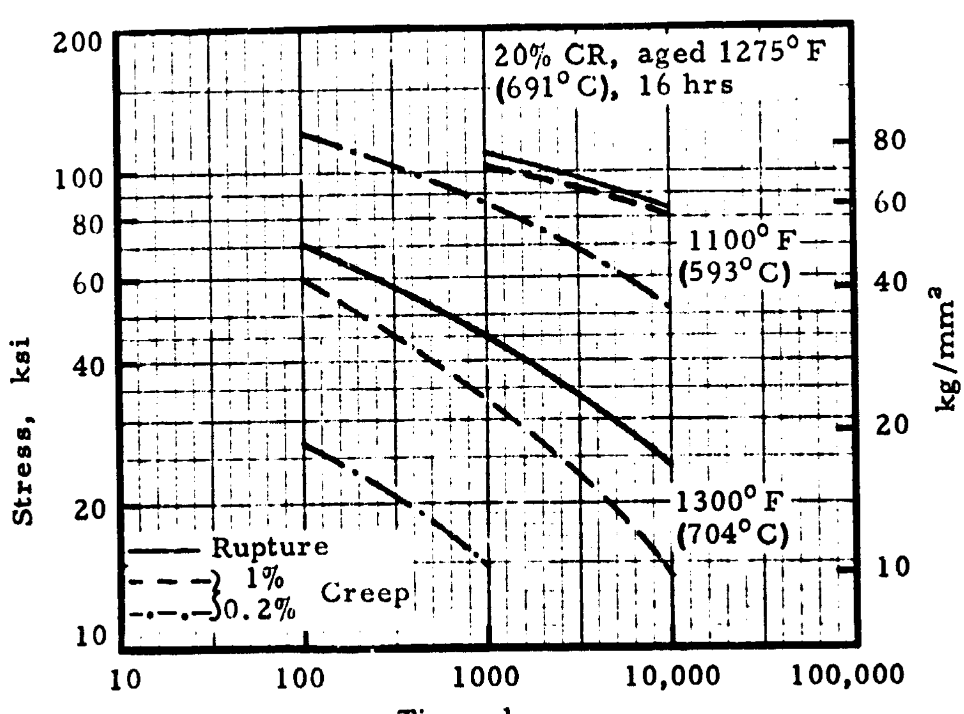

FIGURE 8.414. – Creep and creep rupture curves for cold rolled and aged Alloy 718 sheet at elevated temperatures (derived from Larson-Miller parameter). (Ref. 8.5)

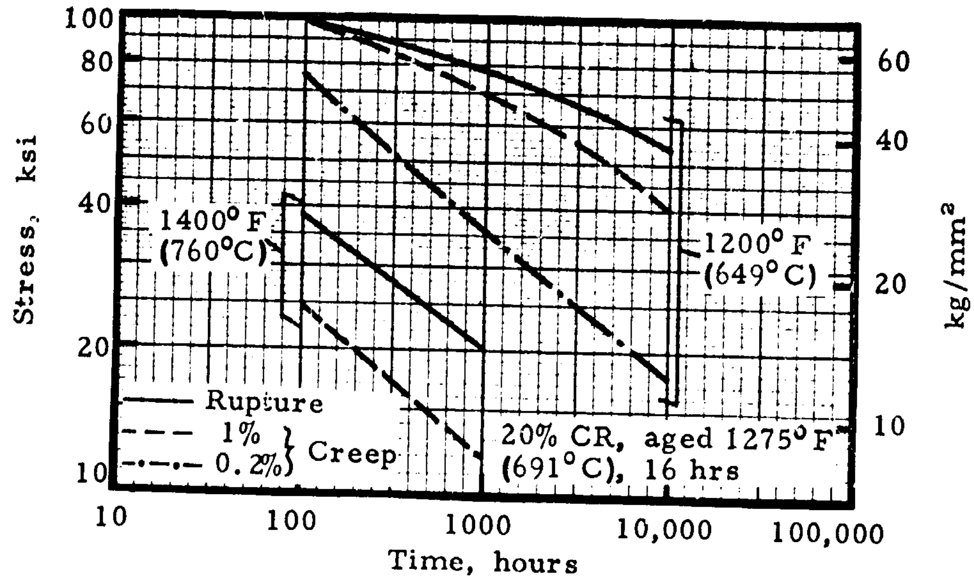

FIGURE 8.415. – Creep and creep rupture curves for cold rolled and aged Alloy 718 sheet at elevated temperatures (derived from Larson-Miller parameter).
(Ref. 8.5)

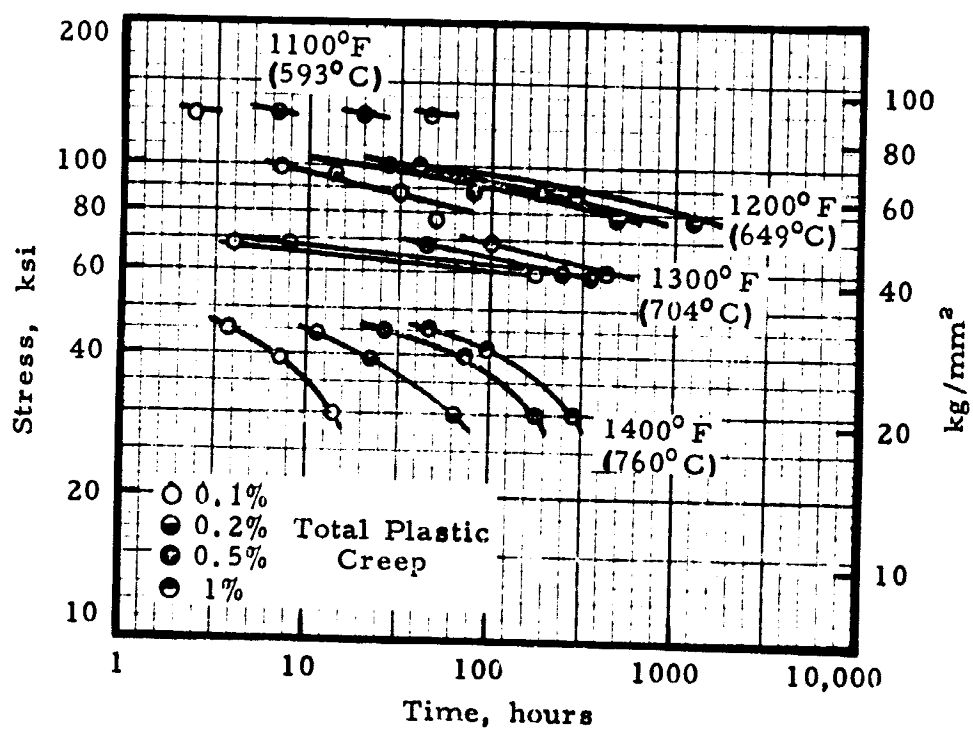

FIGURE 8.416. – Total plastic creep curves at elevated temperatures for hot rolled Alloy 718 bar stock, 0.625 inch (15.9 cm).
(Ref. 8.3)

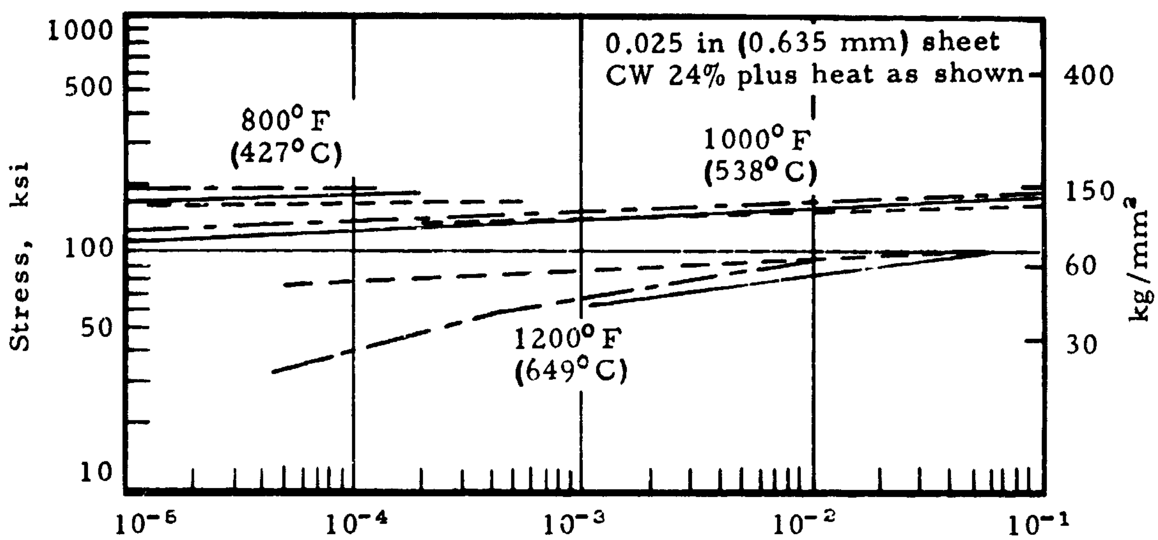

FIGURE 8.417. – Minimum creep rate for Alloy 718 sheet at elevated temperatures. (Ref. 8.7)

[–·–· CW + 1325° F(718° C), 8 hr, FC to 1150° F(621° C) in 10 hr, AC.
—— CW + 1750° F(954° C), 1 hr + 1325° F(718° C), 8 hr, FC to 1150°F (621° C) in 10 hr, AC.
– – – CW + 1950° F(1066° C), 1 hr + 1350° F(732° C), 8 hr, FC to 1200° F(649° C) in 12 hr, AC.]

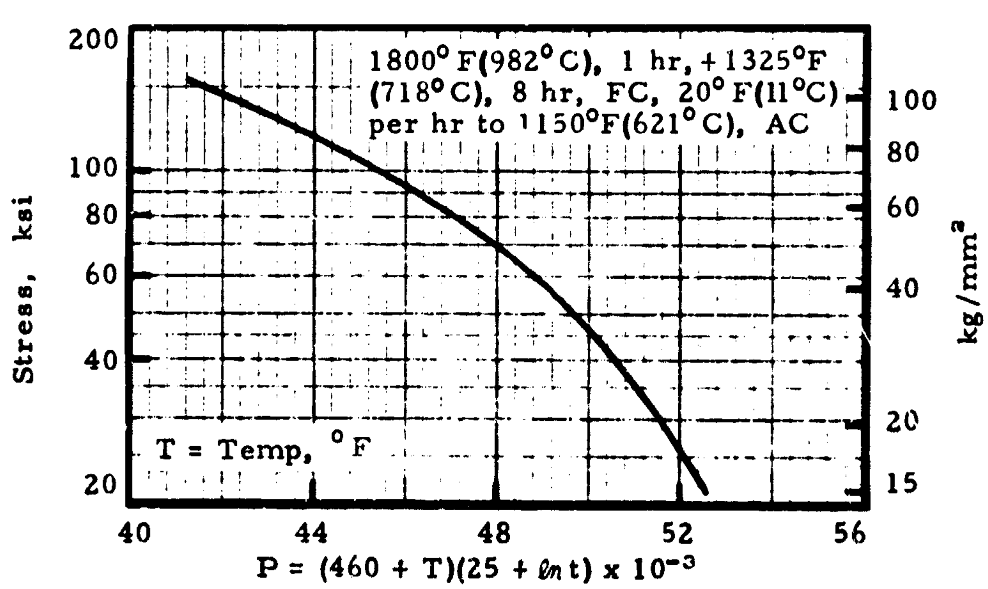

FIGURE 8.421. – Master curve for creep rupture of annealed and aged Alloy 718 bar; 0.625 in (15.9 mm). (Ref. 8.3)

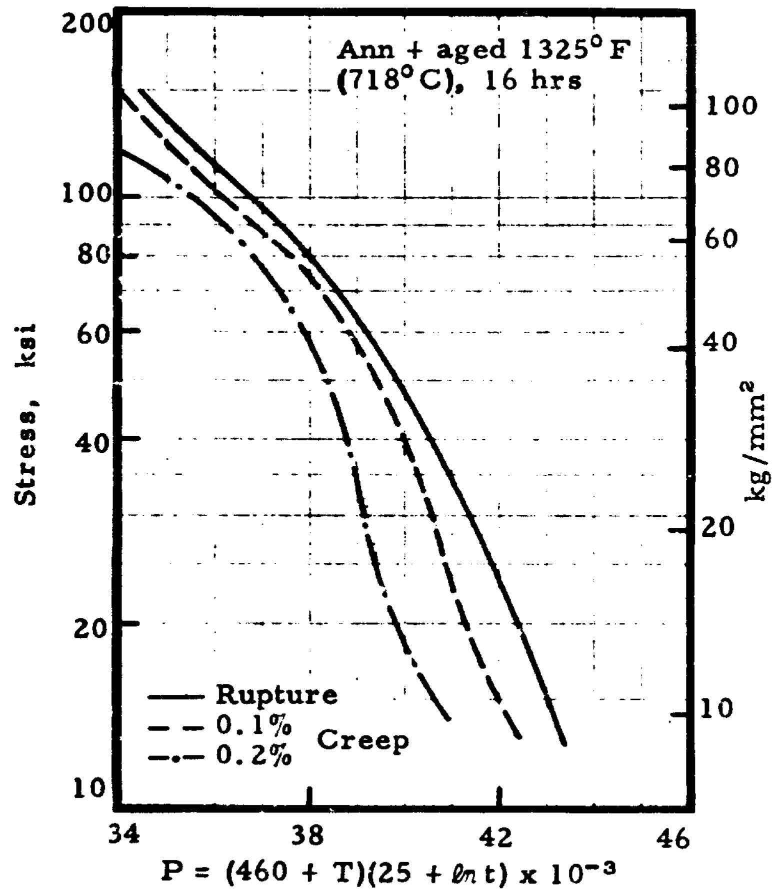

FIGURE 8.422. — Linear parameter master curves for creep and creep rupture of Alloy 718 aged sheet.

(Ref. 8.3)

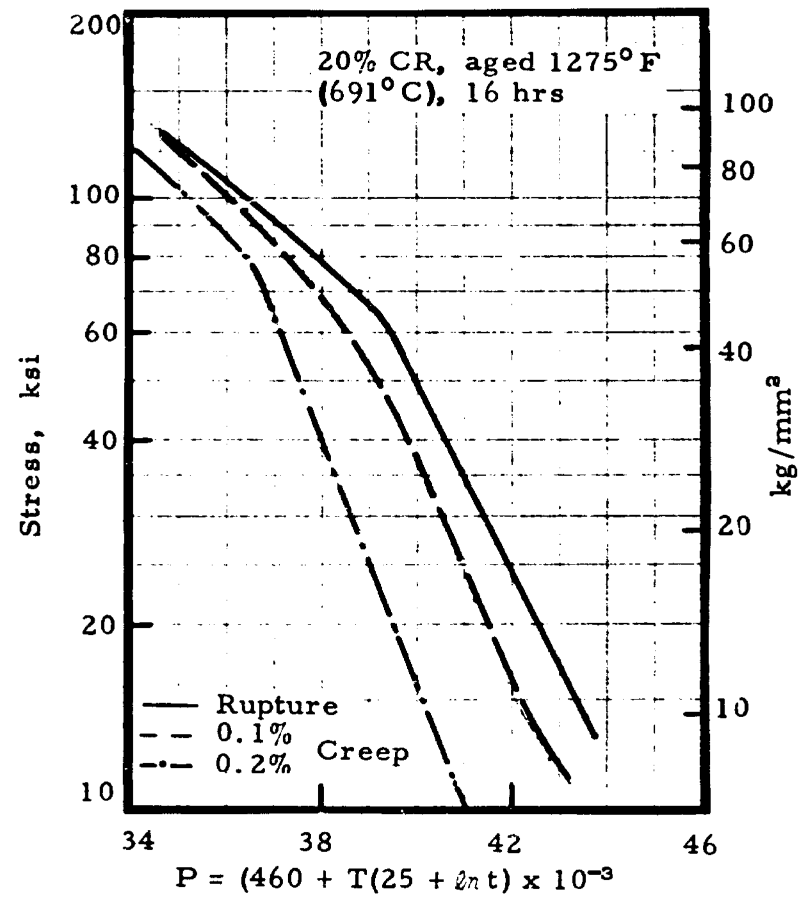

FIGURE 8.423. — Linear parameter master curves for creep and creep rupture of Alloy 718 cold rolled and aged sheet.

(Ref. 8.5)

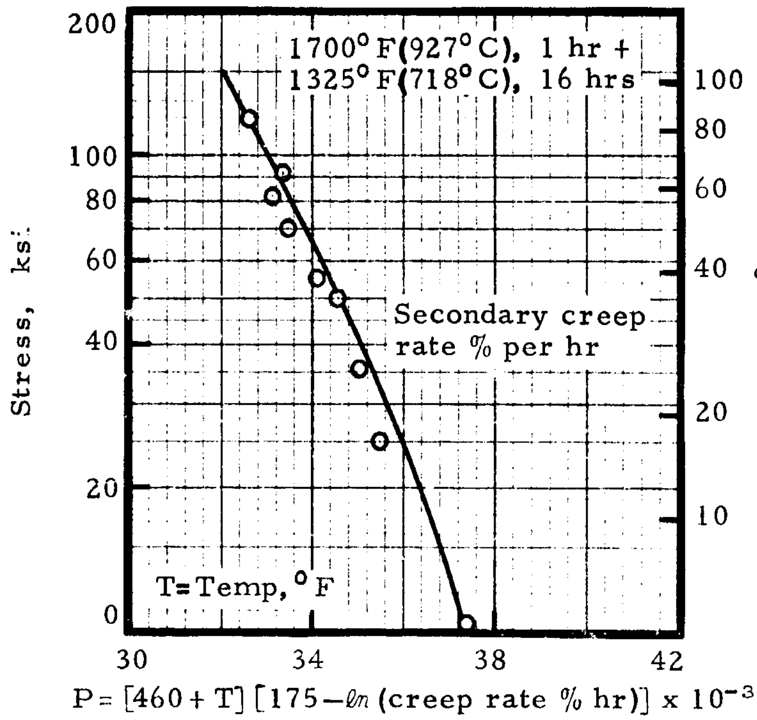

FIGURE 8.424. – Linear parameter master curve for hot rolled Alloy 718 bar; 3/4 in (19 mm) diam.
(Ref. 8.5)

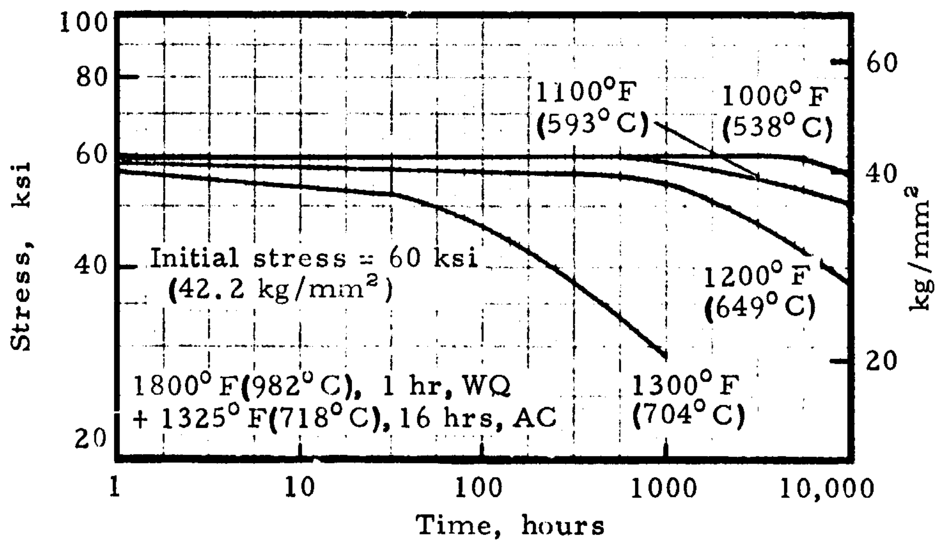

FIGURE 8.431. – Effect of time and temperature on stress relaxation of hot rolled annealed and aged Alloy 718 bar; 0.625 in (3.175 mm).
(Ref. 8.5)

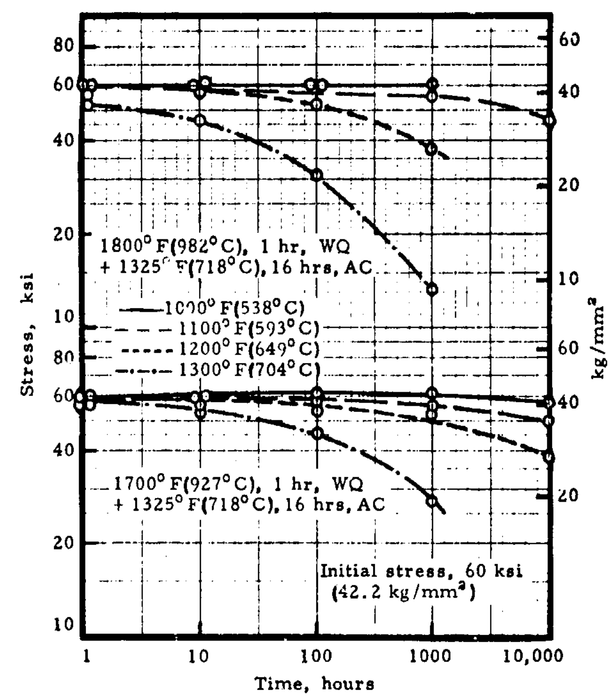

FIGURE 8.432. – Residual stresses for various temperatures and times for Alloy 718 hot rolled bar; 5/8 in (15.9 mm) diam.

(Ref. 8.6)

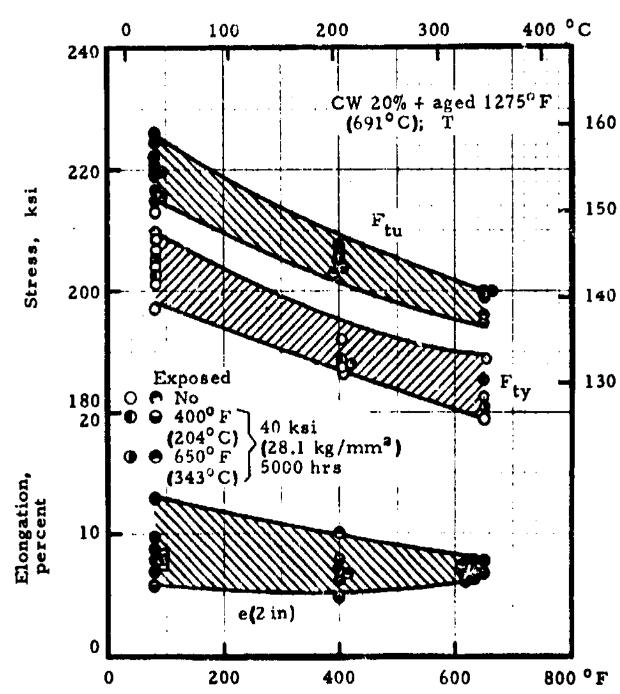

FIGURE 8.52. – Effect of prior exposure at elevated temperatures under stress on tensile properties of Alloy 718 sheet; 0.025 in (0.635 mm).

(Ref. 8.9)

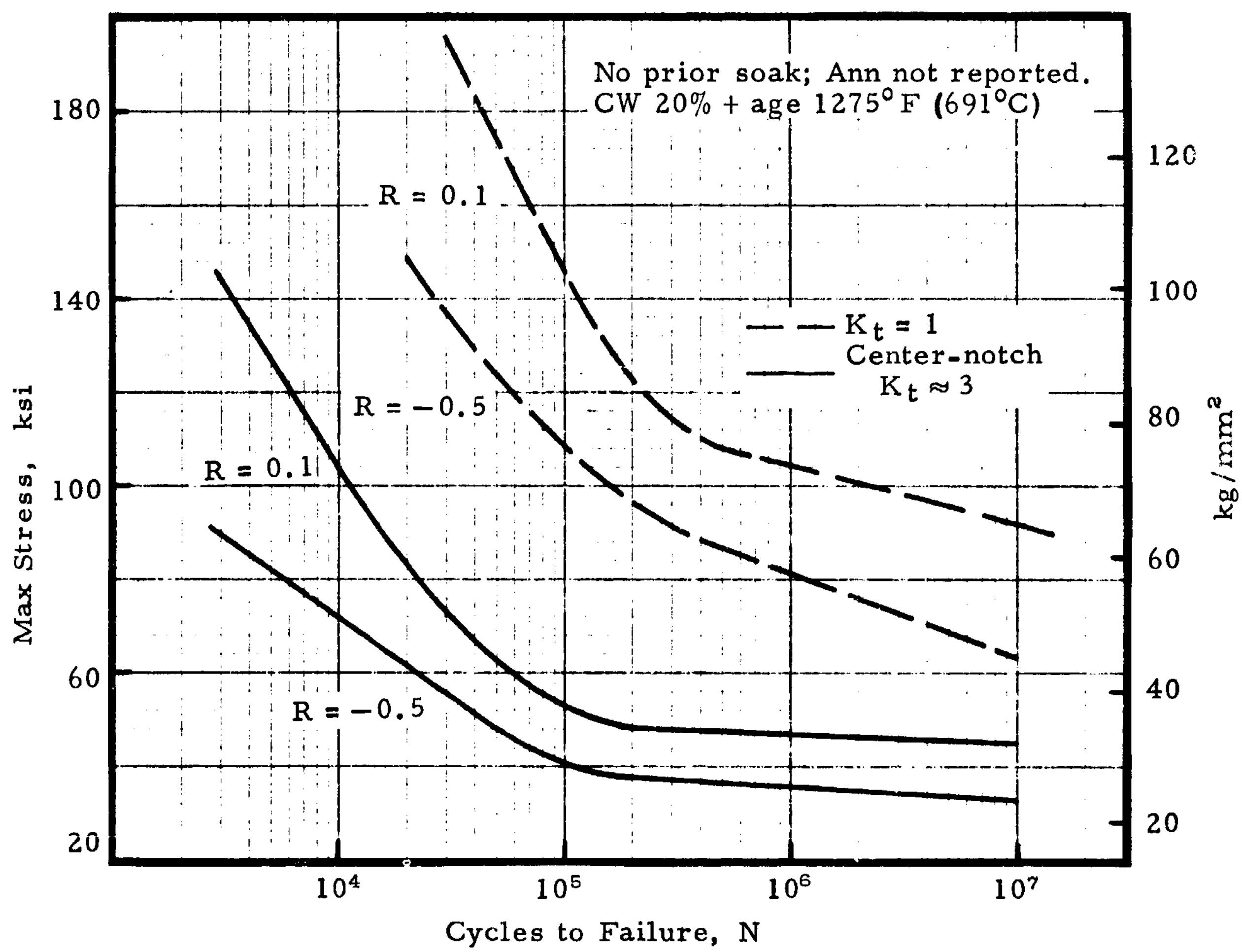

FIGURE 8.61. – Comparison of S-N curves for unnotched and notched Alloy 718 sheet at room temperature; 0.025 in (0.635 mm).

(Ref. 8.9)

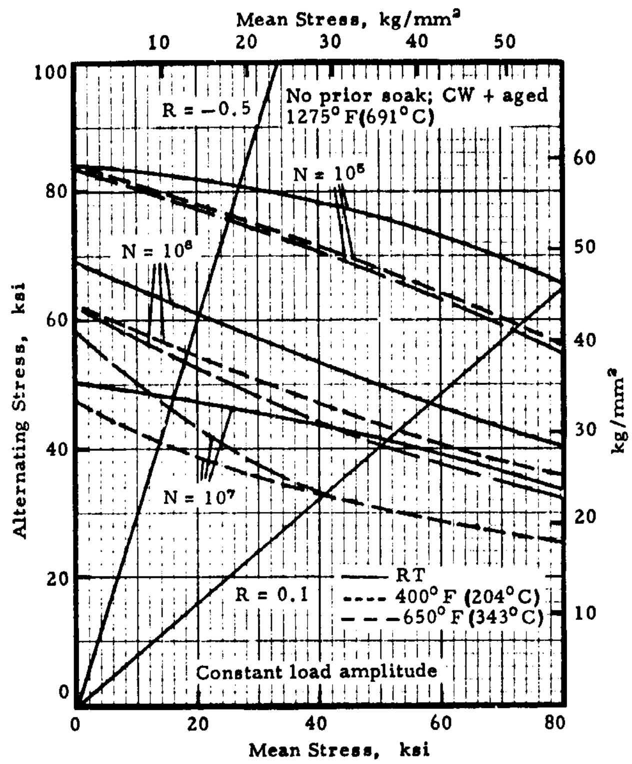

FIGURE 8.62. — Stress range fatigue diagram for unnotched Alloy 718 sheet at room and elevated temperatures; 0.025 in (0.635 mm).

(Ref. 8.9)

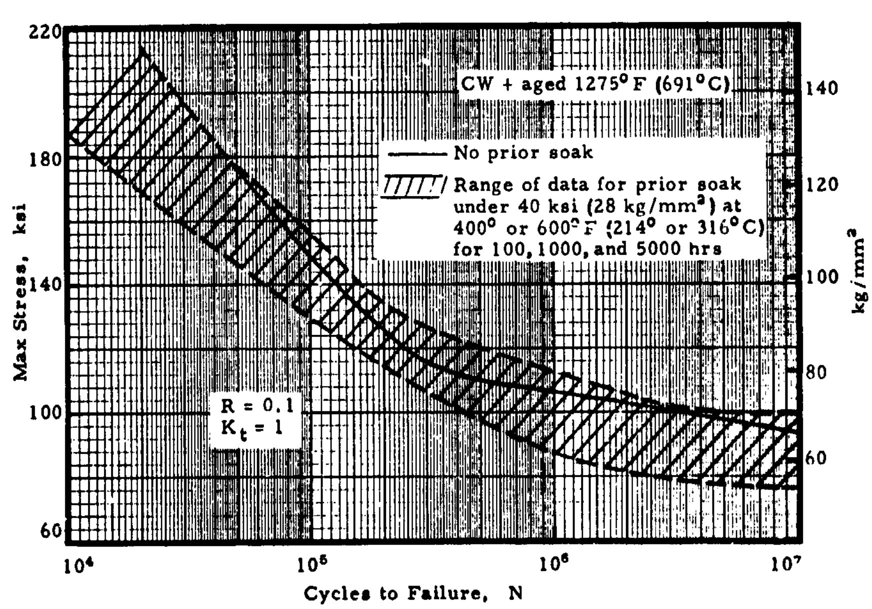

FIGURE 8.63. — Effect of prior soak at elevated temperatures on S-N fatigue curves at room temperature for unnotched Alloy 718 sheet; 0.025 inch (0.635 mm) thickness.

(Ref. 8.8)

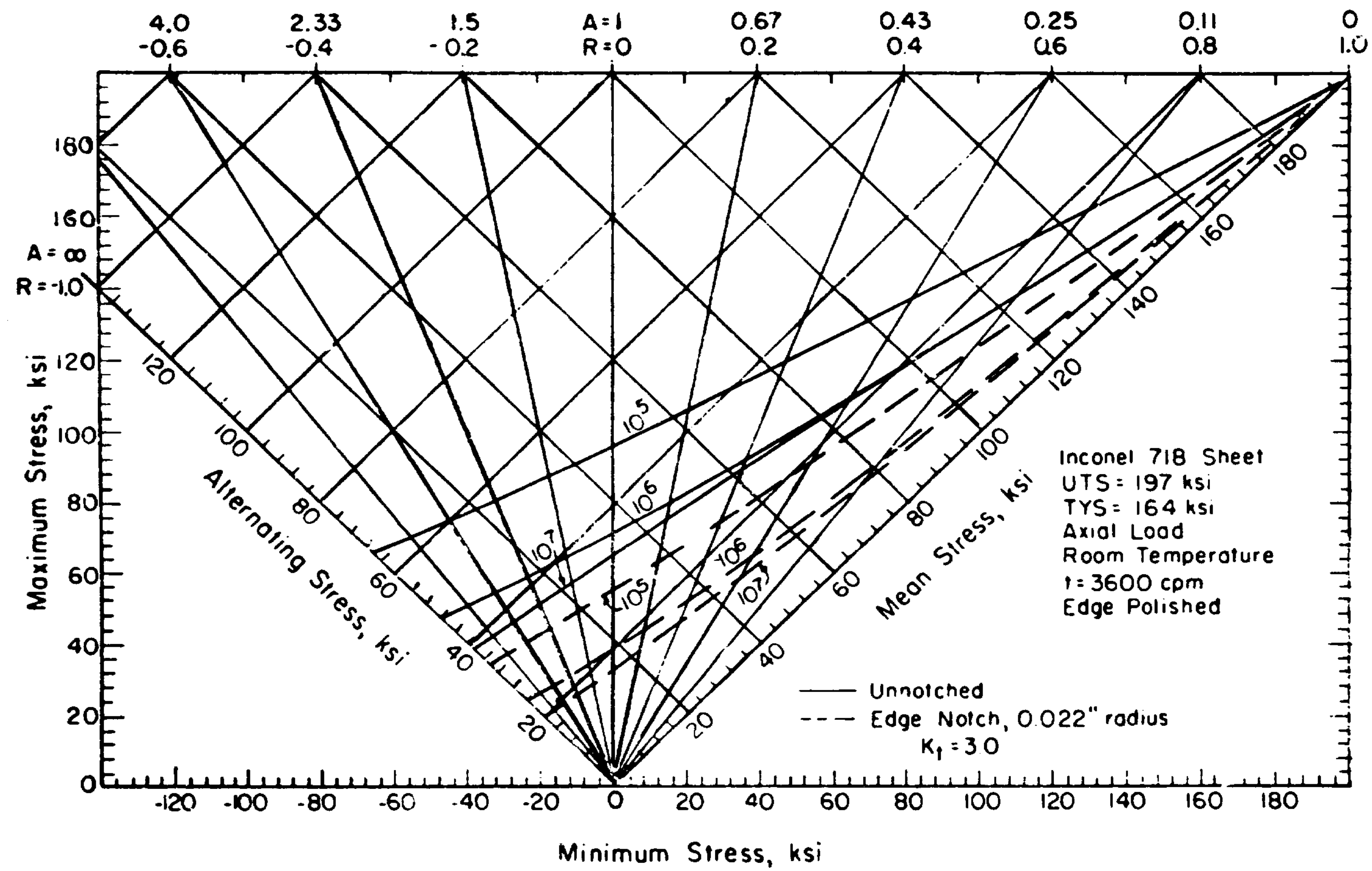

FIGURE 8.65. – Typical constant-life fatigue diagram for Alloy 718 at room temperature.
[1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2]

(Ref. 8.10)

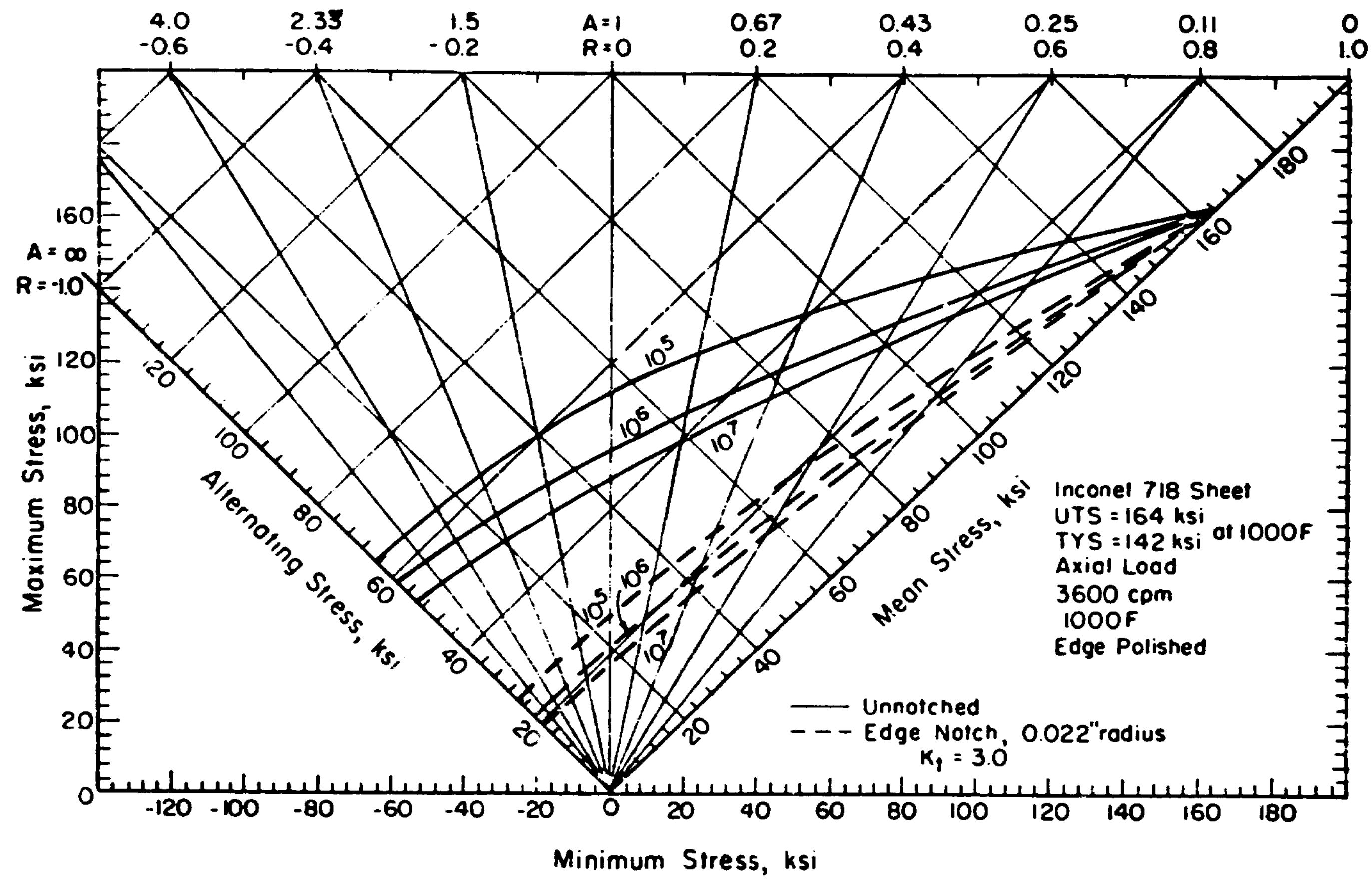

FIGURE 8.66. — Typical constant-life fatigue diagram for Alloy 718 at 1000° F (538° C)
[1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm^2]

(Ref. 8.10)

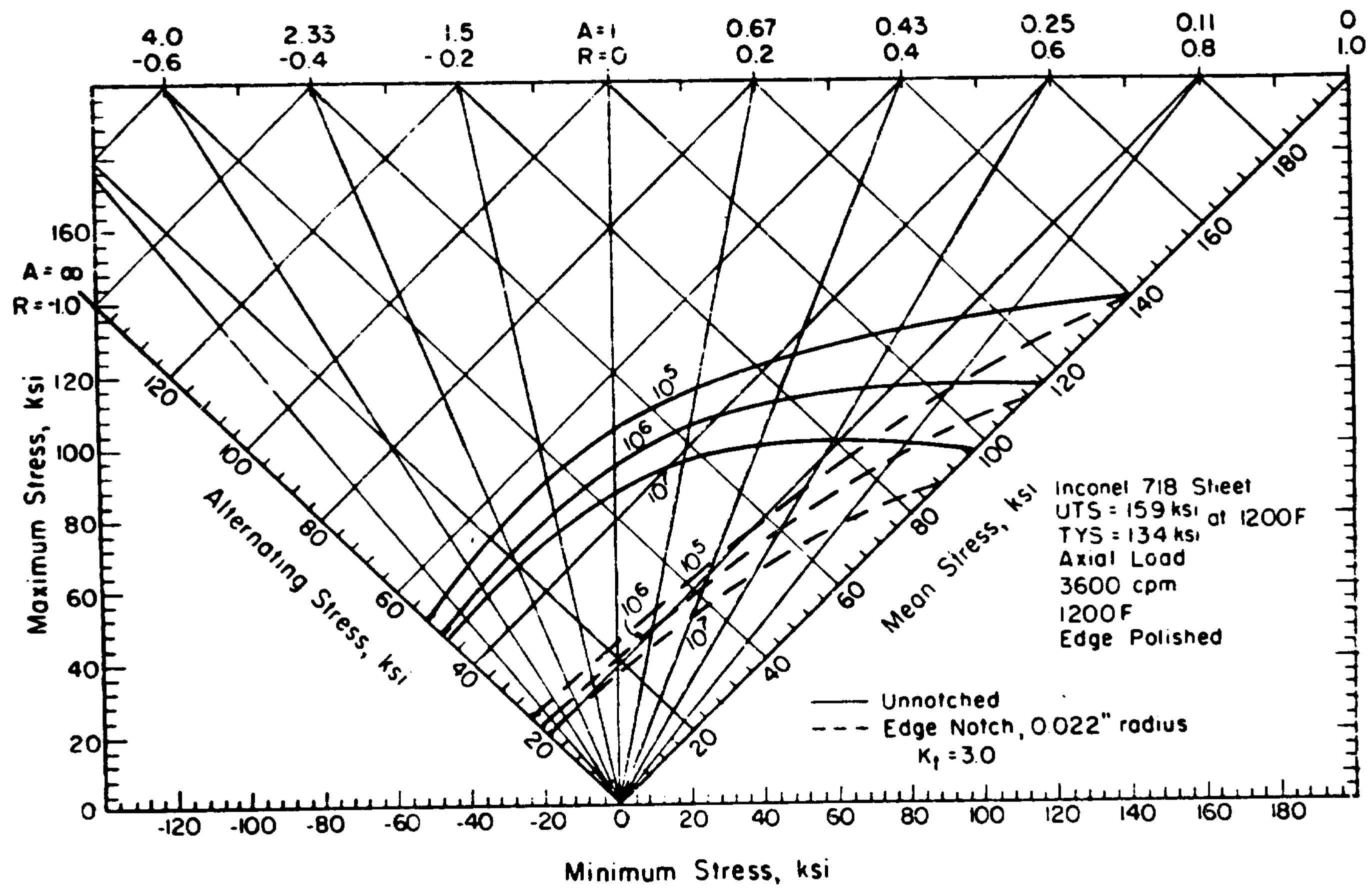

FIGURE 8.67. — Typical constant-life fatigue diagram for Alloy 718 at 1200° F (649° C).
[1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm²]
(Ref. 8.10)

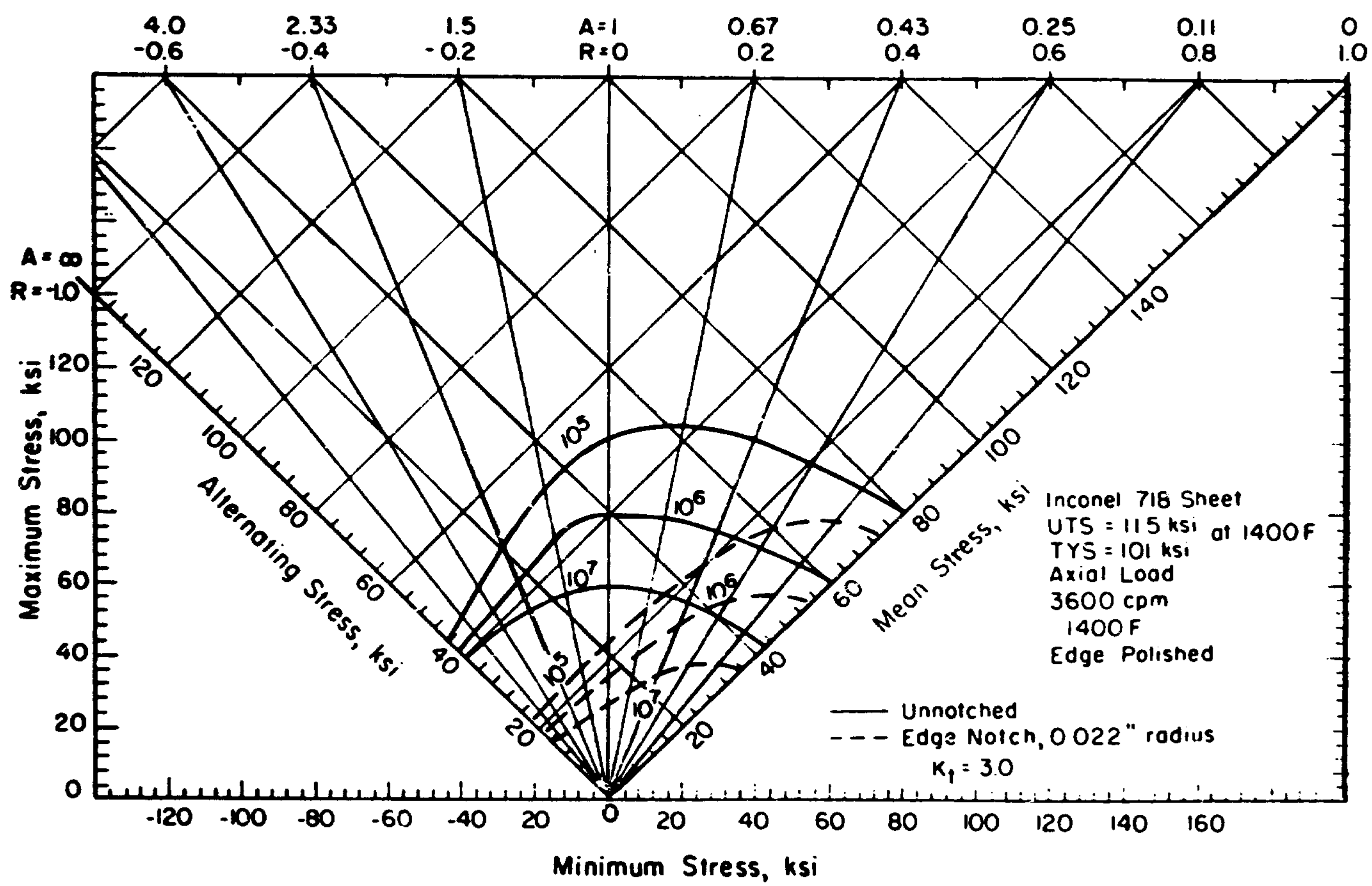

FIGURE 8.68. – Typical constant-life fatigue diagram for Alloy 718 at 1400°F (760°C).
[1 inch = 25.4 mm; 1 ksi = 0.70307 kg/mm²]

(Ref. 8.10)

Chapter 8 - References

8.1 International Nickel Company, Huntington Div., Current Data Report, "Inconel 718, Age Hardenable Nickel-Chromium Alloy," May 1961.

8.2 Aerospace Material Specifications, Society of Automotive Engineers, latest Index, May 1971.

8.3 International Nickel Co., Huntington Div., "Inconel Alloy 718," February 1968.

8.4 Materials in Design Engineering, Materials Selector Issue, Mid-October 1965.

8.5 International Nickel Company, Huntington Div., Basic Data Report, "Inconel 718, Age-Hardenable Nickel-Chromium Alloy," September 1960.

8.6 Alloy Digest, "Inconel 718" (Filing Code: Ni-65), Engineering Alloys Digest, Inc., April 1961.

8.7 T.M. Cullen and J.W. Freeman, "The Mechanical Properties of Inconel 718 Sheet Alloy at 800, 1000, and 1200 F, University of Michigan, NASA CR-268, July 1965.

8.8 A.J. McCulloch et al., "Fatigue Behavior of Sheet Materials for the Supersonic Transport," Vol. I., Summary and Analysis of Fatigue and Static Test Data, AFML-TR-64-399, January 1965.

8.9 A.J. McCulloch et al., "Fatigue Behavior of Sheet Materials for the Supersonic Transport," Vol. II, Static Test Data, S-N Test Data and S-N Diagrams, AFML-TR-64-399, January 1965.

8.10 Military Handbook-5A, Dept. of Defense, "Metallic Materials and Elements for Flight Vehicle Structures," FSC 1500, February 1966; latest change order January 1970.

Chapter 9

PHYSICAL PROPERTIES

9.1 Density at room temperature.

Annealed, 0.296 lbs/in^3; 8.18 g/cm^3.
Aged, 0.297 lbs/in^3; 8.21 g/cm^3 (ref. 9.1).

9.2 Thermal Properties

9.21 Thermal conductivity (K), figure 9.21
9.22 Thermal expansion (α), figure 9.22.
9.23 Specific heat (c_p). 0.104 Btu/lb/°F (0.104 cal/g/°C) (ref. 9.4).
9.24 Thermal diffusivity.

9.3 Electrical Properties

9.31 Electrical resistivity.
Annealed, 127 microhms-cm at room temperature.
Aged, 121 microhms-cm at room temperature (ref. 9.1).

9.4 Magnetic Properties

9.41 Permeability (H = 200). 1.001 at 70° F (21° C) for annealed or age-hardened products (ref. 9.2).
9.42 Susceptibility
9.43 Curie Temperature.
Annealed, <–320° F (–196° C)
Aged, –170° F (–112° C) (ref. 9.2).

9.5 Nuclear Properties

9.6 Other Physical Properties

9.61 Emissivity.
9.62 Damping Capacity.

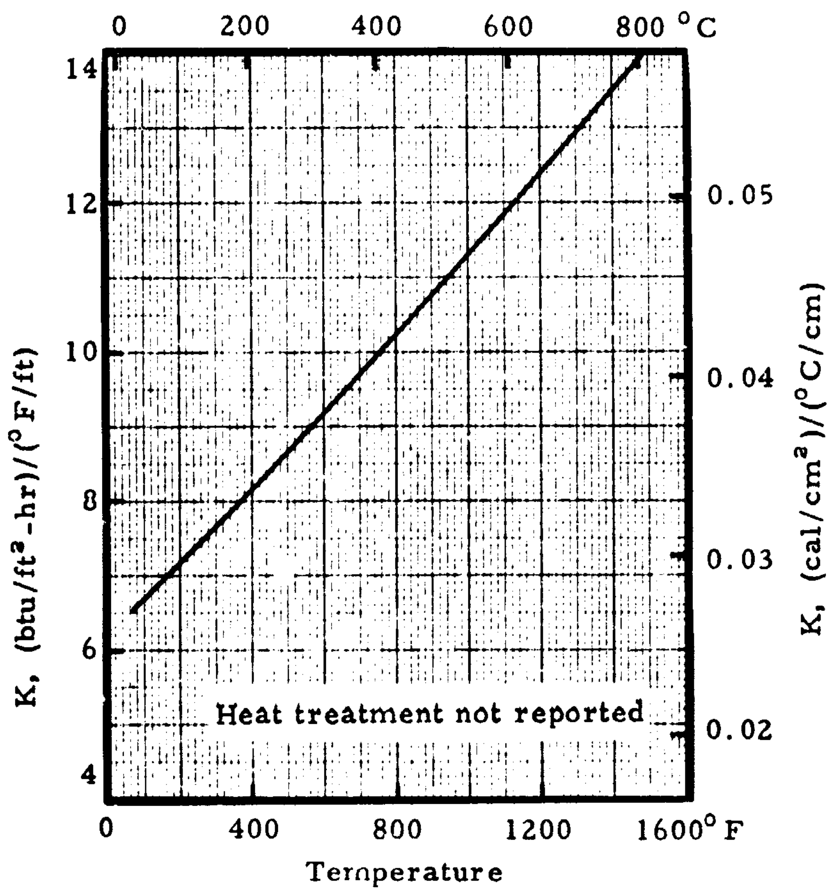

FIGURE 9.21. – Thermal conductivity, K, of Alloy 718

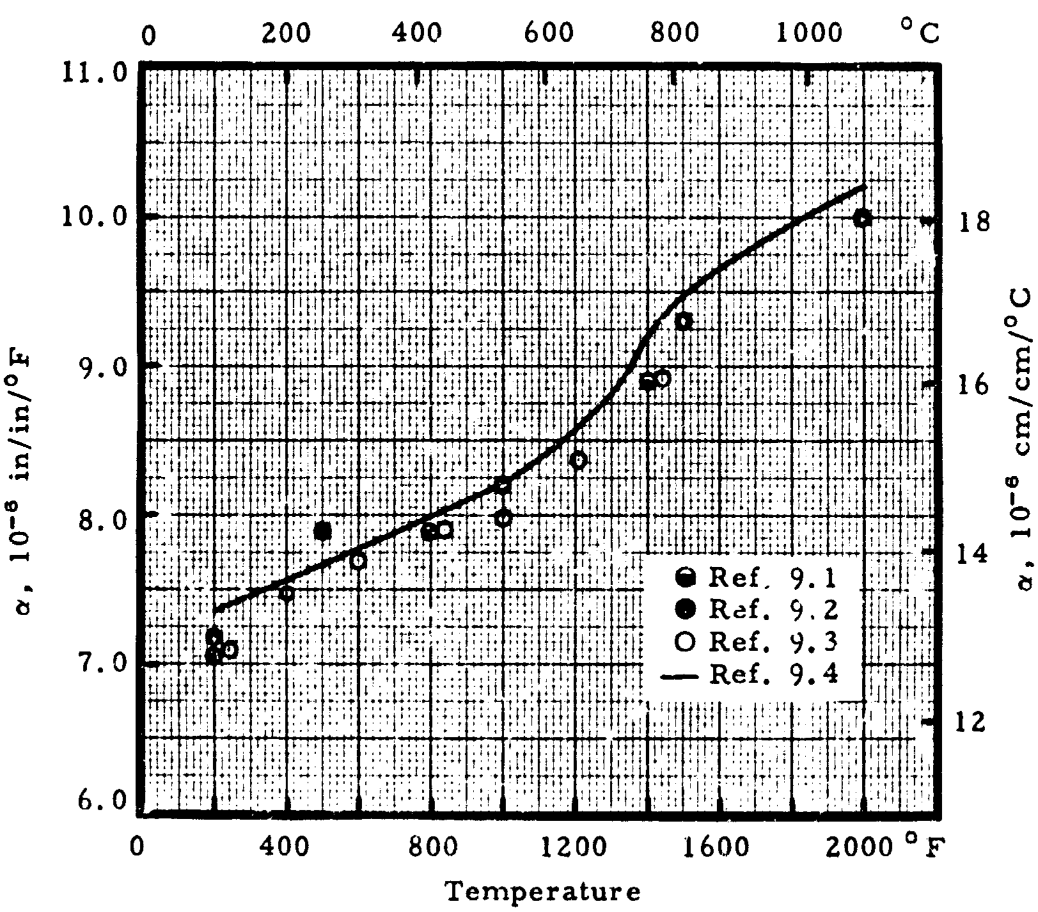

FIGURE 9.22. — Mean coefficient of linear thermal expansion for Alloy 718 from room temperature to temperature indicated.

Chapter 9 - References

9.1 Alloy Digest, "Inconel 718" (Filing Code, Ni-65), Engineering Alloys Digest, Inc., April 1961.

9.2 International Nickel Co., Huntington Div., "Handbook of Huntington Alloys," Fifth Edition, January 1970.

9.3 General Electric Co., "Inconel 718, Specification B," December 1959.

9.4 International Nickel Co., Huntington Div., "Inconel Alloy 718," February 1968.

Chapter 10

CORROSION RESISTANCE AND PROTECTION

10.1 General. Nickel and the high-nickel alloys are characterized by their excellent resistance to many kinds of corroding media. In general, these alloys are not attacked by inside or outside rural or suburban atmospheres unless a sulfurous condition is present. Marine atmospheres may have a slight effect. They are completely resistant to corrosion by fresh waters, but quiet and stagnant sea water may attack these alloys by causing pitting. Rapid-flowing sea water has less effect (refs. 10.1, 10.2).

The complex nickel-base alloys, containing closely controlled amounts of several elements are oxidation resistant. All of these alloys will oxidize, however, at high temperatures if oxygen is present and the rate of oxidation will depend upon alloy composition, temperature, oxygen concentration, diffusion rates, and a host of other variables. Light surface oxidation is often not objectionable in these alloys, and may even be beneficial if the oxide is tightly adherent and protective. Intergranular oxidation, on the other hand, can be a serious problem as the penetration of the oxide front reduces the effective cross-section and may also act as a notch to reduce fatigue resistance. Precipitation-hardenable nickel-base alloys are particularly susceptible to intergranular oxide penetration. The rate of oxidation is affected by stress and it appears that oxidation rate is increased when a "critical" stress level is reached (ref. 10.6).

10.2 Nickel-Chromium-Iron Alloys. This class of alloys, in general, is resistant to corrosion by alkalies, dry gases at room temperature, neutral or alkaline salts, oxidizing acids (at moderate temperatures) and oxidizing alkaline salts. The nickel-chromium-iron alloys are attacked by wet chlorine, bromine, sulfur dioxide, and gases of sulfur compounds.

They are moderately resistant to sulfuric and hydrochloric acids at ambient temperatures, but are not normally used with hot or concentrated hydrochloric acid. These alloys have complete resistance to organic acids such as occur in food products, fair resistance to hot concentrated organic acids such as acetic and formic acids, and are highly resistant to fatty acids at elevated temperatures (refs. 10.1, 10.2).

10.3 Resistance of Inconel Alloy 718. Comprehensive information on the corrosion resistance of this particular alloy does not appear to be available as yet. It has been reported, however, that the alloy has excellent resistance to oxidation at temperatures up to 1800° F (982° C) (ref. 10.3) and that the alloy has been used successfully in sea water (ref. 10.4).

The stress corrosion susceptibility of Inconel Alloy 718 (and numerous other alloys) in chloride solutions has been investigated by the Douglas Aircraft Co. (ref. 10.5). Unnotched sheet specimens were tested by alternate immersion in syntehtic sea water and also in 5 percent salt spray tests under stresses up to 90 percent of F_{ty}. Precracked specimens were tested by alternate immersion. Sheet conditions included the base temper (aged condition), aged plus exposure at 650° F (343° C) for 1000 hours, a braze cycle heat treatment (BCHT), and BCHT plus TIG welded with Inconel 718 filler metal. The results of the study indicate that, within the conditions of the tests employed, the Inconel Alloy 718 sheet was immune to stress corrosion in chloride salt solutions. None of the specimens failed during stress-corrosion testing regardless of temper, welding or surface preparation, nor did any specimens show reduction of mechanical properties due to stress corrosion.

10.31 This alloy, like most nickel-base alloys, is susceptible to sulfur embrittlement or attack by elements such as lead, bismuth, etc. It is, therefore, essential to remove all foreign matter such as grease, oil, etc. from the alloy prior to any heating operations (ref. 10.3).

10.32 There are indications that Inconel Alloy 718 is subject to hydrogen embrittlement when exposed to hydrogen pressures ranging from one to more than 7000 atmospheres at ambient temperatures (ref. 10.7), and it is suggested that the alloy not be used for gaseous hydrogen tankage.

In one study at Rocketdyne, the strength of notched specimens tested in 1 ksi of hydrogen was shown to be 42 percent less than the strength when tested in 1 ksi of helium (ref. 10.8). In a continuation of the work, the results indicated a reduction of only 15 percent in 2 ksi of hydrogen (compared with helium) at ambient temperature; no reduction was noted in tests conducted at cryogenic temperatures. (Note: 1 ksi = 0.7 kg/mm², 2 ksi = 1.4 kg/mm².)

An investigation at Boeing indicated extensive reduction of fracture toughness resulting from a high-pressure high-purity hydrogen environment (ref. 10.10).

In work performed at the NASA Manned Spacecraft Center (ref. 10.11), it was indicated that cryogenic vessels constructed of Inconel Alloy 718 are subject to flaw growth in a hydrogen environment under various conditions of temperature, pressure, and stress. Welded areas of pressure vessels have lower resistance to crack propagation than the parent metal. Extreme conditions for safe operation of cryogenic storage vessels are 450 psig at −100° F (i.e., after a cryo proof test conducted with liquid nitrogen at 2000 psig). (450 psi = 0.3 kg/mm²; 2000 = 1.4 kg/mm².)

10.4 Protective Measures. Surface protection is usually not required when the alloy is used in the temperature range from -320° F (-196° C) to 1300° F (704° C) for many service applications. However, surface treatments have been developed to improve some of the characteristics of nickel-base alloys, and these are discussed in Chapter 11.

Chapter 10 - References

10.1 N. E. Woldman, "Nickel and High Nickel Alloys," Materials and Methods, Manual 21, December 1946.

10.2 International Nickel Co., "Nickel and Nickel-Base Alloys, Their Use in the Design of Corrosion-Resistant Machinery and Equipment," Technical Bulletin T-13.

10.3 E.H. Schmidt, "Correlation of Experimental Data for Fabrication of Inconel 718," Rocketdyne/North American Report No. RD-62-10, July 1962.

10.4 International Nickel Co., Huntington Div., "Handbook of Huntington Alloys," Fifth Edition, February 1968.

10.5 Douglas Aircraft Co., "Chloride Stress Corrosion Susceptibility of High Strength Stainless Steel, Titanium Alloy, and Superalloy Sheet," ML-TDR-64-44, Vol. I, March 1964.

10.6 C.H. Lund and H.J. Wagner, "Oxidation of Nickel and Cobalt-Base Superalloys," DMIC Report 214, March 1965.

10.7 J.E. Campbell, "Effects of Hydrogen Gas on Metals at Ambient Temperatures," DMIC Report S-31, April 1970.

10.8 R.J. Walter and W.T. Chandler, "Effects of High Pressure Hydrogen on Metals at Ambient Temperatures," Reports R-7780-1, R-7780-2, and R-7780-3 under Contract NAS8-19, Rocketdyne, February 28, 1969.

10.9 R.J. Walter and W.T. Chandler, "Effect of Hydrogen Environment on Inconel-718 and Ti-6Al-4V under Simulated J-2 Engine Operating Conditions," Report R-7920 under Contract NAS8-19C, Rocketdyne, 30 June 1969.

10.10 P.M. Lorenz, "Effects of Pressurized Hydrogen Upon Inconel 718 and 2219 Aluminum," Paper W9-13.2 presented at 1969 WESTEC Conf., Los Angeles, California, March 10-13, 1969.

10.11 R. Forman and R.K. Allgeier, "Stainless Steel 301 and Inconel 718 Hydrogen Embrittlement," NASA Tech Brief 70-10621, December 1970.

Chapter 11

SURFACE TREATMENTS

11.1 General. A number of surface treatments have been developed that result in improved characteristics in nickel-base alloys. Among the characteristics that can be improved are lubricity, resistance to corrosive attack by oxidizing and/or sulfur-containing atmospheres, and resistance to wear, erosion, and fatigue. These treatments may be grouped into two general categories: mechanical treatments and coating treatments (ref. 11.1).

11.2 Mechanical Treatments. Mechanical surface treatments such as burnishing, peening, explosive hardening, and planishing are not used to any great extent for nickel-base alloys. When used, however, they serve a variety of functions from improvement of surface finish to increasing fatigue strength and surface hardness. Improvements in mechanical properties result largely from the residual compressive stress introduced into the metal surface by these treatments. Burnishing and planishing are used to improve surface finish, while explosive hardening, peening, and planishing are used to cold work the metal and/or to develop residual compressive stresses (refs. 11.1 through 11.5). A tabulation of mechanical surface treatments used or considered for use with nickel-base alloys is presented in table 11.1.

The burnishing of nickel-base alloys is accomplished in a manner similar to that used for other metal alloys, except that the work hardening characteristics of nickel-base alloys should be taken into account in the burnishing process (refs. 11.2, 11.3).

Experimental studies (ref. 11.5) have indicated that explosive hardening processes can be applied to nickel-base alloys. As yet, however, commercial application of these processes to nickel-base alloys has not developed to any extent.

Peening is a well knwon process used to develop compressive stress in a metal surface. This process is not commonly used for nickel-base alloys, but it appears that these alloys do not have characteristics that prevent the use of peening (ref. 11.6). It has been shown (ref. 11.7) that hammer peening can be used to prevent cracking of repair welds made in Rene' 41 and Astroloy upon subsequent reheat treatment.

Planishing is the production of a smooth surface finish by a rapid succession of blows delivered by polished dies, hammers, or by rolling in a planishing mill. Most nickel-base alloys can be planished successfully. Roll planishing is a useful mechanical treatment for fusion welds, especially butt-welds. Since planishing is actually a type of cold-forming operation, a roll-planished weld is effectively cold worked. With nickel-base alloys that work-harden readily, the degree of working can be such as to effect a considerable increase in the strength of a weld joint (refs. 11.1 and 11.8). Also, in some cases, it may be possible to impart sufficient cold work to a weld for it to recrystallize when subsequently heated to an annealing temperature. In this way, the weld grain structure becomes that of a wrought material and is more homogeneous. This technique has been applied to Inconel Alloy 718 fusion butt-welds in sheet metal components (ref. 11.9).

Very little specific information is available on mechanical surface treatments as applied to Inconel 718 products. It would be expected, however, that these treatments can be successfully applied to this alloy.

11.3 Surface Coating Treatments. Coating treatments for nickel-base alloys include diffusion coating, electroplating, electroless plating, hard-facing, and treatments for purpose of lubrication.

Most diffusion coatings used in the United States for nickel-base alloys are rich in aluminum. They are used primarily to protect the alloy from the degrading effects of service environments. These coatings have not been particularly successful when used for parts subject to sea-air environments where sulfur may also be present (e.g., from jet engine fuels). Under these conditions, a severe type of sulfidation attack has been known to occur (ref. 11.1). Diffusion coatings based on boron have been developed in the Soviet Union to obtain very hard cases on nickel-base alloys. Research to develop these and other improved diffusion coatings is in progress in this country.

Nickel alloys generally are not electroplated or electroless-plated because they often inherently possess the corrosion or wear resistance for which plating is usually applied. Where plating is employed, care must be taken to remove the passive surface film that occurs naturally on these alloys.

Hard facing is the process of applying special hard materials (hard-face alloys) to a metallic part by a welding method or comparable technique. The objective of hard facing is to increase the resistance of a part to abrasion, wear or erosion, corrosion, oxidation, thermal shock, or to combinations of these factors. A number of hard facing materials have been developed and they are commonly applied by means of the oxy-acetylene torch. This method allows good control of the operation and produces smooth deposits. Other welding techniques and other methods of application, such as metallizing, plasma-arc deposition, and flame plating have been used to apply hard facings. Although hard facing is not often applied to nickel-base alloys, it has been used to improve the resistance of Inconel 600 to steam erosion (refs. 11.10 through 11.13).

Surface treatments have been developed to provide nickel-base alloys with lubricity under conditions of high temperature or high vacuum where oils and greases would deteriorate. These treatments include lead monoxide films, ceramic-bonded calcium fluoride coatings, application of molybdenum disulfide or tungsten disulfide for lubricity at elevated temperatures and vapor deposition of gold for lubricity under high vacuum (refs. 11.14, 11.15).

Although relatively little specific information is available on the application of surface coatings to Inconel Alloy 718, it appears that many of these coating treatments could be applied to this alloy.

A more detailed discussion of surface treatments for nickel-base alloys is available in r ference 11.1.

TABLE 11.1. — Mechanical Surface Treatments for Nickel-Base Alloys

Source	Ref. 11.1		
Surface Treatment	Characteristic Effect	Satisfactory Results with Process Listed	
		known(c)	expected(d)
Burnishing	Smooth, mirror-like surface	x	
Planishing	Smooth surface		x
	Cold working of welds	(a)	
Peening	Cold working of welds and wrought components		x
	Crack prevention in welds	(b)	
	Improve fatigue strength		x
	Correct distortion in welds		x
	Improve stress corrosion cracking resistance		x
Explosive hardening	Increase strength of welds		x
	Increase tensile and yield strength	x	

(a) Applied successfully to Inconel 600 and Inconel 718.
(b) Applied successfully to Rene' 41 and Astroloy
(c) Expected to be successful on other nickel-base alloys also
(d) Expected to impart noted characteristic to nickel-base alloys.

Chapter 11 - References

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Chapter 12

JOINING TECHNIQUES

12.1 General. Inconel Alloy 718 can be joined satisfactorily by fusion and resistance welding techniques and by brazing. Adhesive bonding and mechanical fasteners of various kinds may also be used where strength-to-weight ratio of the part is not critical.

12.2 Welding. In general, the alloy exhibits excellent weldability and allows considerable flexibility in the control of welding procedures. These characteristics and the relative ease of welding this alloy may be attributed to its sluggish response to thermal treatments (see Chapter 3). In particular, its relatively slow aging response permits welding without the serious danger of cracking caused by rapid hardening during the heating and cooling portions of the weld process.

There has been, however, a problem with hot cracking in the weld-affected zone that appears to be primarily heat oriented and is aggravated by large grain size. The relationship of the chemical and thermomechanical history of a weld to the presence of microfissures in the weld was examined (ref. 12.19) and it was determined that proper mill processing procedure can minimize the undesirable effects of low-melting grain boundary films, principally through control of grain size and secondary phase morphology.

12.21 Fusion Welding. Most fusion welding of this alloy has been done by the "tungsten-inert-gas" (TIG) process. Welding by the "metal-arc-consumable electrode" (MIG) method and by electron-beam techniques have also been used but to a much lesser extent. Shielded metal-arc and submerged-arc processes are not employed for this alloy (refs. 12.1, 12.7).

12.211 Tungsten-Inert-Gas-Process. The TIG process has been used to weld material in thicknesses ranging from 0.020 to 1.5 inches 0.508 - 38 mm). Filler metals may or may not be used. Argon is the commonly used protective gas, with helium preferred for deep-penetration welds. Fully efficient weld joints require complete cleaning of joint areas prior to welding, and light interlayer grinding should be employed between passes. The alloy is similar to other nickel-base alloys in that it does not flow readily when molten. Thus, for most joints over about 1/8-inch thick, designs which contribute to full joint penetration are necessary. In one study on welding 1/4-inch and 1/2-inch plate, difficulty was encountered in obtaining full penetration weld joints, and it was demonstrated that U-groove joints gave the best results, with double-U grooves necessary for the thicker plate (ref. 12.1). (Note: 1 inch = 25.4 mm.)

In the same study, it was shown that consistent penetration and higher welding speeds were more readily obtained by using helium gas in preference to argon gas for TIG welding of 1/4- and 1/2-inch plate; also, porosity was reduced. Properly made welds, however, are not affected by the type of shielding gas employed. Optimum TIG weld settings for plate, when helium shielding gas is used, are presented in table 12.1.

The effect of shielding gas on TIG butt-welds in 0.045-inch sheet has also been studied. No difficulties were encountered with either helium or argon gas, although helium gas shielding did require less heat input and resulted in cleaner weld appearance. This difference in appearance did not cause any detectable effects. Process settings used in this study are shown in table 12.2.

A number of filler metals have been evaluated during weldability studies with Rene' 41 and Inconel 718 filler metals receiving the most attention because their use allows the weld metal to respond to aging treatments. Hastelloy W, Hastelloy R-235, Haynes 25, Incoweld A, and Inconel 69 have also been investigated (refs. 12.1, 12.3, 12.4, 12.5). It appears from the results of studies made to date that the Inconel 718 and Rene' 41 filler metals are preferred for welds in sheet stock. Shop experience has shown that more process problems have occurred when Rene' 41 filler is used or when welding manually. Thus, automatic or semi-automatic welding with Inconel 718 filler is preferred. If manual methods are used, they must be carefully controlled.

Studies have been made of highly restrained welds in thick plate in the range from 0.75 to 1.5 inch (ref. 12.3). When TIG welding with Rene' 41 filler was employed, it was concluded that there was no need for weld stress relief prior to aging and that heavy sections can be welded in the fully-aged condition even under restrained conditions. It was also concluded that welds in heavy sections can be repaired without annealing, and that the repair welds could be aged directly with no difficulty. The results of other investigations have indicated that the use of Hastelloy R-235 filler wire produces good weld tensile and rupture properties in 1/4- and 1/2-inch TIG plate.*

TIG welds with no filler in 0.025-, 0.050-, and 0.125-inch* sheet were evaluated as part of the supersonic transport research program (ref. 12.2). The results indicated that Inconel 718 showed exceptional welding characteristics for its alloy class. Defect-free welds were consistently obtained when the cleaning and welding procedures normally used for nickel-base alloys were employed. Circular patch tests indicated no "hot short" problem, and it was possible to make simulated repair welds without cracking. It was determined that the alloy can be welded in the annealed or in the cold rolled (20%) and aged

* 1 inch = 25.4 mm.

condition. Joint efficiencies determined in this investigation ranged from 64 percent at a test temperature of -100° F (-73° C) to 60 percent at a test temperature of 600° F (316° C). Bend tests on welded samples indicated a minimum bend radius of 1t for the 0.025-inch gage and 4t for the 0.125-inch gage.*

It has been reported (ref. 12.2) that for severely strained joints, the low freezing temperature of Inconel 718 filler metal is a serious limitation; for such joints, Rene' 41 filler is preferred.

12.212 Electron-Beam Welding. Limited information is available on the welding of Inconel Alloy 718 by electron-beam techniques. The results of one study indicated that butt-welds can be made in parts up to 0.875-inch thick with commercial equipment and by welding from each side. Weld strengths equal to double-aged base metal were obtained and the welds were more gas-free than the base metal. It was reported that considerably less shrinkage was also encountered in comparison with TIG welds (ref. 12.4). Another study (ref. 12.2) revealed that electron-beam welding of 0.025- to 0.125-inch sheet resulted in room temperature static strength and fracture properties that were higher than those obtained on the same material by TIG methods. More recently, it has been determined that electron-beam welding cannot produce joints of adequate strength and integrity to join loading stubs to Alloy 718 plate in the short-transverse configuration (ref. 12.19).*

12.213 Mechanical Properties of Fusion Welds. As discussed in Chapter 3, Section 3.122, the properties and microstructure of Inconel Alloy 718 are influenced markedly by chemical composition and heat treatment. These factors also influence the properties of weldments in this alloy. Recommended heat treatments and compositions have undergone many changes since the alloy was first developed, and it appears that these and other factors are still being studied to determine optimum conditions.

In a recent study (ref. 12.6), the tensile properties of TIG welded 0.25-inch plate were obtained over a range of temperatures from -423° to 1500° F (-253° to 816° C). It should be noted that the heat treatment employed in these studies was the higher annealing and aging temperatures recommended by the major producer of the alloy for tensile limited applications (see Chapter 3, Section 3.221). The results of the weld tests are compared to the base metal values in figure 12.1. High weld strengths were obtained up to about 1200° F (649° C). Cryogenic weld properties were excellent. It was reported that the high weld properties as compared with parent metal properties were probably due to low hardener content in the parent metal plate.*

In figure 12.2, typical tensile properties of automatic TIG butt-welded sheet are presented for various temperatures. In this investigation, mill-annealed material was welded and then given a post-weld age treatment. Most of the failures occurred in the

* 1 inch = 25.4 mm.

heat affected zone except at 1800° F (982° C) where all failures were in the parent metal. Little difference in properties was observed when comparing samples welded with Rene' 41 filler metal to those welded with Alloy 718 filler metal. Rene' 41 welds did have a greater hardness gradient across the weld zone. Tensile properties of welded specimens were about equal to parent metal properties, but elongations were lower in all cases.

The ultimate strength of TIG welded unnotched and notched sheet specimens at test temperatures from –110° F to 650° F (–79° to 343° C) are presented in figure 12.3. The effect of low temperatures on the strength of TIG welded sheet is shown in figure 12.4.

The net fracture strength obtained for various weld procedures are compared to original parent metal static strength in figure 12.5.

Cree-rupture data for TIG welded plate at 1200° and 1350° F (649° and 732° C) are compared to parent metal rupture properties in figure 12.6.

Axial tension fatigue properties of TIG welded sheet are presented in figure 12.7 for smooth and notched specimens at room temperature. Figure 12.8 shows fatigue data for TIG welded sheet at various test temperatures from –110° to 650° F (–79° to 343° C). Typical weld joint efficiency of TIG welded sheet joints is given in figure 12.9.

12.22 Resistance Welding. The alloy can be resistance seam and spot welded if proper precautions are taken. The most severe condition occurs in the spot welding of thin-gage material in the aged condition. This material may be spot welded by using schedules with low heat input and extended weld times with very flat electrode tip radii to help maintain sheet-to-sheet contact (refs. 12.1, 12.2, 12.10).

In one study (ref. 2.10), spot diameters of 0.100 inch for the spot welding of 0.020-inch sheet and 0.24 inch for 0.060-inch sheet permitted spots as close as 0.188 and 0.500 inch, respectively, before shunting occurred. The minimum edge distance was 0.125 and 0.250 inch, respectively, for these spot weld samples. The results of a comparison between age plus welded specimens and weld plus aged are given in figure 12.10. In all cases, the lap shear strength of single spot weld joints was improved by aging after welding. Cross tension results, however, were about 10 percent higher when the aged plus weld procedure was employed. This behavior was also observed in another study as shown in figure 12.1 for 0.025- and 0.050-inch spot welded sheet. It has also been observed (refs. 12.10, 12.11) that the ductility ratio (cross tension/lap shear) indicated that aging after welding decreased ductility. However, in no case did the ductility ratio fall below 30 percent which is considered to be adequate resistance weld joint ductility. (Note: 1 inch = 25.4 mm.)

Typical spot weld machine settings are given in table 12.3.

A study of resistance seam welding of sheet has indicated that a satisfactory seam weld should be at least twice as wide as the sheet thickness, with at least 30 percent penetration into each sheet and 20 to 40 percent overlap (ref. 12.10). Typical seam weld machine settings for 0.020- and 0.060-inch sheet are given in table 12.4. Best strength properties were obtained when the seam welded samples were aged after welding.

The effect of temperature on the strength of flash welded bar is shown in figure 12.12. Joint efficiency ranged from 100 percent at room temperature to 95 percent at 1400° F (760° C) based on yield strength.

12.3 Brazing. The alloy can be brazed successfully if the procedures normally employed for alloys of this class are used. The braze-ability of Inconel 718 is comparable to that of PH15-7Mo stainless steel and is better than that of alloys containing over 2 percent aluminum plus tantalum.

In a study to compare the wettability of Inconel 718 by three nickel-base and three silver-base brazing alloys on 0.045-inch sheet (ref. 12.13), specimen surfaces were prepared by alkaline cleaning and liquid honing before brazing in a vacuum furnace at approximately $3\text{-}5 \times 10^{-4}$ torr(5×10^{-9} kg/mm^2). Various brazing temperatures from 1675° to 2075° F (913° to 1135° C) were used for times of 10 to 15 minutes. The results indicated that the nickel-base alloys (Coast Metals 50, Coast Metals 52, and Coast Metals 56LC) exhibited superior wetting and flow characteristics when applied to Inconel 718. As a result of this study, tests were made to determine room temperature shear strength of joints made with CM 52 and CM56LC (ref. 12.14). The results are given in table 12.5. The strongest joints were obtained with a 15-minute brazing cycle. However, it was concluded that long cycles were detrimental due to serious intergranular penetration by the filler metal and adverse thermal effect on the parent Inconel 718 sheet. It has been reported that brazing above 1800° F (982° C) may reduce the ductility of aged Inconel 718 in the temperature range 1200°–1500° F (649°–816°C) as shown in figure 12.13. The effect of solution treat temperatures on aged parent metal tensile properties is illustrated in figure 12.14. These curves indicate that a brazing temperature of 2150° F (1177° C) will result in a 15- to 20-percent degradation of aged parent metal properties.

It is recommended that each brazing alloy and procedure selected for use should be subjected to temperature and time surveys to determine the optimum combination of parameters required for satisfactory joints. Specimens of the base metal should accompany the braze specimen throughout the braze cycle and subsequent thermal treatment to determine the effect of the thermal cycling on base metal properties (ref. 12.14).

12.4 Adhesive Bonding. Nickel base alloys can be bonded using presently available techniques and adhesives. Relatively little work has been done on adhesive bonding of these alloys, however, because nickel-base alloys are normally used at temperatures above the present maximum service temperatures of organic adhesives. Inorganic adhesives of sufficient ductility and low enough maturing temperatures have not as yet been developed sufficiently to compete with brazing and welding techniques for these alloys. For special applications, however, where elevated temperature effects, high strength joints, and corrosion resistance are not factors, adhesive bonding may have advantages over other joining procedures.

Ref. 12.15 is recommended as an informative summary of the state of the art of adhesive bonding of nickel-base alloys.

TABLE 12.1. — Optimum TIG Weld Settings for Plate when Helium Shielding Gas is Used (a)

Source	Ref. 12.1					
Alloy	Inconel Alloy 718					
Thickness, in (b)	0.250			0.500 (e)		
Pass number	1	2	3	1	2	3
Current, amp	70-75	70-75	80-85	90-95	90-95	100-110
Arc voltage (c)	13-15	13-15	14-16	14-16	14-16	15-17
Weld speed, in/min	1.5-2.0	1.5-2.0	1.5-2.0	2.0	2.0	2.0
Filler wire, dia, in	0.063	0.094	0.094	0.063	0.094	0.094
Wire feed rate, in/in weld	2	4	4	2	4	4
Torch gas, cu-ft/hr (d)	30	30	30	35	35	35

(a) Joint design: 0.156 root radius, 0.04-0.05 land single U-groove
(b) 1 in = 25.4 mm
(c) Voltages are averages due to erratic nature when using helium
(d) 1 cu-ft = 0.0283 m^3
(e) Five or six passes are needed for 0.5-inch plate.

TABLE 12.2. — Process Settings for Automatic TIG Welds in Sheet

Source	Ref. 12.1	
Alloy	Inconel Alloy 718	
Thickness, in (a)	0.045 Sheet	
Automatic TIG Welding Process	Shielding Gas	
	Argon	Helium
Current, amp.	80	40
Arc voltage, V	8-16	16-18
Weld speed, in/min	8	6-8
Filler wire, dia, in	0.030-0.035	0.030-0.035
Wire feed rate, in/min	12-15	8-9
Torch gas, cu-ft/hr (b)	20-24	20
Backup gas, cu-ft/hr	4	4

(a) 1 inch = 25.4 mm
(b) 1 cu-ft = 0.0283 m^3

TABLE 12.3. – Typical Spot Weld Machine Settings

Source	Ref. 12.10			
Alloy	Inconel Alloy 718 Sheet			
Machine Setting	Material Condition and Thickness			
	0.020 in, As Rec(a)	0.020 in, Aged	0.060 in, As Rec	0.060 in, Aged
Preheat, %	---	8	---	---
Preheat impulses	---	2	---	---
Preheat time, cycles	--	10	---	---
Weld heat, %	16	16	40	38
Weld impulses	2	2	2	2
Weld time, cycles	4	10	8	8
Current decay heat, %	10	---	35	35
Current decay time, cycles	3	---	6	6
Cool time, cycles	0.5	.5	1.5	1.5
Squeeze time, cycles	21	21	21	21
Hold time, cycles	50	50	61	61
Weld force, lb (b)	660	750	2850	2900
Forge delay, cycles	11-B (c)	11-B (c)	O-E (c)	O-E (c)
Forge force, lb	1500	1950	5380	5400
Electrode class, RWMA	III	III	III	III
Electrode diam, in	5/8	5/8	5/8	5/8
Electrode radius, in	3	10	5	5

(a) 1 inch = 25.4 mm
(b) 1 lb = 0.4536 kg
(c) B = beginning of weld; E = end of weld.

TABLE 12.4. – Typical Seam Weld Machine Settings

Source	Ref. 12.10			
Alloy	Inconel Alloy 718 Sheet			
Machine Setting	Material Condition and Thickness			
	0.020 in, As Rec(a)	0.020 in, Aged	0.060 in, As Rec	0.060 in, Aged
Weld heat, %	45	45	65	65
Weld impulses	4	4	8	8
Weld time, cycles	5	5	4	4
Cool time, cycles	0.5	0.5	0.5	0.5
Motor speed	50	50	70	70
Motor rotation, cycles	5	5	5	5
Drive (b)	---	---	---	---
Tip force, lb (c)	800	800	2000	2000
Forge time, cycles	5	5	5	5
Wheel class, RWMA	III	III	III	III
Wheel thickness, in	1/2	1/2	1/2	1/2
Wheel radius, in	3	3	3	--
External cooling	Yes	Yes	No	No

(a) 1 inch = 25.4 mm
(b) 1 lb = 0.4536 kg
(c) Intermittent.

TABLE 12.5. – Average Shear Strength of Vacuum Brazed Lap Joints

Source	Ref. 12.14					
Alloy	Inconel Alloy 718, 0.043-0.051 in Sheet (a)					
Braze Metal	Brazing Temp, °F	Brazing Temp, °C	Brazing Time, min	Failure Location	Failure Stress ksi	Failure Stress kg/mm²
CM 52	1950	1066	15	Base metal	28.2	19.8
	2000	1093	15	Braze joint	27.1	19.1
	2050	1121	15	Braze joint	19.8	13.9
	1950	1066	3	Braze joint	23.3	16.4
	2000	1093	3	Braze joint	27.8	19.5
	2050	1121	3	Braze joint	27.6	19.4
CM 56LC	2050	1121	15	Braze joint	31.0	21.8
	2100	1149	15	Base metal(b)	25.5	17.9
	2150	1177	15	Base metal(b)	17.2	12.1
	2050	1121	3	Braze joint	27.5	19.3
	2100	1149	3	Braze joint	23.2	16.3
	2150	1177	3	Braze joint	25.6	18.0

(a) 1.09–1.30 mm.
(b) In fillet. Calculated failure stress.

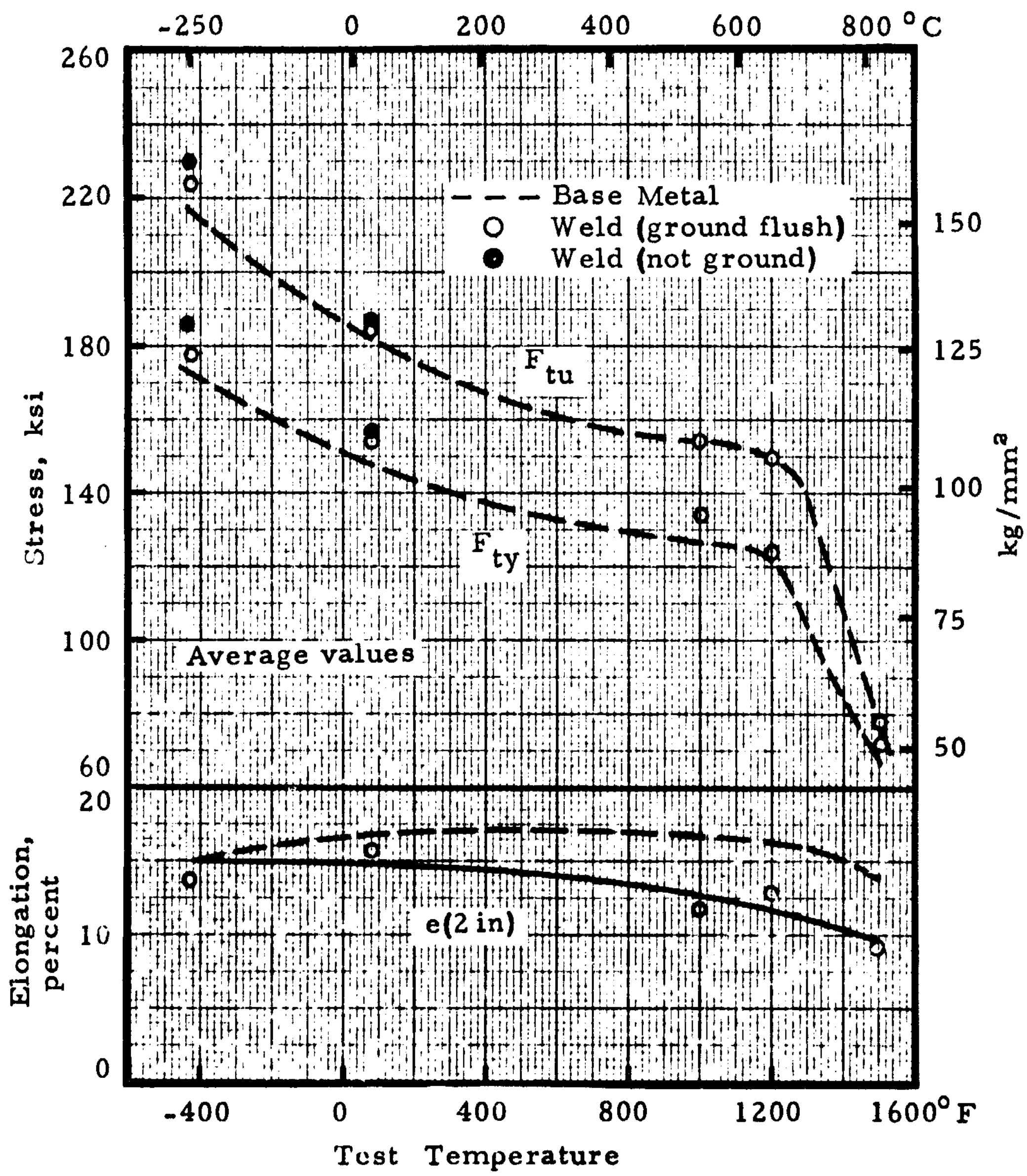


FIGURE 12.1. — Tensile properties of TIG welded Alloy 718 plate; 0.25 inch (6.35 mm).

[1950° F (1066° C), 1 hr, AC + 1400° F (760° C) 10 hrs, FC to 1200° F (649° C), hold 20 hrs]

Ref. 12.6

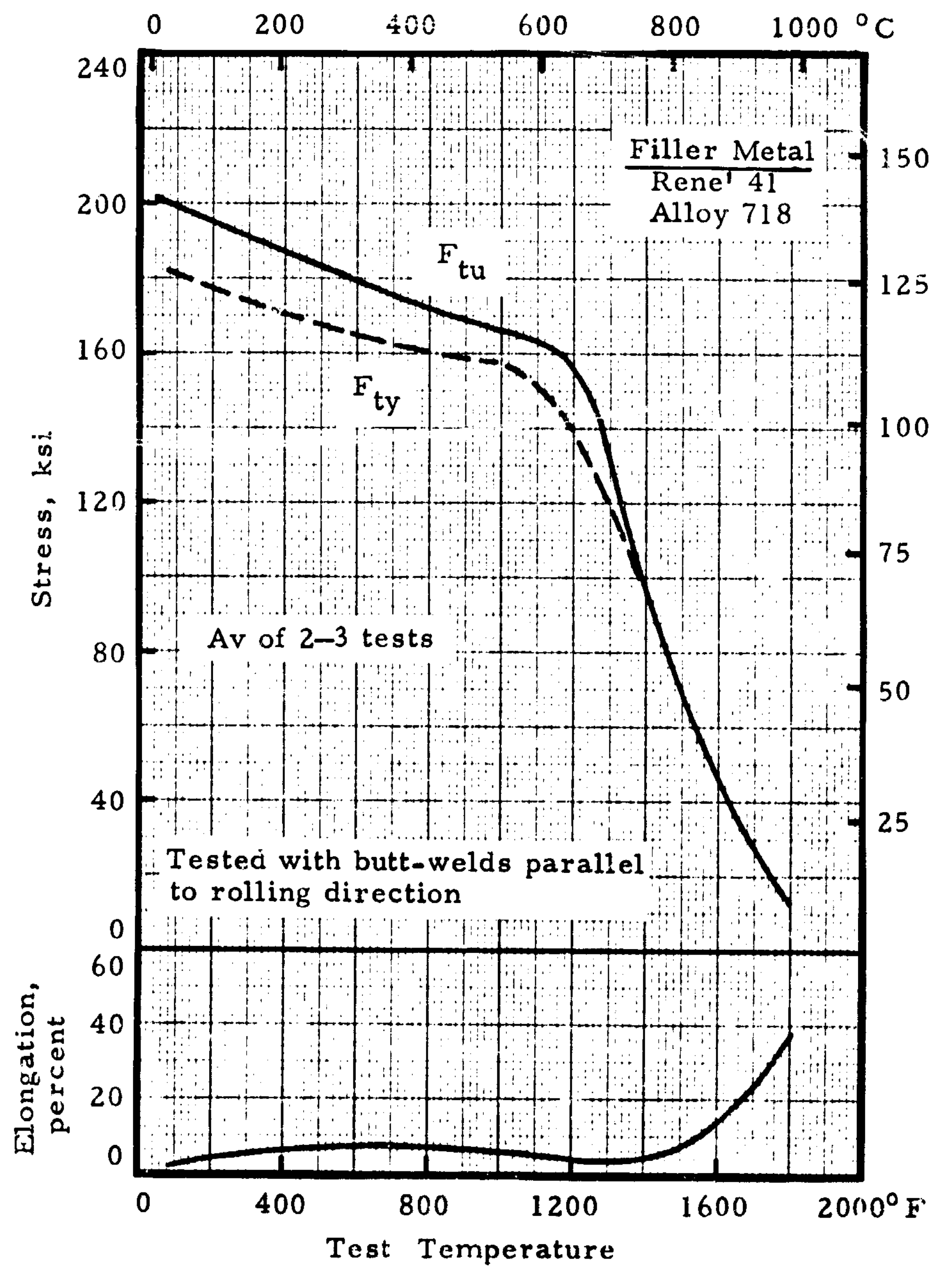


FIGURE 12.2. – Tensile properties of automatic TIG butt-welded Alloy 718 sheet after post-weld aging; 0.045 inch (1.14 mm).

[Mill ann; age 1325° F (718°C), 8 hrs, FC 20° F (11°C)/hr to 1150° F (621°C), AC.

(Ref. 12.1)

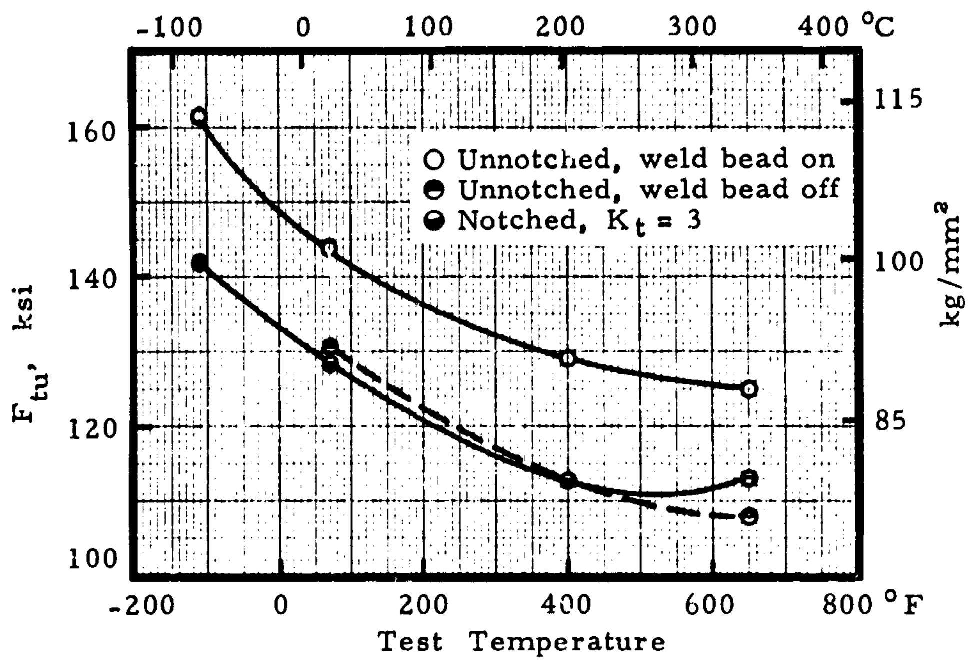


FIGURE 12.3. — Ultimate strength of TIG welded unnotched Alloy 718 sheet specimens; 0.125 inch (3.75 mm). [Aged 1275° F (691° C), 8 hrs, FC at 20° F (11° C) to 1150° F (621° C), hold 10 hrs, AC + TIG weld] (Ref. 12.2)

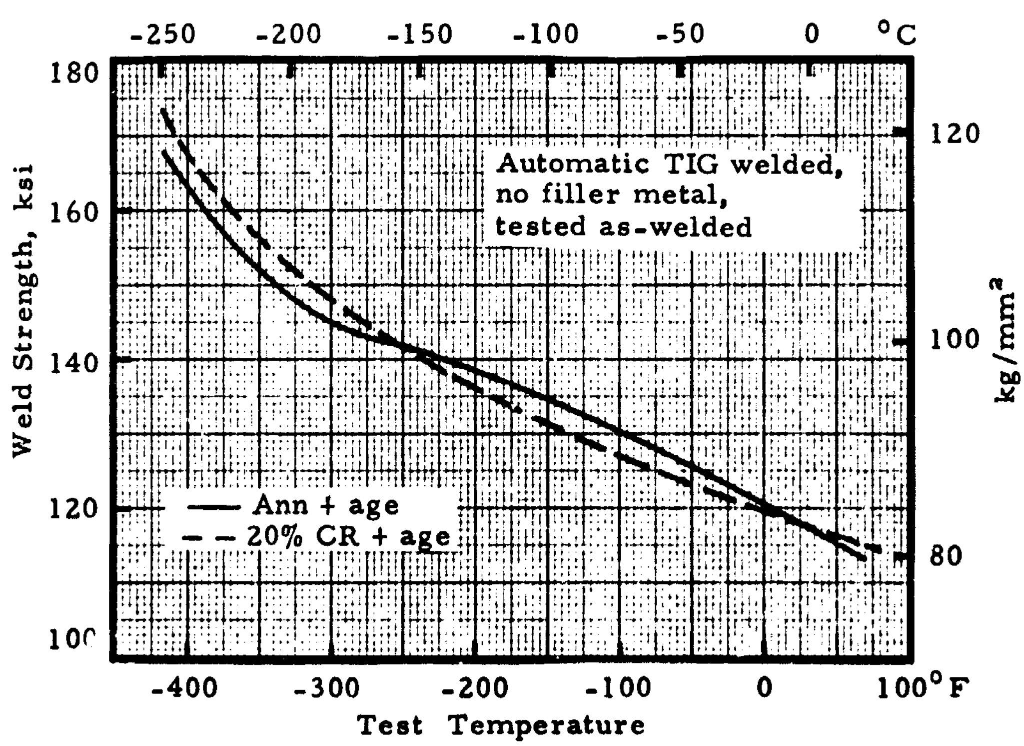


FIGURE 12.4. — Effect of low temperatures on the strength of TIG welded Alloy 718 sheet; 0.030 inch (0.762 mm). [Aged 1325° F (718° C), 8 hrs, FC to 1150° F (621° C), hold 18 hrs total, AC] (Ref. 12.8)

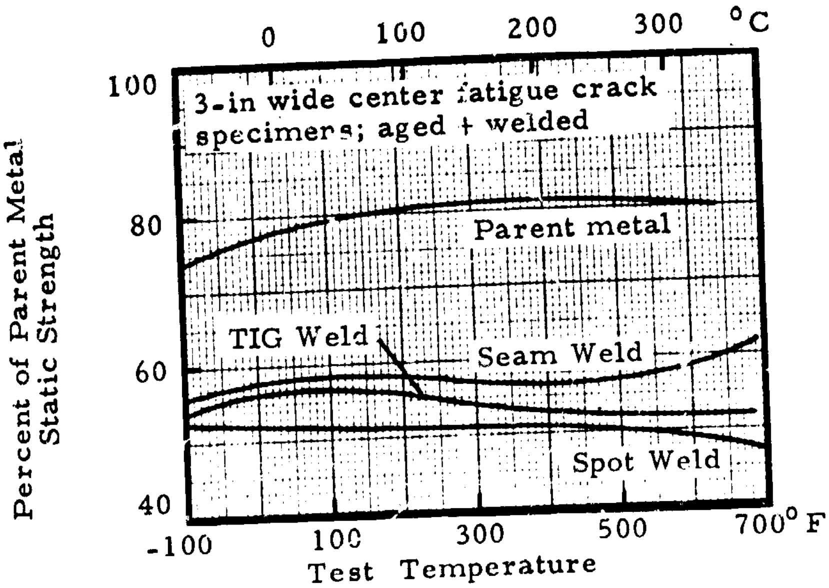


FIGURE 12.5. — Net fracture strength of Alloy 718 for various weld procedures compared to parent metal static strength; 0.025—0.125 in (0.635—3.75 mm) sheet. [CR 20% + aged 1275° F (718°C), 8 hrs, FC 20° F (11° C)/hr to 1150°F (621° C), hold 10 hrs, AC] (Ref. 12.2)

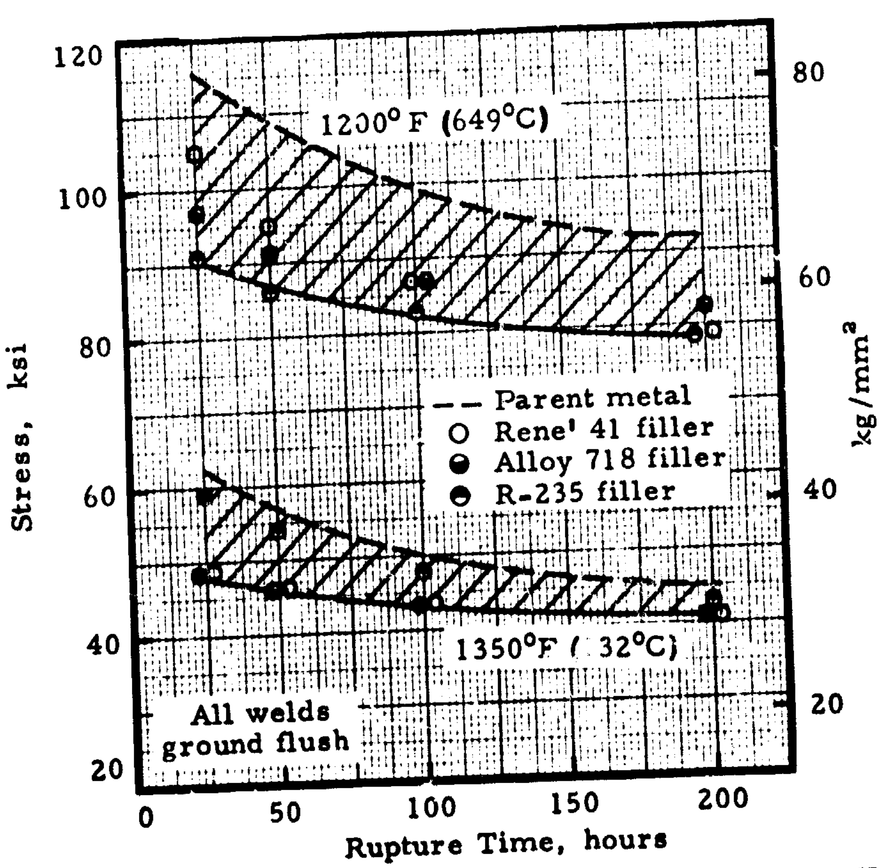


FIGURE 12.6. — Creep rupture data for Alloy 718 plate TIG welded with various filler metals; 0.50 in (12.7 mm). [TIG weld + aged 1325° F (718° C), 16 hrs, AC] (Ref. 12.9)

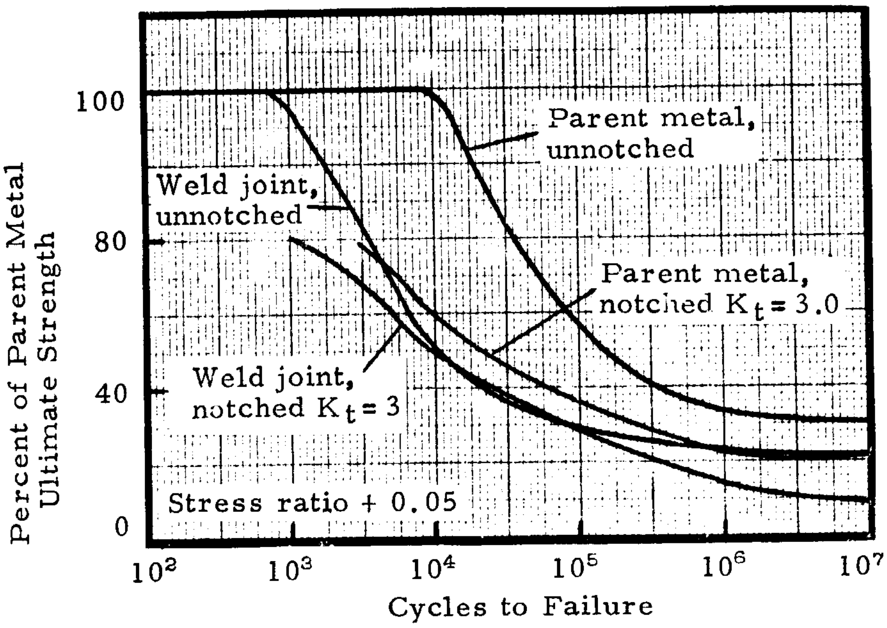


FIGURE 12.7. – Axial-tension fatigue properties of Alloy 718 parent metal and weld joints at room temperature; 0.032–0.125 in (0.81 to 3.8 mm) sheet, TIG welded.
(Ref. 12.1)

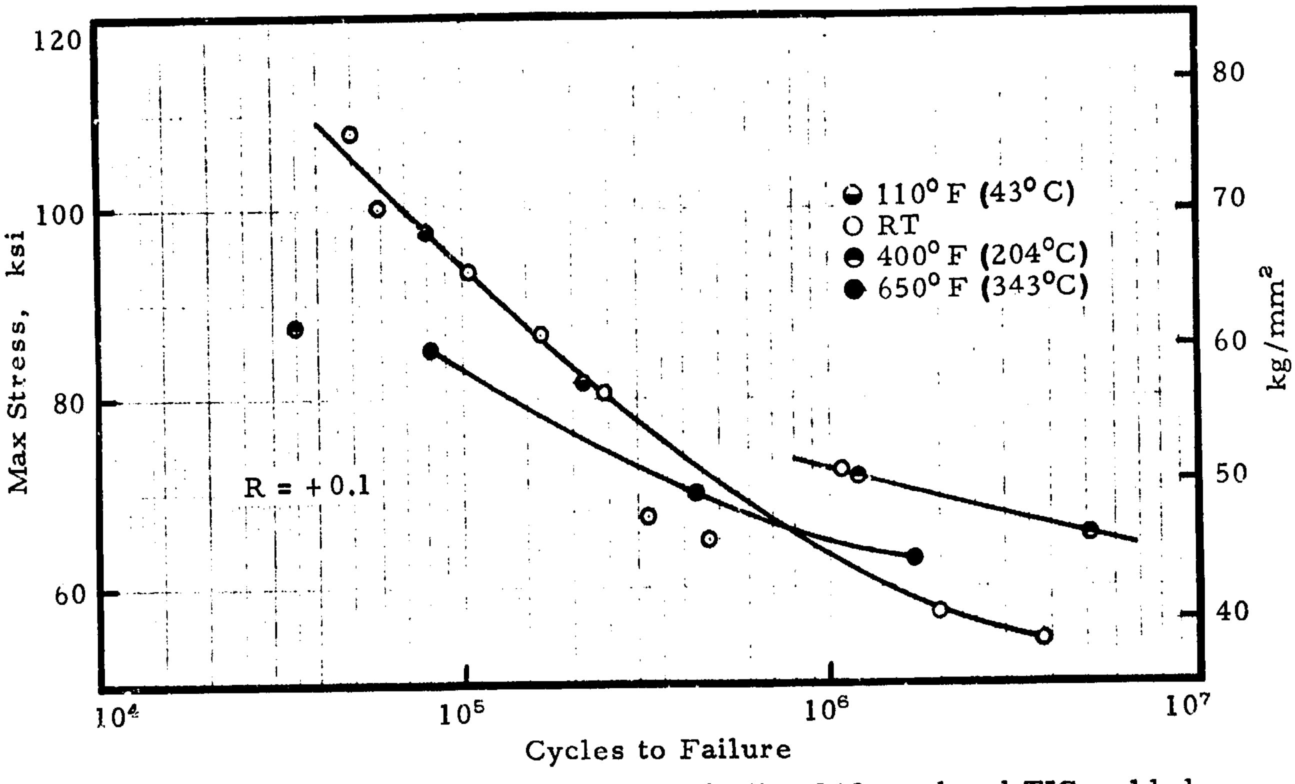
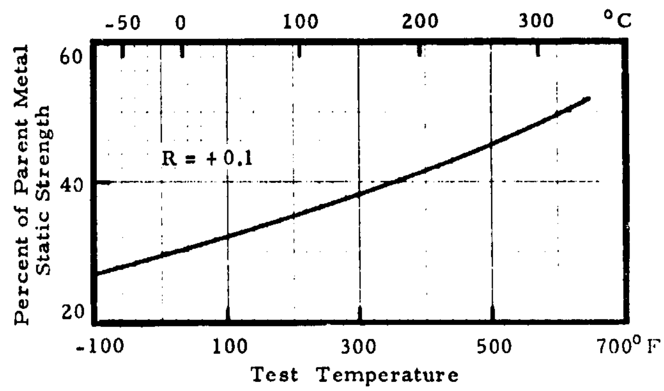


FIGURE 12.8. – Fatigue strength of Alloy 718 aged and TIG welded sheet at various test temperatures; 0.125 in (3.75 mm).
(Ref. 12.2)



F URE 12.9. — Axial-fatigue TIG weld joint efficiency i. Alloy 718 sheet at various test temperatures; 0.025–0.125 in (0.635–3.75 mm), aged.
(Ref. 12.2)

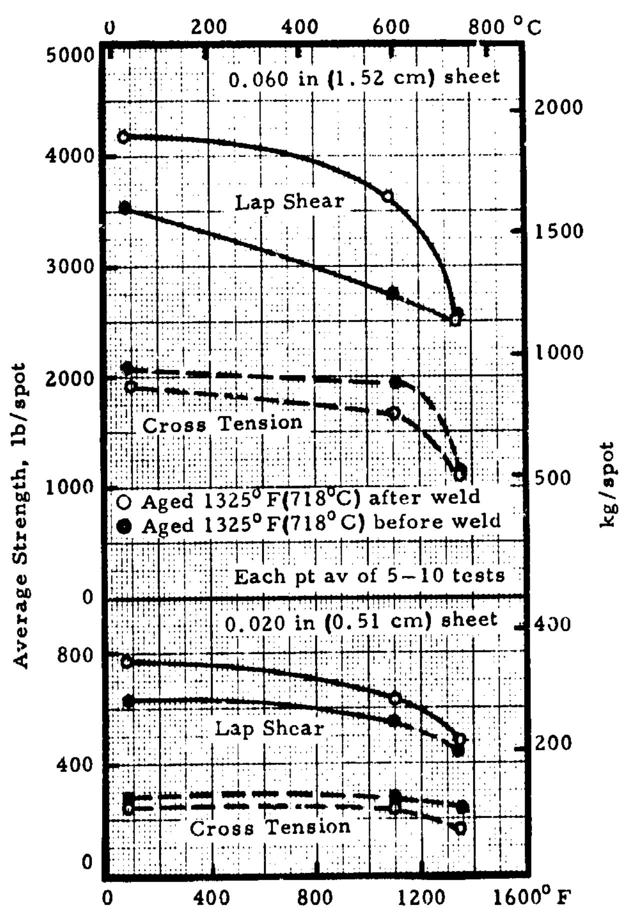


FIGURE 12.10. — Single spot weld lap shear and cross tension data for Alloy 718 at room and elevated temperatures.
(Ref. 12.10)

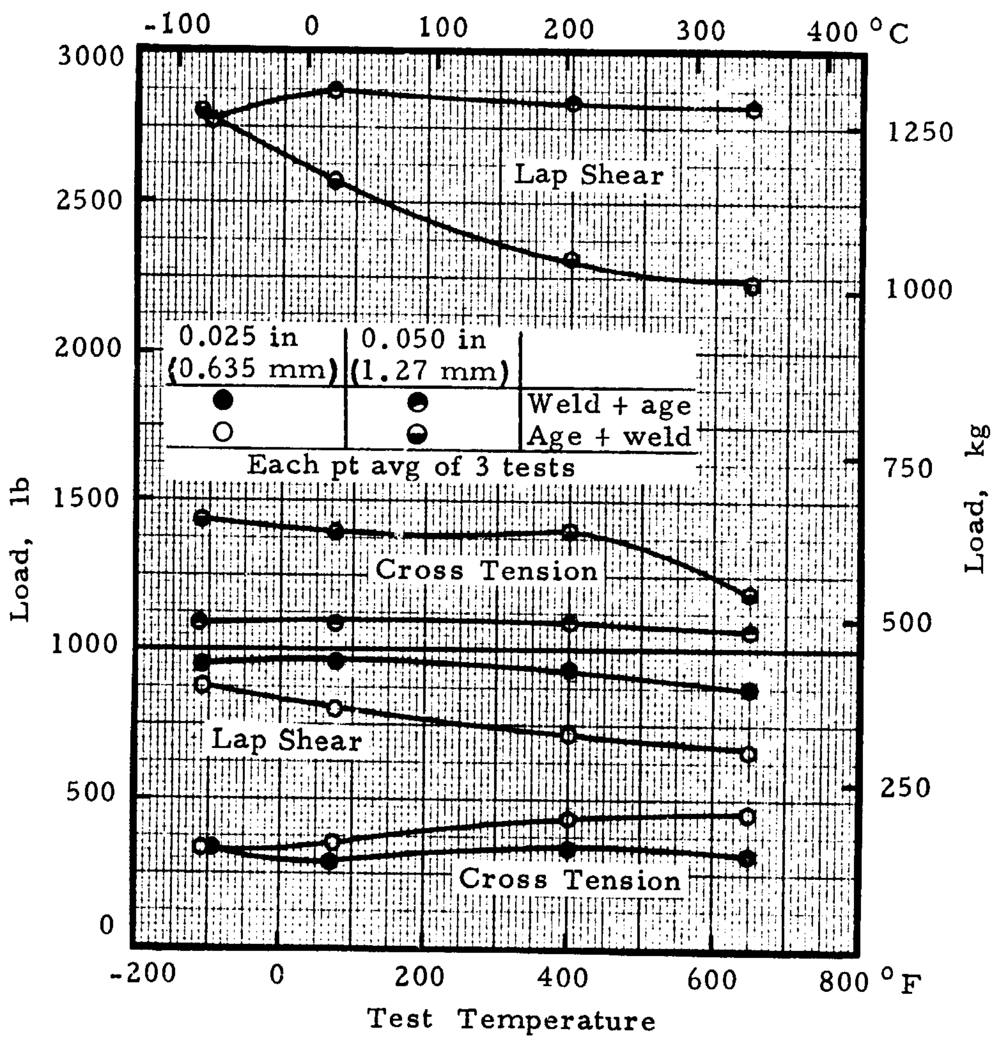


FIGURE 12.11. — Single spot weld lap shear and cross tension data for Alloy 718 sheet at various test temperatures. [Aged 1275° F (718° C), 8 hrs, FC at 20° F (11° C)/hr to 1150° F (621° C), 10 hrs, AC]

(Ref. 12.2)

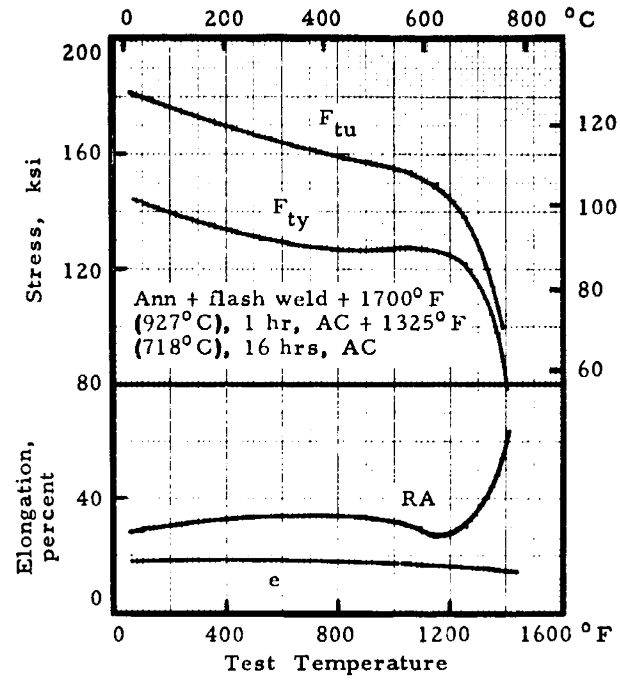


FIGURE 12.12. – Effect of room and elevated temperature on tensile properties of flash welded Alloy 718 bar; 5/8 in (15.9 mm). (Ref. 12.1)

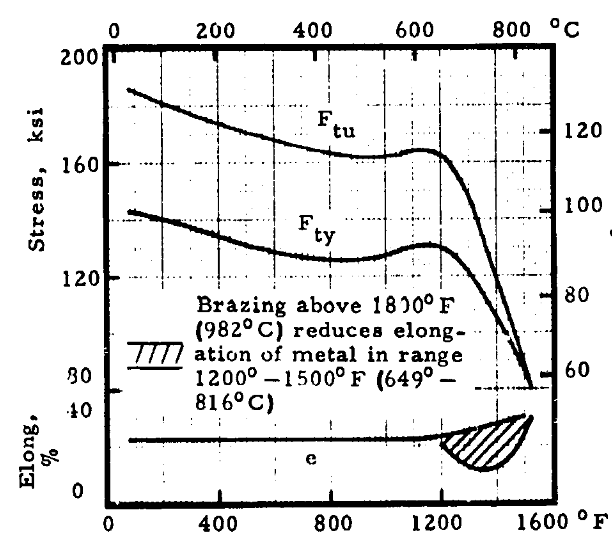


FIGURE 12.13. – Effect of room and elevated temperature on tensile properties of Alloy 718 sheet and effect of brazing on elongation. (Mill ann, aged 1325° F (718°C) 16 hr) (Ref. 12.9)

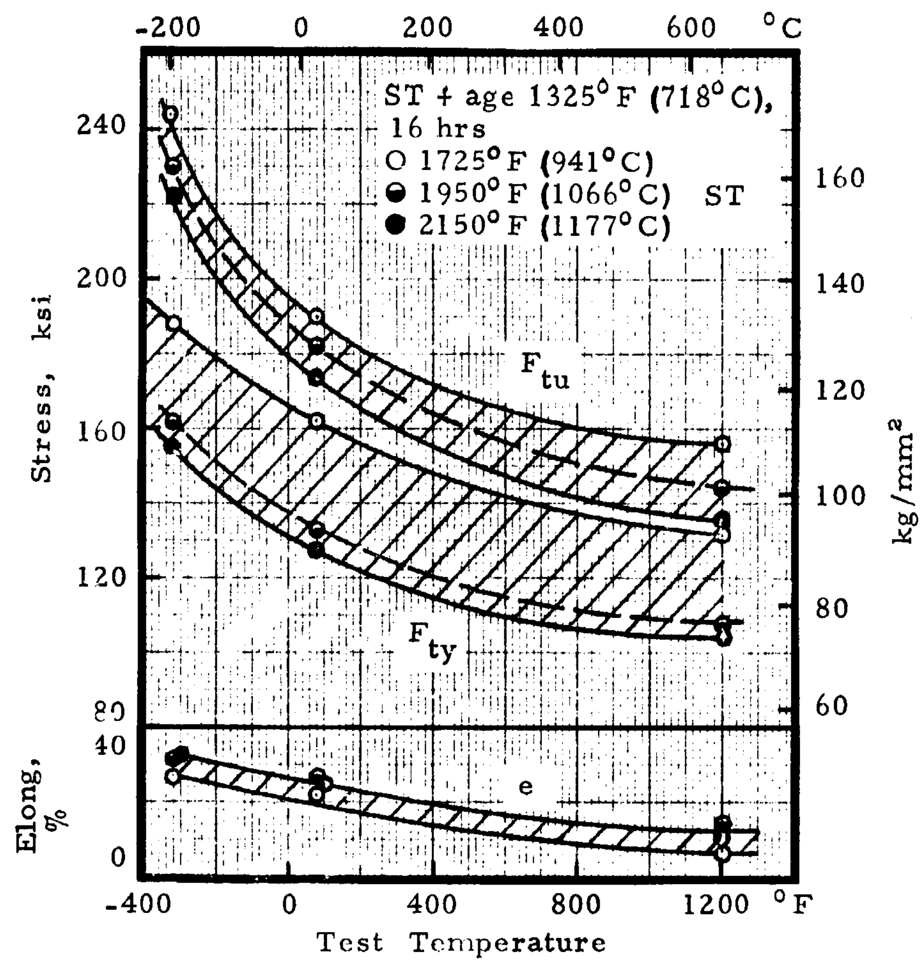


FIGURE 12.14. – Effect of test temperature on tensile properties of Alloy 718 for various solution anneal temperatures.

(Ref. 12.1)

Chapter 12 - References

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