AUTHOR: W. D. KLOPP

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

1 **GENERAL**
Waspaloy is a widely used superalloy with primary applications in aircraft turbine engines as forged turbine and compressor disks. Other applications include turbine cases, shafts, and blades. Waspaloy was originally developed in the late 1940s as a turbine blade material. However, the increase in engine operating temperatures led to the development of higher strength cast alloys which have largely replaced Waspaloy in blade applications. The combination of good tensile and fatigue properties of Waspaloy at intermediate temperatures have made it attractive for disk applications in both turbine and compressor sections. In recent years, the mechanical properties of Waspaloy have been upgraded by thermal-mechanical processing to produce a superior disk material referred to as Super Waspaloy. In particular, the tensile and fatigue properties at intermediate temperatures of Super Waspaloy are superior to those of standard Waspaloy. Waspaloy is strengthened by a combination of solution strengthening, carbide strengthening, and gamma-prime precipitate strengthening. The volume fraction of gamma-prime precipitate is normally about 20 volume percent. This amount of gamma-prime is sufficient to provide good strengthening, but low enough to allow fabricability. This intermediate level of gamma-prime precipitate makes Waspaloy responsive to thermal-mechanical processing so that mechanical properties can be tailored to the intended application.

1.01 **Commercial Designation**
Waspaloy.

1.02 **Alternate Designations**
Super Waspaloy, UNS N07001.

1.03 **Specifications**
Specifications, Table 1.03.

1.04 **Composition**
Composition, Table 1.04.

1.05 **Heat Treatment**

1.051 A considerable portion of the useful strength of Waspaloy is derived from precipitation of the $M_3(Al,Ti)$ gamma-prime phase. Heat treatment schedules for the alloy generally involve solutioning of gamma-prime by heating at a temperature above the gamma-prime solvus and subsequent precipitation of gamma-prime as fine, highly strengthening, semicoherent particles during stabilization/precipitation heat treatments below the gamma-prime solvus temperature. Variations in gamma-prime precipitate morphology and in associated mechanical properties are obtained by varying the heat treatment schedules and also by appropriate combinations of hot working and heat treatment. The variation of gamma-prime solvus temperature range with titanium plus aluminum content is shown in Figure 1.052.

1.052 Variation of gamma-prime solvus range with titanium plus aluminum content for Waspaloy, Figure 1.052.

1.053 Carbide phases in Waspaloy assist in strengthening primarily by pinning grain boundaries, which reduces grain boundary sliding during high temperature creep. The carbide phases present are MC and $M_{23}C_6$. The distribution of carbon between these phases was shown by the study of Jackman et al. (38) to be a function of both heat treatment and carbon level, as illustrated in Figure 1.054. At 2250 F, a significant portion of the available carbon is tied up as primary undissolved MC, which is unaffected by subsequent lower temperature heat treatments. On aging at temperatures between 1900 and 2250 F, additional MC precipitates, while at temperatures below 1900 F both MC and $M_{23}C_6$ precipitate. The amount of $M_{23}C_6$ precipitate decreases with decreasing carbon content. Aging first at a high temperature such as 1950 F increases the amount of MC precipitate and reduces the amount of carbon available to precipitate at $M_{23}C_6$ during subsequent lower temperature aging treatments. Finer grained wrought structures show similar precipitate-temperature reactions as the large grained cast structures described in Figure 1.054 with the exception of moderately greater amounts of $M_{23}C_6$, which precipitates preferentially at grain boundaries (38).

1.054 Effects of carbon content and precipitation temperature on carbon distribution in cast Waspaloy, Figure 1.054 (a) 0.057 percent carbon, (b) 0.034 percent carbon, and (c) 0.020 percent carbon.

1.055 Standard heat treatments for Waspaloy are described in Table 1.056. Material covered by AMS 5544, 5706, and 5708 is supplied in the "soft" solution heat treated condition for forming or joining. These parts must be further heat treated after fabrication to gain useful strength. Material covered by AMS 5704, 5707, and 5709 is supplied in the fully heat treated condition.

1.056 Standard heat treatments for Waspaloy, Table 1.056.

1.057 After welding the assemblies are generally re-solution, stabilization, and precipitation heat treated.

Re-solution – 1800 to 1850 F for 2 hours, air cool.
Stabilization – 1535 to 1565 F for 4 hours, air cool.
Precipitation – 1385 to 1415 F for 16 hours, air cool.

1.058 Forming. Severely formed components which are not subsequently welded require re-solution, stabilization, and precipitation heat treating.

Re-solution – 1800 to 1850 F for 7 to 15 minutes, air cool.
Stabilization – 1535 to 1565 F for 4 hours, air cool.
Precipitation – 1385 to 1415 F for 16 hours, air cool.

1.059 Mildly formed or unformed components which are not subsequently welded require only stabilization and precipitation heat treating.

Stabilization – 1535 to 1565 F for 4 hours, air cool.
Precipitation – 1385 to 1415 F for 16 hours, air cool.

1.0510 Effect of cobalt content and heat treatment on gamma-prime content of Waspaloy, Figure 1.0510.

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Waspaloy

1.06 **Hardness**
(See also Table 3.011.)

1.061 Hardness range of this material after solution, stabilization, and precipitation heat treatment is RC 34–44.

1.062 Effect of solution annealing temperature on hardness and grain size of hot rolled and cold drawn wire, Figure 1.062.

1.063 Room temperature hardness of solution annealed (0.5 hour at 1975 F) Waspaloy after aging at 1400, 1550, and 1700 F is shown in Figure 1.064. Hardness after aging at 1400 F increases with increasing aging time, reflecting continued precipitation of fine gamma-prime particles. Hardness decreases after aging for 24 hours at 1550 F or 1 hour at 1700 F as overaging of gamma-prime occurs. Increasing hardness with increasing aging time indicates sensitivity to time-dependent notch embrittlement and should be avoided, while decreasing hardness indicates insensitivity to time-dependent notch embrittlement (40). The standard heat treatment includes a stabilization anneal at 1550 F which effectively eliminates time-dependent notch sensitivity. (See also 3.049.)

1.064 Effect of aging exposures at 1400, 1550, and 1700 F on hardness of solution annealed Waspaloy, Figure 1.064.

1.07 **Forms and Conditions Available**

1.071 Forms available are bar, forgings, and sheet in the full range of thicknesses common for vacuum melted material.

1.072 Tubing is available on an experimental basis.

1.073 All of the above products can be supplied in the solution treated or aged conditions.

1.074 Sand and investment castings are available in the as-cast or heat-treated conditions.

1.08 **Melting and Casting Practice**

1.081 Induction vacuum melting and casting is the preferred process. Other vacuum melting processes are also used, although the product is not as strong. Electric furnace air melting produces a distinctly inferior material which is now obsolete. Melting practice for various products as specified by AMS is as follows:

AMS 5704, AMS 5706, AMS 5707, AMS 5708, AMS 5709	Multiple melting using consumable electrode process in the remelt cycle or vacuum induction melted.
AMS 5544, AMS 5586	Multiple melting using vacuum consumable electrode process in the remelt cycle or vacuum induction plus consumable electrode remelt.
AMS 5828	Vacuum induction melting.

1.082 Limited data suggest that vacuum-induction-melted/electroslag-remelted material has better hot workability and creep ductility than straight vacuum-induction-melted Waspaloy (41).

1.09 **Special Considerations**

1.091 Thermal-mechanical processing.

1.0911 The mechanical properties of Waspaloy are substantially influenced by hot working and by heat treatment. Properties have been upgraded in recent years through increased knowledge of thermal mechanical processing and can be tailored to provide optimized balance of properties for specific applications, such as compressor and turbine disks. See 4.01.

1.092 Weld cracking.

1.0921 Waspaloy is subject to weld microcracking and to post-weld heat treat cracking. These problems can be avoided or alleviated by proper pre-weld and post-weld heat treatment procedures and by use of appropriate welding techniques. See 4.034 and 4.036.

1.093 Time-dependent notch sensitivity.

1.0931 Waspaloy exhibits time-dependent notch sensitivity in the temperature range 1000–1300 F when the gamma-prime precipitate is below a certain critical size (see Figure 3.0410). This sensitivity can be avoided by incorporation of a stabilization treatment at 1550 F or higher (such as in the AMS specified heat treatment schedule) so that the gamma-prime particle size is adequately large. See 3.049.

1.094 Reduction of cobalt content.

1.0941 Interest in the role of cobalt on the properties of alloys such as Waspaloy has been sparked in recent years by high cobalt prices and the possibility of supply disruptions. Waspaloy is of particular interest because of its high usage and significant cobalt content. Mauer et al. (39) determined the tensile and creep properties of Waspaloy with reduced cobalt content. Decreasing the cobalt content of Waspaloy from 13.5 percent (nominal) to zero has only a minor effect on tensile properties but decreases the 1350 F creep rupture life by about 70 percent. At room temperature, the yield strength was decreased by about 4 percent and the ultimate strength by about 2 percent on reducing the cobalt content from 13.25 to 0 percent. Ductility, however, was essentially unaffected (Figure 3.0214). At 1000 F, no significant effects on tensile properties due to cobalt reduction were observed (Figure 3.0319). The effect of cobalt content on the creep-rupture properties of Waspaloy was more significant. At 1350 F and 80 ksi, the creep-rupture life of Waspaloy decreased monotonically from 40–70 hours to 8–20 hours as cobalt content was reduced from 13.25 to 0 percent (Figure 3.0411). A reduction in creep-rupture life was also observed at 1500 F and 42.5 ksi as cobalt content was reduced from 13.25 to 8 percent (Figure 3.0412). These reductions in creep strength could be associated with changes in stacking fault energy, carbide precipitation, or gamma-prime precipitate morphology. The gamma-prime solvus temperature did not change with decreasing cobalt content. However, the weight percent of gamma-prime precipitate does decrease moderately with decreasing cobalt content, as shown in Figure 1.0510. It was suggested from the results of this study that the contribution of cobalt to the strength of Waspaloy may not justify its cost and that other means, such as increasing aluminum and titanium contents, could be utilized to restore creep strength in cobalt-reduced or cobalt-free Waspaloy (39, 42).

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1.095 Hydrogen effects.

1.0951 High pressure hydrogen significantly decreases the low cycle fatigue life and increases the fatigue crack propagation rate at both ambient and cryogenic temperatures. See 3.05119 and 3.05121.

2 PHYSICAL PROPERTIES AND ENVIRONMENTAL EFFECTS

2.01 Thermal Properties

2.011 Melting range, 2425 to 2475 F (1).

2.012 Phase changes.

2.0121 Time-temperature-transformation diagrams.

2.013 Thermal conductivity, Figure 2.013.

2.014 Thermal expansion, Figure 2.014.

2.015 Specific heat.

2.016 Thermal diffusivity.

2.02 Other Physical Properties

2.021 Density 0.296 lb/in.^{3}, 8.20 g/cc (1).

2.022 Electrical properties.

2.0221 Electrical resistivity, Figure 2.0221.

2.023 Magnetic properties.

2.0231 Magnetic permeability, Figure 2.0231.

2.024 Emittance.

2.025 Damping capacity.

2.03 Chemical Environments

2.031 Oxidation.

2.0311 Waspaloy forms a predominantly Cr_2O_3-rich scale which is protective but less oxidation resistant than Al_2O_3-rich scales. The Cr/Al ratio for Waspaloy, at about 14:1, is substantially above the ratio of 4:1 which generally separates alloys forming predominantly Cr_2O_3-rich scales from those forming the slower growing Al_2O_3-rich scales. In common with other chromia-forming superalloys, Waspaloy suffers substantial internal oxidation at high temperatures, primarily along grain boundaries. The high temperature metal losses from oxidation are shown in Figure 2.0312 (46, 47).

2.0312 Oxidation of Waspaloy after 100 hours at 1600 to 1900 F, Figure 2.0312.

2.032 Hot corrosion.

2.0321 Waspaloy has intermediate resistance to hot corrosion as comapred to other commercially available sheet superalloys. The data shown in Figure 2.0322 are for 1650 F, generally accepted as the temperature of maximum attack for most superalloys (48).

2.0322 Hot corrosion of Waspaloy and other sheet superalloys after 200 hours at 1650 F, Figure 2.0322.

2.033 Stress corrosion.

2.0331 Waspaloy is highly resistant to stress corrosion cracking at room temperature. Stressed specimens were immersed for 10 minutes in a 3.5 percent NaCl solution followed by 50 minutes' drying for a 6-month total test period. Subsequent tests indicated no degradation of room temperature tensile properties (49).

2.04 Nuclear Environments

3 MECHANICAL PROPERTIES

3.01 Specified Mechanical Properties

3.011 Specified mechanical properties at room temperature, Table 3.011.

3.012 Specified tensile properties at 1000 F, Table 3.012.

3.013 Specified stress rupture properties, Table 3.013.

3.02 Mechanical Properties at Room Temperature

3.021 Tension – stress-strain diagrams – tension properties.

3.0211 True stress-true strain curve of bar from turbine disk specimen and from fragment of overspeeded (burst) disk, Figure 3.0211.

3.0212 Static and cyclic stress-strain curves at room temperature for specimens from turbine wheel forgings, Figure 3.0212.

3.0213 Effects of forging temperature and deformation on tensile properties of Waspaloy at room temperature, Table 3.0213.

3.0214 Effect of cobalt content on tensile properties of Waspaloy at room temperature, Figure 3.0214.

3.022 Compression – stress-strain diagrams – compression properties.

3.023 Impact.

3.0231 Effects of forging on Charpy V-notch impact fracture energy of Waspaloy at room temperature, Table 3.0231.

3.024 Bending.

3.025 Torsion and shear.

3.026 Bearing.

3.027 Stress concentration.

3.0271 Notch properties.

3.02711 Effect of subsequent heat treatment on smooth and sharp notch tensile properties of annealed sheet, Figure 3.02711.

3.02712 Effect of heat treatment on smooth and sharp notch tensile properties of 20 percent cold worked sheet, Figure 3.02712.

3.02713 Effect of heat treatment on smooth and sharp notch tensile properties of 40 percent cold worked sheet, Figure 3.02713.

3.03 Mechanical Properties at Various Temperatures

3.031 Tension – stress-strain diagrams – tension properties.

3.0311 Effect of test temperature on tensile properties of bar and forgings, Figure 3.0311.

3.0312 Effect of low temperatures on tensile properties of annealed sheet, Figure 3.0312.

3.0313 Effect of low temperatures on tensile properties of annealed plus aged sheet, Figure 3.0313.

3.0314 Effect of test temperature on tensile properties of annealed plus aged sheet with and without prior exposure to stress and temperature, Figure 3.0314.

3.0315 Effect of test temperature on tensile properties of cold worked and aged sheet with and without prior exposure to stress and temperature, Figure 3.0315.

3.0316 Effect of finish rolling temperature on tensile properties of Waspaloy at 70 and 1000 F, Figure 3.0316.

3.0317 Effect of hot rolling reduction on tensile properties of Waspaloy at 70 and 1000 F, Figure 3.0317.

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

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3.0318 Typical tensile properties of Waspaloy and Super Waspaloy at 70 to 1250 F, Table 3.0318.

3.0319 Effect of cobalt content on tensile properties of Waspaloy at 1000 F, Figure 3.0319.

3.032 Compression – stress-strain diagrams – compression properties.

3.0321 Compressive stress-strain curves at high temperatures and high strain rates are shown in Figures 3.0322 and 3.0323. Of interest in these curves is flow softening, indicative of dynamic recrystallization during deformation. This behavior promotes hot workability. Part of the flow softening may also be caused by adiabatic heating during working. Yield drops at 1922 to 2102 F are attributed to short range ordering of the gamma-prime forming elements aluminum, cobalt, and titanium. At lower temperatures, the gamma-prime phase precipitates and the yield drops disappear. The flow stress-temperature curves, Figure 3.0324, show decreasing flow stresses with decreasing strain rates and with decreasing temperature. These curves also indicate a change in slope in the temperature range 1900 to 2100 F, coincident with the range for the yield point drops (53). Stress-temperature compression flow curves at lower temperatures from a separate study are shown in Figure 3.0325 (54).

3.0322 Effect of strain rate on compressive flow curves for Waspaloy at 1742 F, Figure 3.0322.

3.0323 Effect of temperature on compressive flow curves for Waspaloy at a strain rate of 5/minute, Figure 3.0323.

3.0324 Temperature dependence of yield strength of Waspaloy in compression, Figure 3.0324.

3.0325 Effect of temperature and strain rate on the compressive yield strength of Waspaloy, Figure 3.0325.

3.033 Impact.

3.034 Bending.

3.035 Torsion and shear.

3.036 Bearing.

3.037 Stress concentration.

3.0371 Notch properties.

3.03711 Effect of low temperatures on notch strength ratio of annealed and of annealed plus aged sheet, Figure 3.03711.

3.03712 Effect of notch acuity on notch strength ratio of sheet at room and elevated temperatures, Figure 3.03712.

3.03713 Effect of test temperature on notch strength and notch strength ratio of annealed plus aged sheet with and without prior exposure to stress and temperature, Figure 3.03713.

3.03714 Effect of test temperature on notch strength and notch strength ratio of cold worked and aged sheet with and without exposure to stress and temperature, Figure 3.03714.

3.0372 Fracture toughness.

3.038 Combined properties.

3.04 Creep and Creep-Rupture Properties

3.041 Creep-rupture life as a function of temperature for Waspaloy, Figure 3.041.

3.042 Effect of plastic prestrain on creep-rupture behavior of bar at 1350 F, Figure 3.042.

3.043 Effect of grain size on creep-rupture properties of notched and smooth bar at 1500 F, Figure 3.043.

3.044 The effects of volume fraction of fine gamma-prime precipitate on the creep-rupture life of Waspaloy are shown in Figure 3.045. The gamma-prime particle size distribution in Waspaloy is normally bimodal, reflecting precipitation during two or more heat treatments below the gamma-prime solvus temperature. The amount of fine gamma-prime precipitate can be controlled by varying the temperatures and durations of the solution and stabilization heat treatments. Maximum rupture life is obtained at a volume fraction of fine gamma-prime precipitate of about 0.3 (37).

3.045 Creep-rupture life of Waspaloy at 1350 F and 75 ksi as a function of volume fraction of fine gamma-prime precipitate formed during stabilization aging, Figure 3.045.

3.046 Effect of solution annealing temperature on rupture life and elongation of hot rolled and cold drawn wire at 1500 F and 40 ksi, Figure 3.046.

3.047 Effects of forging temperature and deformation on creep rupture properties of Waspaloy at 1500 F and 47 ksi, Table 3.047.

3.048 Larson-Miller plot of creep-rupture strength of Waspaloy and Super Waspaloy, Figure 3.048.

3.049 Waspaloy exhibits time-dependent notch sensitivity in the temperature range 1000–1300 F when the gamma-prime precipitate is below a certain critical size. This notch-sensitivity is most apparent during creep exposure and results in notched-to-smooth rupture strength ratios as low as 0.44. It is observed in material that has been aged at 1400 F directly after solution annealing and is related to the fine gamma-prime particle size, approximately 75 A, developed during the low temperature aging. Aging at higher temperatures, such as 1550 or 1700 F, results in larger gamma-prime particles, 600 and 1000 A, respectively. Time-dependent notch sensitivity is not observed in material aged at 1550 or 1700 F, as shown in Figure 3.0410. Gamma-prime particles smaller than a certain critical size, between 75 and 600 A, are sheared by dislocations, giving rise to localized deformation. Particles larger than the critical size are bypassed by dislocations, promoting homogeneous deformation and absence of time-dependent notch sensitivity (40, 55, 56). (See also Section 1.063.)

3.0410 Stress for rupture in 1000 hours as a function of temperature for smooth and notched Waspaloy sheet, Figure 3.0410.

3.0411 Effect of cobalt content on creep-rupture properties of Waspaloy at 1350 F and 80 ksi, Figure 3.0411.

3.0412 Effect of cobalt content on creep-rupture properties of Waspaloy at 1500 F and 42.5 ksi, Figure 3.0412.

3.0413 Stress relaxation for applied strain of 2.06 percent at 1350 and 1500 F, Figure 3.0413.

3.05 Fatigue Properties

3.051 Mechanical fatigue.

3.0511 Low-cycle fatigue behavior of Waspaloy at room temperature, Figure 3.0511.

3.0512 The low-cycle fatigue behavior of Waspaloy is sensitive to temperature and to cycle frequency. Increasing the temperature from 70 to 1200 F decreases cyclic life by about a factor of 10, as

	Ni
20	Cr
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4	Mo
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1	Al

Waspaloy

shown in Figure 3.0513. Crack propagation rates are essentially identical at 1020 and 1200 F and are about 10-fold greater than those observed at 70 F, as shown in Figure 3.0514. Shear of gamma-prime precipitate particles occurs in Waspaloy at room temperature but not at elevated temperatures. This results in more homogeneous plastic deformation at elevated temperatures. Decreasing cyclic frequency is seen in Figures 3.0515–3.0517 to increase the fatigue crack propagation rates at 1200 F (58, 59).

3.0513 Low-cycle fatigue behavior of Waspaloy at 70, 1020, and 1200 F, Figure 3.0513.

3.0514 Low-cycle fatigue crack propagation rates for Waspaloy at 70, 1020, and 1200 F, Figure 3.0514.

3.0515 Low-cycle fatigue crack propagation rates for Waspaloy at 1200 F at frequencies from 1 to 120 cpm, Figure 3.0515.

3.0516 Low-cycle fatigue crack propagation rates for Waspaloy at 1200 F, Figure 3.0516.

3.0517 Low-cycle fatigue crack propagation rates at three cyclic frequencies for Waspaloy at 1200 F, Figure 3.0517.

3.0518 Low-cycle fatigue stress-strain curves for Waspaloy at 70 and 1200 F, Figure 3.0518.

3.0519 Crack propagation rates for Waspaloy are affected by grain size. Coarser grain sizes markedly reduce the crack propagation rates at 1200 F in both air and helium, as shown in Figure 3.05110. The effect of grain size is related to its role in promoting slip on secondary systems in the region ahead of the crack tip. Gamma-prime particle size does not markedly affect crack growth rates, Figure 3.05111. Optimization of the microstructure to reduce fatigue crack propagation rates may adversely affect other properties. For example, coarser grain sizes, which reduce crack growth, will likely enhance crack initiation and creep strength will be lowered by overaged microstructures. Microstructure must be optimized for the total spectrum of properties desired in service (61–63).

3.05110 Low-cycle fatigue crack propagation rate as a function of grain size for Waspaloy in air or in helium at 1200 F, Figure 3.05110.

3.05111 Effect of gamma-prime particle size on low-cycle fatigue crack propagation rate in Waspaloy at 1200 F, Figure 3.05111.

3.05112 Strain-controlled low-cycle fatigue behavior of forged Waspaloy and Super Waspaloy at 70, 1000, and 1250 F, Figure 3.05112.

3.05113 The effect of hold time on the low-cycle fatigue life of Waspaloy at 1200 F is shown in Figure 3.05114. The imposition of a 15-minute hold time at the maximum tensile strain, representative of some service conditions, causes a significant reduction in fatigue life at total strain ranges greater than 1 percent but has a negligible effect at lower total strain ranges. Minimal differences are noted between completely reversed push-pull (R = -1) fatigue and completely tensile (R = 0) fatigue. Crack propagation rates also are affected by tensile hold time, as illustrated in Figure 3.05115. Increasing tensile hold time increases the crack propagation rate. Hold time effects are larger at higher stress intensity factor ranges, consistent with the greater effect of hold time on fatigue life at higher total strain ranges. Fatigue crack initiation in Waspaloy during straight fatigue is transgranular, usually at surface defects such as machining marks. Crack propagation is also transgranular. However, in creep-fatigue, both initiation and propagation of cracks in Waspaloy are intergranular (60, 64).

3.05114 Low-cycle fatigue life as a function of total strain range for Waspaloy at 1200 F, Figure 3.05114 [(a) R_e = -1, and (b) R_e = 0].

3.05115 Effect of hold time on crack propagation rates for Waspaloy at 1200 F, Figure 3.05115.

3.05116 Under actual service conditions, power excursions occur routinely. These excursions result in overloads on such components as turbine disks, the results of which are not predictable by the linear damage accumulation rule. Laboratory characterizations of fatigue behavior under cycles including controlled overload conditions indicate that the average fatigue crack propagation rate decreases with increasing overload ratio, Figure 3.05117. The crack propagation rate also decreases with increasing number of regular cycles between individual overload cycles, Figure 3.05118. An exception to the latter trend occurs when the number of cycles between overloads is small; this condition results in an increase in crack propagation rates as compared to the rates determined under constant fatigue conditions. The instantaneous crack propagation rate increases when the overload is applied, but subsequently decreases on removal of the overload to a rate lower than that characteristic of the regular fatigue cycle. This phenomenon is known as delayed retardation and continues for a certain time period under normal cycling, during which the crack propagation rate slowly accelerates back to the unretarded rate (65).

3.05117 Effect of overload ratio on load-controlled low-cycle fatigue crack propagation rate of Waspaloy at 1200 F, Figure 3.05117.

3.05118 Effect of cycles between overloads on load-controlled low-cycle fatigue crack propagation rate of Waspaloy at 1200 F, Figure 3.05118.

3.05119 The low-cycle fatigue life of Waspaloy is significantly degraded in 5000 psi hydrogen at room temperature and 540 F as compared to testing in 5000 psi helium. However, no difference between the two environments is observed at 1250 F, Figure 3.05120.

3.05120 Effects of high-pressure hydrogen on low-cycle fatigue life of Waspaloy, Figure 3.05120, (a) room temperature, (b) 540 F, and (c) 1250 F.

3.05121 High-pressure hydrogen seriously degrades the fatigue crack growth resistance of Waspaloy at room and cryogenic temperatures. At room temperature, crack propagation rates are about two magnitudes greater in high-pressure hydrogen than in air. At -300 F, the rates in hydrogen are about four times greater than room temperature rates in air. These data are shown in Figure 3.05122. The increased crack propagation rates in hydrogen are accompanied by brittle transgranular or intergranular fracture. In contrast, ductile fracture is observed in air-tested specimens (68).

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3.05122 Effects of hydrogen on simulated space shuttle main engine cycle crack propagation rate of Waspaloy at RT and -300 F, Figure 3.05122.
3.052 Thermal fatigue.
3.0521 Comparison in thermal shock of uncoated airfoil section with corresponding samples coated with proprietary aluminum and aluminum-base diffusion coatings, Figure 3.0521.

3.06 **Elastic Properties**
3.061 Poisson's ratio.
3.062 Modulus of elasticity, Figure 3.062.
3.063 Modulus of rigidity.
3.064 Tangent modulus.
3.065 Secant modulus.

4 FABRICATION

4.01 **Forming**

4.011 Increased knowledge of thermal-mechanical processing and its application to Waspaloy are reflected in the large increase in room temperature yield strength of Waspaloy produced in 1977 as compared to that available in 1960 (see Figure 4.012). Thermal-mechanical processing includes marriage of forging operations with post-forge heat treatments, in particular to control the morphology and distribution of the gamma-prime and carbide phases (69).

4.012 Room-temperature yield strength of Waspaloy (1960–1977), Figure 4.012.

4.013 Hot rolling studies by Bailey (51) have shown that (a) tensile yield and ultimate strengths tend to decrease with increasing finish rolling temperature and to increase with increasing total reduction, and (b) tensile ductility increases with increasing total reduction but is independent of finish rolling temperature. These data are shown in Figures 3.0316 and 3.0317. Preheat temperature in the range 2050 to 2250 F is relatively unimportant. These differences in tensile properties are attributed to differences in size and distribution of gamma-prime and carbide phases and to the dislocation structures generated by the hot working schedules, which persist through subsequent heat treating. Grain size also may have a minor effect. In order to achieve optimum tensile properties in Waspaloy, it is advisable to take a heavy total reduction, 40 to 70 percent, and to finish deform with reductions of 10 to 30 percent per pass at temperatures below the gamma-prime solvus temperature, i.e., in the 1725 to 1825 F range.

4.014 Extensive thermal-mechanical processing (TMP) studies of Waspaloy over the past decade and a half, particularly for turbine disk applications, have resulted in the development of a modification known as Super Waspaloy. This modification utilizes minor changes in chemistry and changes in TMP to achieve superior tensile and low-cycle fatigue properties with some sacrifice in creep rupture properties. The study by Donachie, et al (50) defined the combined effects of forging temperature and amount of forging deformation on the properties of Waspaloy. In particular, it was shown that forging at 1975 or 1800 F with large (40 percent) reductions per forging cycle gave best strength, ductility, and toughness properties. In contrast, light reductions at 2150 F resulted in lower strength and substantially reduced ductility and toughness, Tables 3.0213, 3.0231, and 3.047. (Note that these trends are similar to those observed in hot rolling, described above in 4.013.) The decreased properties appear related microstructurally to the presence of nearly-continuous MC grain boundary films which do not dissolve on lower temperature reheating and which also reduce the amount of carbon available for subsequent $M_{23}C_6$ carbide precipitation. The $M_{23}C_6$ phase precipitates intergranularly but is not as deleterious to mechanical properties as the grain boundary MC phase.

The later work of Deye and Couts (52) combined minor compositional changes (within the specification limits for Waspaloy), specifically a reduction in carbon content and small increases in aluminum and titanium content, with TMP to produce the modified version of Waspaloy commonly referred to as Super Waspaloy. While standard Waspaloy is normally forged at temperatures of 1950 to 2100 F, well above the gamma-prime solvus temperature, Super Waspaloy is forged below the solvus at 1850 to 1875 F. This results in a much finer grain size for Super Waspaloy (ASTM 8-10 or 10-20 microns) than for standard Waspaloy (ASTM 4-6 or 40-80 microns). The lower carbon content of Super Waspaloy combined with the lower forging temperature also results in a much smaller amount of grain boundary carbide than found in standard Waspaloy. The reduced grain boundary carbide improves tensile and creep rupture ductility in Super Waspaloy. The slightly greater amounts of titanium and aluminum in Super Waspaloy provide a larger volume fraction of gamma-prime, increasing the strength as compared to standard Waspaloy. The differences in chemistry are slight; representative analyses are 0.048 and 0.024C, 3.02 and 3.13Ti, and 1.24 and 1.46Al for Waspaloy and Super Waspaloy, respectively (52). Super Waspaloy shows improved tensile and low cycle fatigue properties as compared to standard Waspaloy, shown in Table 3.0318 and Figure 3.05112. The creep rupture properties of Super Waspaloy and Waspaloy, according to Deye and Couts (52), are comparable at high stresses and low temperatures, but Waspaloy is superior at lower stresses and higher temperatures, Figure 3.048. This combination of properties represents an advantage for Super Waspaloy for air-cooled disk applications where fatigue properties are limiting rather than creep properties.

4.015 Waspaloy can be hot formed by gatorizing using, for example, a 4:1 reduction at 1725 F. A major advantage of Gatorizing, which is a slow hot forming process, is that much less force is required at lower temperatures than with conventional forging at higher temperatures (70).

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

4.02 **Machining and Grinding**

4.021 Waspaloy can be rough turned and and finish machined using appropriate cutting tool materials, tool geometry, cutting speeds and feeds and also considering cutting forces and cutting temperatures produced. Positive-rake throw-away insert tools are recommended. Large lead angles should be employed in preference to small lead angles. The depth of cut should be kept greater than 0.015 inch where possible so that the cutting edge cuts cleanly and does not cause glazing. The cutting speed must be high enough for efficiency but not excessive as extreme speed causes undesirably high cutting temperatures and poor tool life. Tungsten carbide tools and cutting fluid are required (71).

4.022 Hot machining can be employed advantageously with Waspaloy. A plasma torch with an argon blanket is used to heat the work surface to about 700 F, allowing cutting speeds up to five times faster than with standard machining techniques (72).

4.023 Waspaloy can also be machined by nonconventional techniques such as electrochemical machining (ECM). ECM tends to produce a soft surface layer on the workpiece which can adversely affect fatigue strength and other mechanical properties (73).

4.03 **Joining**

4.031 Most common welding procedures for Waspaloy include shielded metal arc, gas-tungsten-arc, resistance spot, and resistance seam (74). Low-temperature tensile properties of gas-tungsten-arc welded sheet are shown in Figures 4.032 and 4.033.

4.032 Effect of GTA welding on tensile properties at low temperature of annealed and annealed plus aged sheet, Figure 4.032.

4.033 Joint efficiency at low temperatures of annealed and annealed plus aged sheet after GTA welding, Figure 4.033.

4.034 Waspaloy, like many other superalloys, is subject to microcracking in the heat-affected zone when liquation welding with gas-tungsten-arc or electron beam. Microcracking is a special form of weld cracking which is internal and not detectable by ultrasonic or X-ray examination. It can be detected metallographically. Microcracking is associated with incipient melting of low-melting phases such as borides at grain boundaries or within the grains. It can be alleviated by reducing grain size, by heat treatments which reduce the grain boundary concentrations of aluminum and titanium, and by improved microstructural cleanliness with respect to low-melting impurity phases. Weld pool width-to-height ratio is the prime welding parameter affecting weld microcracking. Narrow weld pools with ratios less than about 1.6 promote microcracking, while wide weld pools with larger ratios result in sound welds. The weld pool morphology is in turn determined by welding speed and material thickness. The incidence of microcracking in Waspaloy is related to welding speed, sheet thickness, and heat treatment as shown in Figure 4.035 (75).

4.035 Effects of welding speed, heat treatment, and sheet thickness on weld microcracking, Figure 4.035.

4.036 Post-weld heat treat (PWHT) cracking can be a problem with Waspaloy, particularly in thick sections. High residual stresses exist in the weld and heat affected zones as a result of the high thermal gradients imposed by the welding process. During heating for PWHT to restore desired mechanical properties in the weld region, both relaxation of residual stresses and hardening by precipitated gamma-prime occur. The gamma-prime hardening is accompanied by a reduction in ductility, which in turn causes cracking in the weld and heat affected zones before the residual stresses can be thermally relaxed. The tendency of superalloys towards PWHT cracking is a function of the total amount of gamma-prime hardener in the alloy. As shown in Figure 4.037, Waspaloy is marginal with respect to PWHT cracking. It is more prone than, for example, Inconel 718 but less prone to cracking than higher hardener content alloys such as Udimet 700. The C-curve for PWHT cracking in Waspaloy as a function of time and temperature is shown in Figure 4.038. This curve is approximate since it varies with material thickness and with heating rate. The C-curve reflects in part the precipitation kinetics of gamma-prime (76). PWHT cracking in Waspaloy can be alleviated by a pre-weld solution heat treatment of 0.5 hour at 1975 F plus WQ to put the material into a "soft" condition (77).

4.037 Effect of aluminum and titanium content on post-weld heat treatment cracking tendency in Waspaloy and several other superalloys, Figure 4.037.

4.038 Post-weld heat treatment cracking tendency as a function of aging time and temperature for Waspaloy, Figure 4.038.

4.039 Pressure bonding of Waspaloy can be enhanced by removal of titanium and aluminum from the bonding surface. Waspaloy can be surface cleaned of aluminum and titanium by heating for 30 minutes in an atmosphere of $70H_2$-30HCl at 1830 F. Subsequent bonding for 4 hours at 1900 F under a pressure of 3 ksi gives metallurgically clean interfaces in Waspaloy/Waspaloy and Waspaloy/IN-100 bonds. Homogenization of aluminum and titanium gradients at the interface after pressure bonding can be accomplished by an additional 15-hour annealing treatment at the same bonding temperature and pressure (78).

4.0310 Waspaloy can be self-welded by inertia bonding and by electron-beam welding to produce sound joints. The joints have low cycle and high cycle fatigue properties and creep properties comparable to those of the base metal (79).

4.04 **Surface Treating**

4.041 Wear resistance of parts can be improved by hard surfacing with a cobalt base alloy.

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

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Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

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Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

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Alloy	Waspaloy	
Product Form	Metallurgical Condition	AMS Specification
Sheet, Strip, Plate	Annealed	5544
Tubing, Welded	Annealed	5586
Forgings	Solution, stabilization, and precipitation heat treated	5704
Bars, Forgings, Rings	Solution heat treated	5706
Bars, Forgings, Rings	Solution, stabilization, and precipitation heat treated	5707
Bars, Forgings	Solution heat treated	5708
Bars, Forgings	Solution, stabilization, and precipitation heat treated	5709
Welding Wire	Vacuum induction melted	5828

TABLE 1.03. SPECIFICATIONS (29-36)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

Alloy	Waspaloy					
Form	Sheet, Strip, Plate, Bars, Forgings, Rings		Welded Tubing		Welding Wire	
Element	Min	Max	Min	Max	Min	Max
Carbon	0.02	0.10	0.02	0.10	0.02	0.10
Manganese	–	0.10	–	0.10	–	0.10
Silicon	–	0.15	–	0.15	–	0.10
Phosphorus	–	0.015	–	0.015	–	0.010
Sulfur	–	0.015	–	0.015	–	0.010
Chromium	18.00	21.00	18.00	21.00	18.00	21.00
Cobalt	12.00	15.00	12.00	15.00	12.00	15.00
Molybdenum	3.50	5.00	3.50	5.00	3.50	5.00
Titanium	2.75	3.25	2.50	3.25	2.75	3.25
Aluminum	1.20	1.60	1.20	1.60	1.20	1.60
Boron	0.003	0.010	0.003	0.010	0.003	0.010
Iron	–	2.00	–	2.00	–	2.00
Copper	–	0.10	–	0.10	–	0.10
Zirconium	0.02	0.08	0.02	0.15	–	0.04
Nickel	Balance		Balance		Balance	

TABLE 1.04. COMPOSITION (29-36)

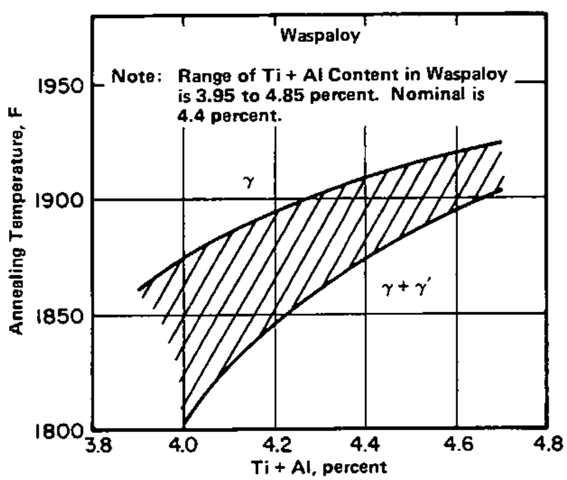
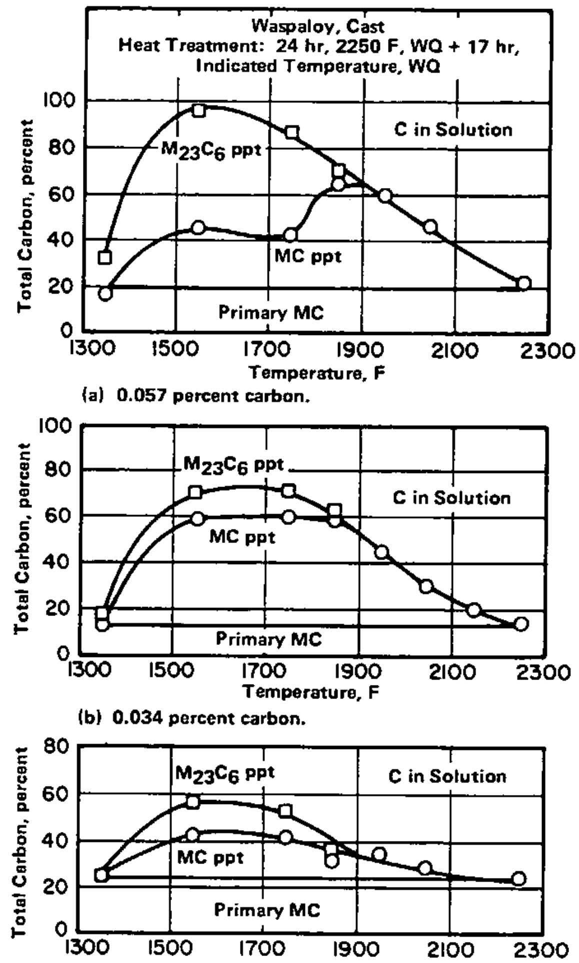


FIGURE 1.052. VARIATION OF GAMMA-PRIME SOLVUS RANGE WITH TITANIUM PLUS ALUMINUM CONTENT FOR WASPALOY (37)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy



(a) 0.057 percent carbon.

(b) 0.034 percent carbon.

(c) 0.020 percent carbon.

FIGURE 1.054. EFFECTS OF CARBON CONTENT AND PRECIPITATION TEMPERATURE ON CARBON DISTRIBUTION IN CAST WASPALOY (38)

Alloy	Waspaloy					
	Solution Heat Treatment		Stabilization Heat Treatment		Precipitation Heat Treatment	
AMS Spec.	Temp, F	Time, hr	Temp, F	Time, hr	Temp, F	Time, hr
5544	1975	0.5, AC	–	–	–	–
5586	(a)	(a)	–	–	–	–
5704	1825-1900	4, OQ/WQ	1550	4, AC	1400	16, AC
5706	1825-1900	4, OQ/WQ	–	–	–	–
5707	1825-1900	4, OQ/WQ	1550	4, AC	1400	16, AC
5708	1975	4, AC[b]	–	–	–	–
5709	1975	4, AC[b]	1550	4, AC[c]	1400	16, AC

Note: The original AMS documents should be consulted for complete specification details.

(a) Suitable to meet subsequent forming requirements.
(b) Equivalent to air cool or faster.
(c) 24 hours for blade forgings.

TABLE 1.056. STANDARD HEAT TREATMENTS FOR WASPALOY (29-35)

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

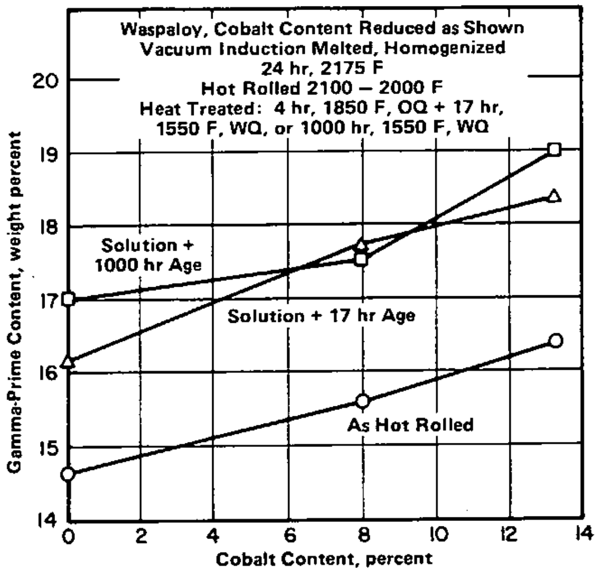


FIGURE 1.0510. EFFECT OF COBALT CONTENT AND HEAT TREATMENT ON GAMMA-PRIME CONTENT OF WASPALOY (39)

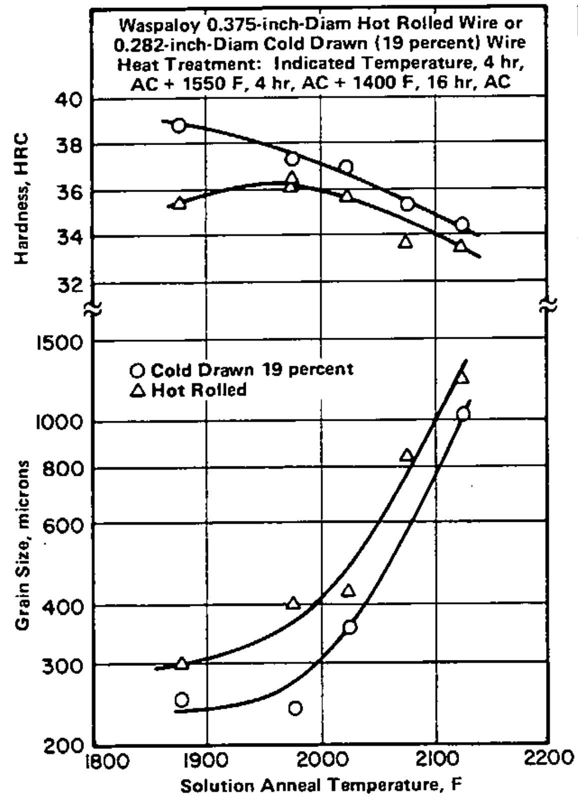


FIGURE 1.062. EFFECT OF SOLUTION ANNEALING TEMPERATURE ON HARDNESS AND GRAIN SIZE OF HOT ROLLED AND COLD DRAWN WIRE (14)

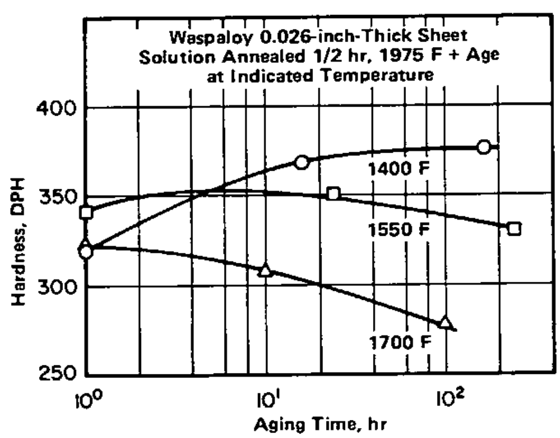


FIGURE 1.064. EFFECT OF AGING EXPOSURES AT 1400, 1550, AND 1700 F ON HARDNESS OF SOLUTION ANNEALED WASPALOY (40)

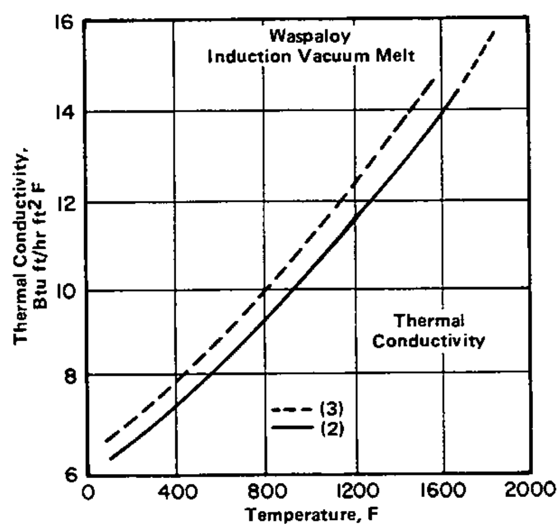


FIGURE 2.013. THERMAL CONDUCTIVITY

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

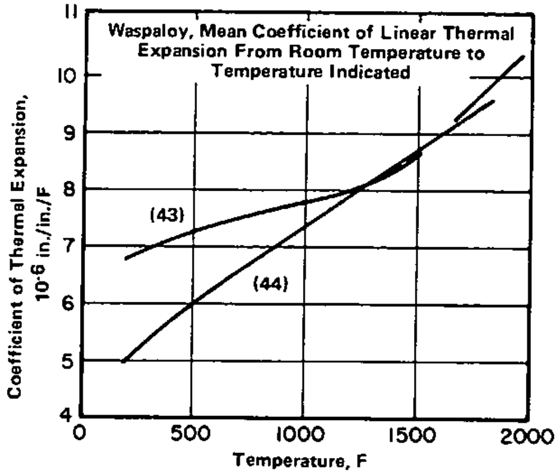


FIGURE 2.014. THERMAL EXPANSION (43, 44)

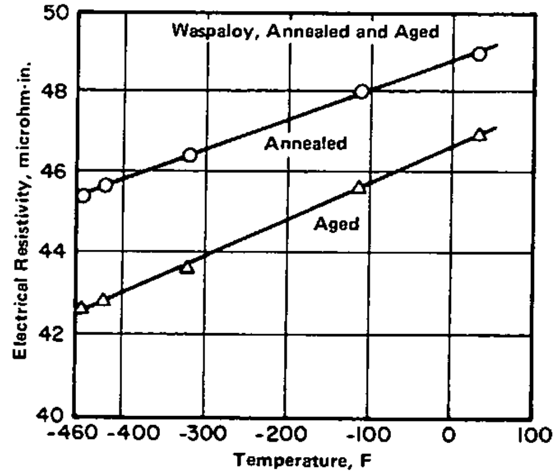


FIGURE 2.0221. ELECTRICAL RESISTIVITY (45)

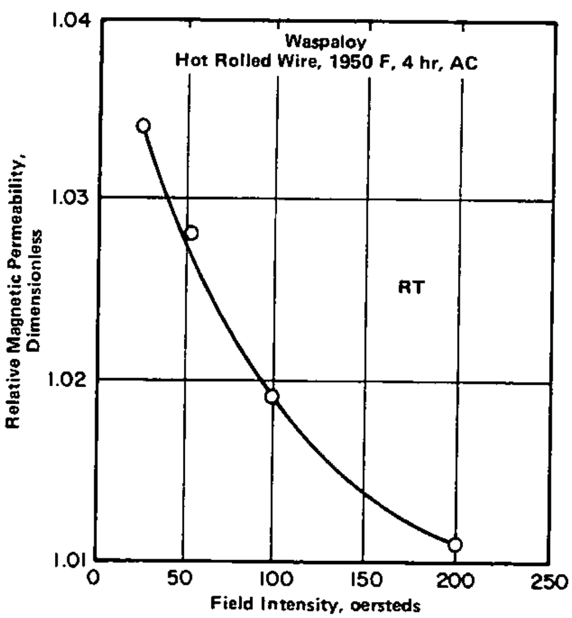


FIGURE 2.0231. MAGNETIC PERMEABILITY (22, 23)

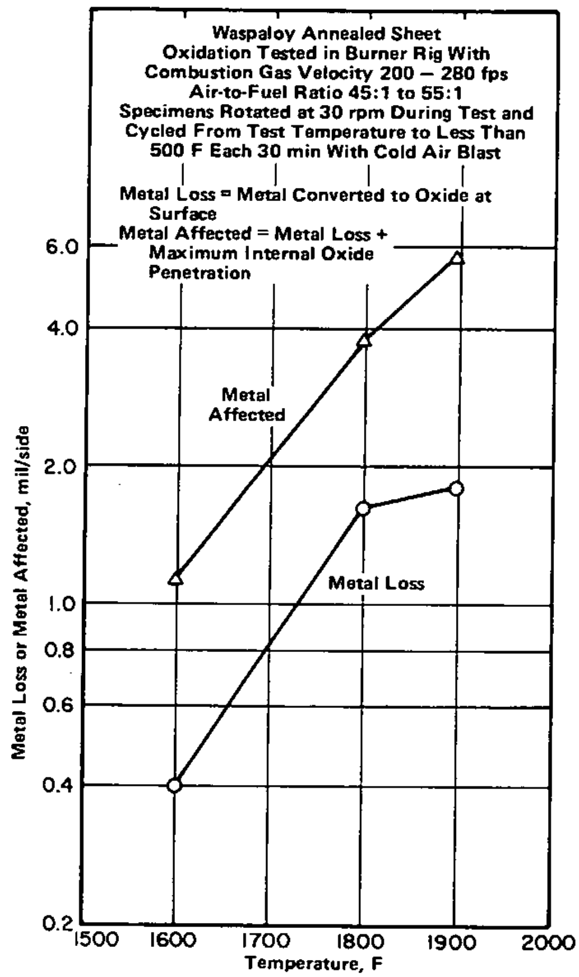


FIGURE 2.0312. OXIDATION OF WASPALOY AFTER 100 HOURS AT 1600 TO 1900 F (47)

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

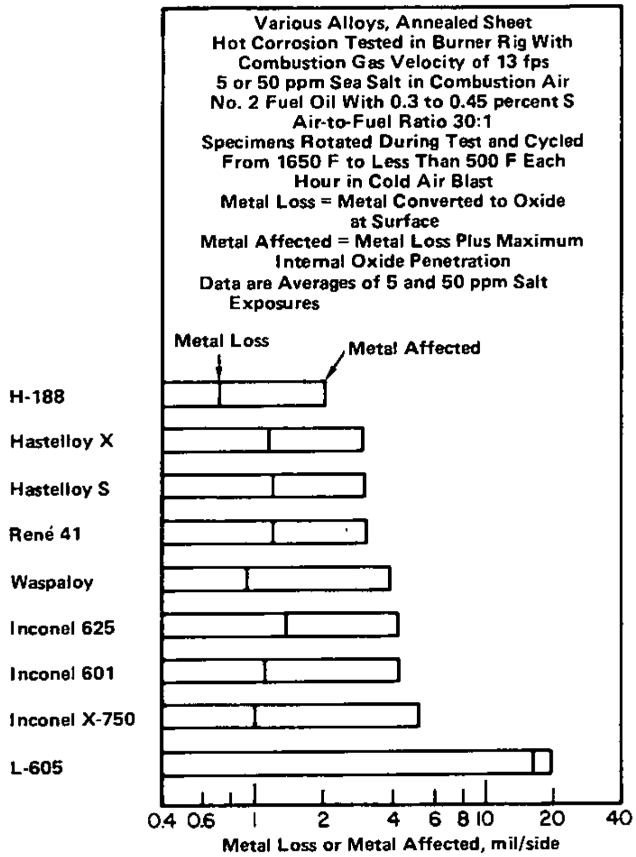


FIGURE 2.0322. HOT CORROSION OF WASPALOY AND OTHER SHEET SUPERALLOYS AFTER 200 HOURS AT 1650 F (48)

Alloy	Waspaloy										
Product Form	AMS Spec.	Metallurgical Condition(a)	Thickness, in.	F_{tu}, ksi Min	F_{tu}, ksi Max	F_{ty}, ksi Min	F_{ty}, ksi Max	e, % Min	RA, % Min	Hardness(b) Min	Hardness(b) Max
Sheet, Strip, Plate	5544	Annealed	≤0.015	–	150	–	85	25	–	–	(100 HRB)
			>0.015-0.115	–	145	–	80	35	–	–	(100 HRB)
			>0.115-0.187	–	155	–	95	35	–	–	(27 HRC)
			>0.187	–	170	–	100	35	–	–	(30 HRC)
		SA, SHT, PHT	≤0.020	–	170	–	110	15	–	–	–
			>0.020	–	175	–	115	20	–	–	–
Tubing, Welded	5586	Annealed	≥0.125 OD(c)	–	145	–	80	35	–	–	–
		SA, SHT, PHT	≥0.125 OD(c)	–	160	–	105	15	–	34 HRC	44 HRC
Forgings	5704	SA, SHT, PHT	≤3.25(d)	175	–	120	–	15	18	(341 HB)	(401 HB)
Bars, Forgings, Rings	5706	SA	Not Specified	–	–	–	–	–	–	–	331 HB
		SA, SHT, PHT	≤3.25(d)	160	–	110	–	15	18	(321 HB)	(401 HB)
Bars, Forgings, Rings	5707	SA, SHT, PHT	≤3.25(d)	160	–	110	–	15	18	(321 HB)	(403 HB)
Bars, Forgings	5708	SA	Not Specified	–	–	–	–	–	–	–	302 HB
		SA, SHT, PHT	Not Specified	–	–	–	–	–	–	32 HRC	42 HRC
Bars, Forgings	5709	SA, SHT, PHT	Not Specified	–	–	–	–	–	–	32 HRC	42 HRC

Note: The original AMS documents should be consulted for complete specification details.

(a) SA = solution anneal; SHT = stabilization heat treatment; PHT = precipitation heat treatment.

(b) Hardness values in parentheses need not be met if tensile requirements are met.

(c) Plus wall thickness ≥0.015 inch.

(d) Least nominal cross section dimension.

TABLE 3.011. SPECIFIED MECHANICAL PROPERTIES AT ROOM TEMPERATURE (29-35)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

Alloy	Waspaloy						
Product Form	AMS Spec.	Metallurgical Condition[a]	Thickness, in.	F_{tu}, ksi Min	F_{ty}, ksi Min	Elongation, % Min	RA, % Min
Sheet, Strip, Plate	5544	SA, SHT, PHT	≤0.020	145	100	13	–
			>0.020	150	105	15	–
Forgings	5704	SA, SHT, PHT	≤3.25[b]	155	105	15	18

Note: The original AMS documents should be consulted for complete specification details.

(a) SA = solution anneal; SHT = stabilization heat treatment; PHT = precipitation heat treatment.
(b) Least nominal cross section dimension.

TABLE 3.012. SPECIFIED TENSILE PROPERTIES AT 1000 F (29, 31)

Alloy	Waspaloy, Full Heat Treatment					
Product Form	AMS Spec.	Thickness, in.	Temp, F	Stress, ksi	Rupture Life, hr Min	Elongation, % Min
Sheet, Strip, Plate	5544	0.015-0.020	1350	62.5	23	4
		>0.020-0.030	1350	65.0	23	4
		>0.030-0.050	1350	67.5	23	4
		>0.050	1350	70.0	23	5
Tubing, Welded	5586	0.015-0.020[a]	1350	62.5	23	4
		>0.020-0.030[a]	1350	65.0	23	4
		>0.030-0.050[a]	1350	67.5	23	4
		>0.050[a]	1350	70.0	23	5
		Not Specified	1500	37.5	23	5
Forgings	5704	Not Specified	1350	80.0	23[b]	5
		Not Specified	1500	42.5	23	5
Bars, Forgings, Rings	5706	≤3.25[c]	1350	75.0	23[b]	8
Bars, Forgings, Rings	5707	Not Specified	1350	75.0	23[b]	8
		Not Specified	1500	40.0	23	5
Bars, Forgings	5708	Not Specified	1500	47.5	23	8
Bars, Forgings	5709	Not Specified	1500	47.5	23	8

Note: The original AMS documents should be consulted for complete specification details.

(a) Nominal wall thickness.
(b) Combination smooth and notched specimen or separate smooth and notched specimens.
(c) Least nominal cross section dimension.

TABLE 3.013. SPECIFIED STRESS RUPTURE PROPERTIES (29-35)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

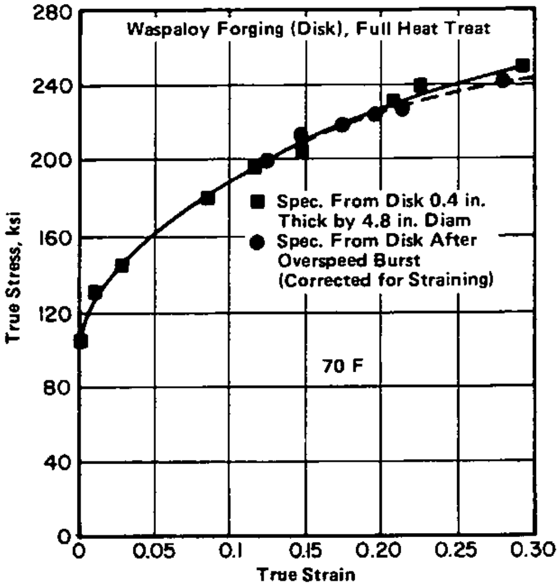


FIGURE 3.0211. TRUE STRESS-TRUE STRAIN CURVE OF BAR FROM TURBINE DISK SPECIMEN AND FROM FRAGMENT OF OVERSPEEDED (BURST) DISK (8)

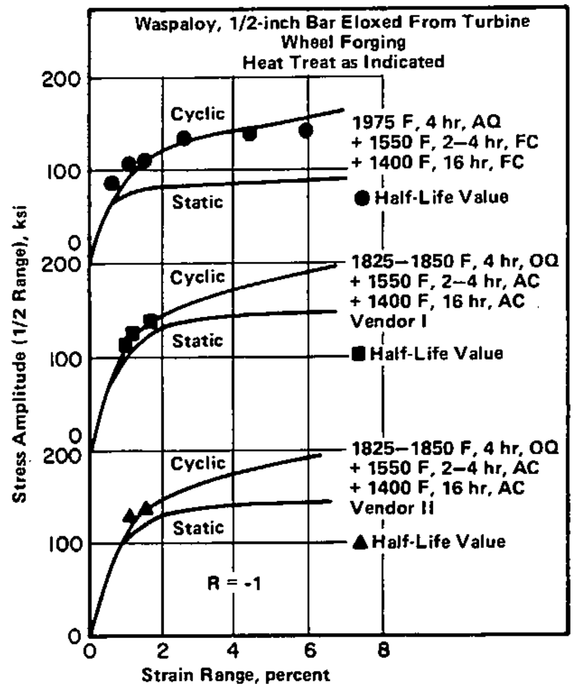


FIGURE 3.0212. STATIC AND CYCLIC STRESS-STRAIN CURVES AT ROOM TEMPERATURE FOR SPECIMENS FROM TURBINE WHEEL FORGINGS (25)

Alloy		Waspaloy			
Forging Schedule		Tensile Properties			
2-hr Forge Preheat Temperature, F	Number of Forge Cycles and Deformation per Cycle, percent(a)	0.2 Percent F_{ty}, ksi	F_{tu}, ksi	Elongation, percent	Reduction in Area, percent
2150	3 at 40 percent	110.4	181.6	21	19
	3 at 20 percent	112.8	151.0	9	10
	2 at 20 percent(b)	103.7	135.0	8	6
1975	3 at 40 percent	107.8	184.0	26	25
	3 at 20 percent	106.8	179.0	26	26
	2 at 20 percent(b)	110.0	183.0	26	24
1800	3 at 40 percent	111.0	185.0	27	27
	3 at 20 percent	107.0	181.0	23	22
	2 at 20 percent(b)	110.5	181.5	23	20

(a) Heat treated after forging as follows:

Gamma-prime solution	4 hours at 1975 F, AC
Carbide stabilize	24 hours at 1550 F, AC
Gamma-prime age	16 hours at 1400 F, AC.

(b) Plus reheat to forge temperature without subsequent deformation.

TABLE 3.0213. EFFECTS OF FORGING TEMPERATURE AND DEFORMATION ON TENSILE PROPERTIES OF WASPALOY AT ROOM TEMPERATURE (50)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

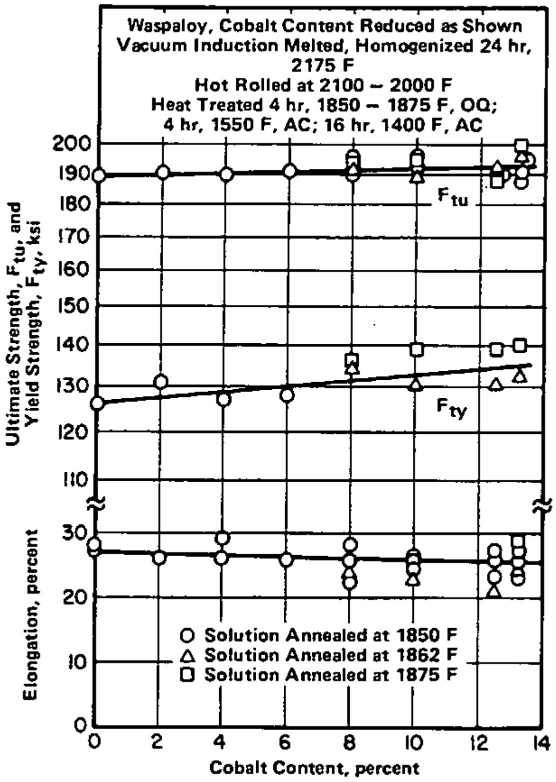


FIGURE 3.0214. EFFECT OF COBALT CONTENT ON TENSILE PROPERTIES OF WASPALOY AT ROOM TEMPERATURE (39)

Alloy	Waspaloy	
Forging Schedule		
2-hr Forge Preheat Temperature, F	Number of Forge Cycles and Reduction per Cycle, percent(a)	Impact Energy, ft-lb(b)
2150	3 at 40 percent	19.2
	3 at 20 percent	11.4
	2 at 20 percent(c)	3.5
1975	3 at 40 percent	19.9
	3 at 20 percent	17.4
	2 at 20 percent(c)	16.8
1800	3 at 40 percent	19.0
	3 at 20 percent	14.4
	2 at 20 percent(c)	16.0

(a) Heat treated after forging as follows:
Gamma-prime solution 4 hr, 1975 F, AC
Carbide stabilize 24 hr, 1550 F, AC
Gamma-prime age 16 hr, 1400 F, AC.
(b) Average of two tests.
(c) Plus reheat to forge temperature without subsequent deformation.

TABLE 3.0231. EFFECTS OF FORGING ON CHARPY V-NOTCH IMPACT FRACTURE ENERGY OF WASPALOY AT ROOM TEMPERATURE (50)

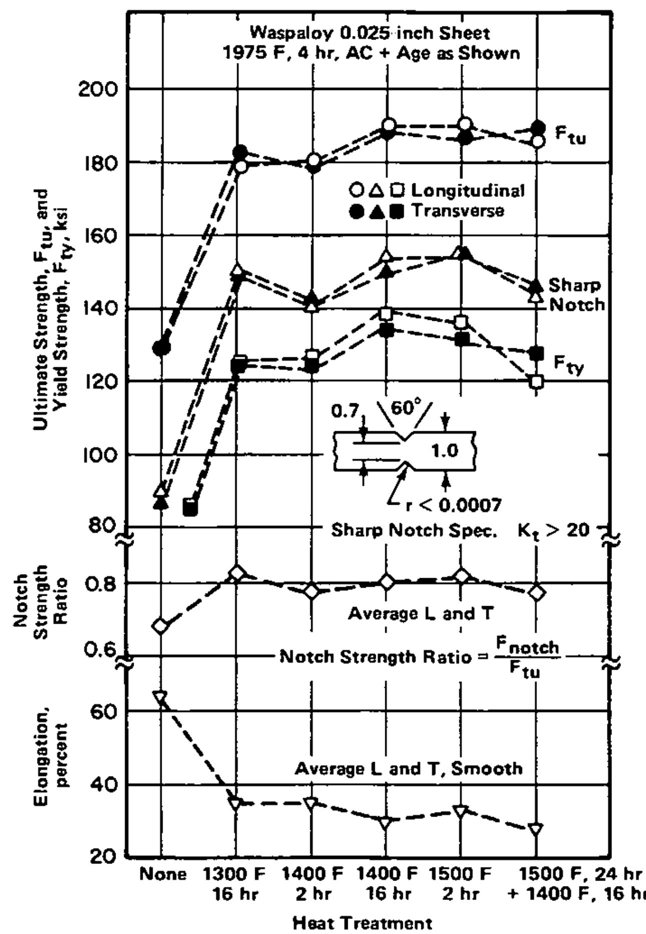


FIGURE 3.02711. EFFECT OF SUBSEQUENT HEAT TREATMENT ON SMOOTH AND SHARP NOTCH TENSILE PROPERTIES OF ANNEALED SHEET (21)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

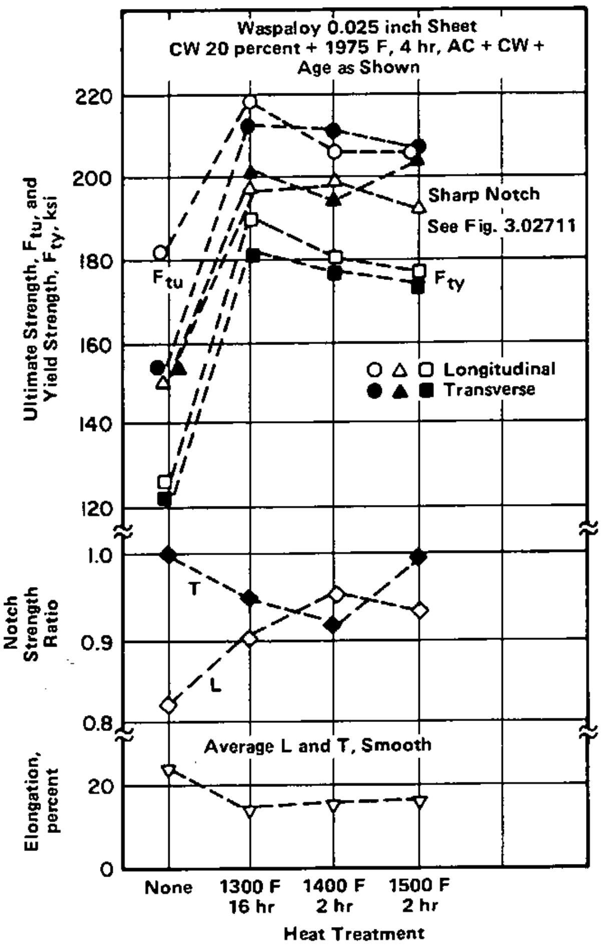


FIGURE 3.02712. EFFECT OF HEAT TREATMENT ON SMOOTH AND SHARP NOTCH TENSILE PROPERTIES OF 20 PERCENT COLD WORKED SHEET (21)

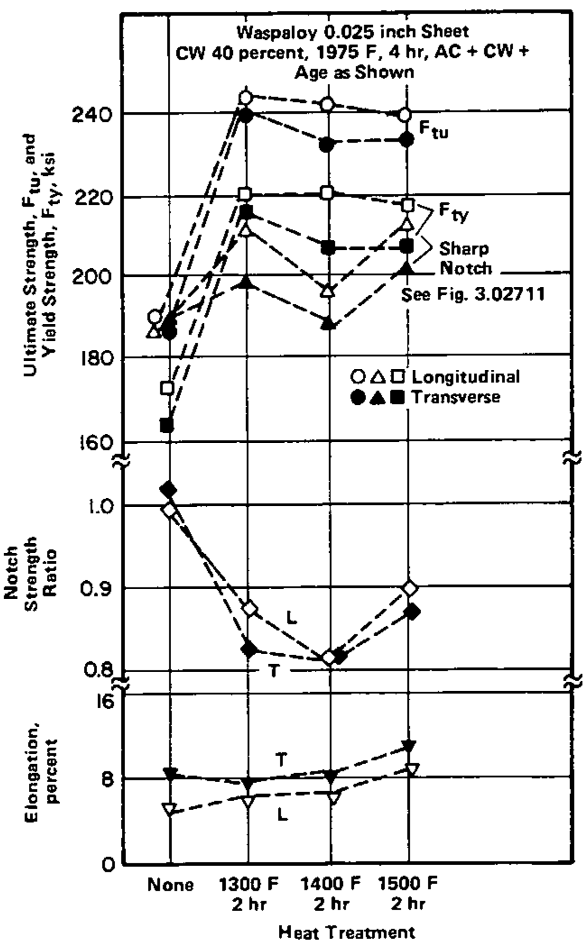


FIGURE 3.02713. EFFECT OF HEAT TREATMENT ON SMOOTH AND SHARP NOTCH TENSILE PROPERTIES OF 40 PERCENT COLD WORKED SHEET (21)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

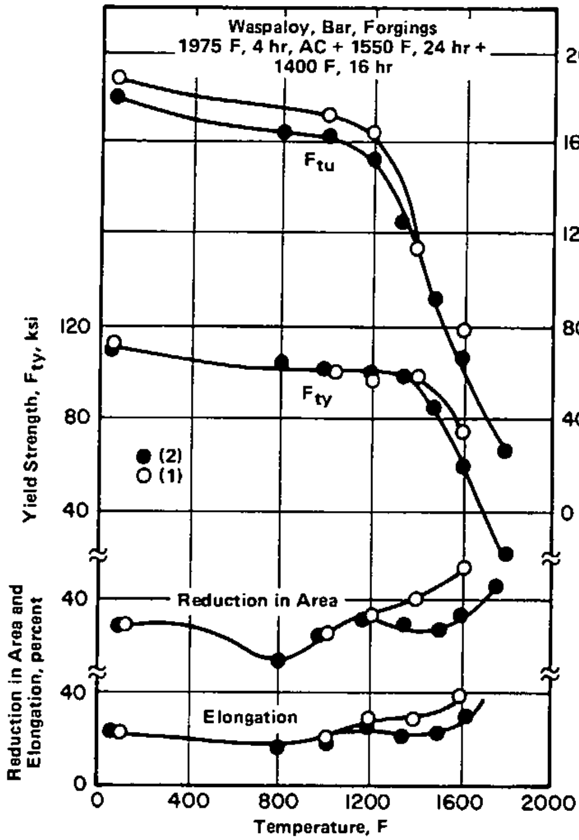


FIGURE 3.0311. EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BAR AND FORGINGS (1, 2)

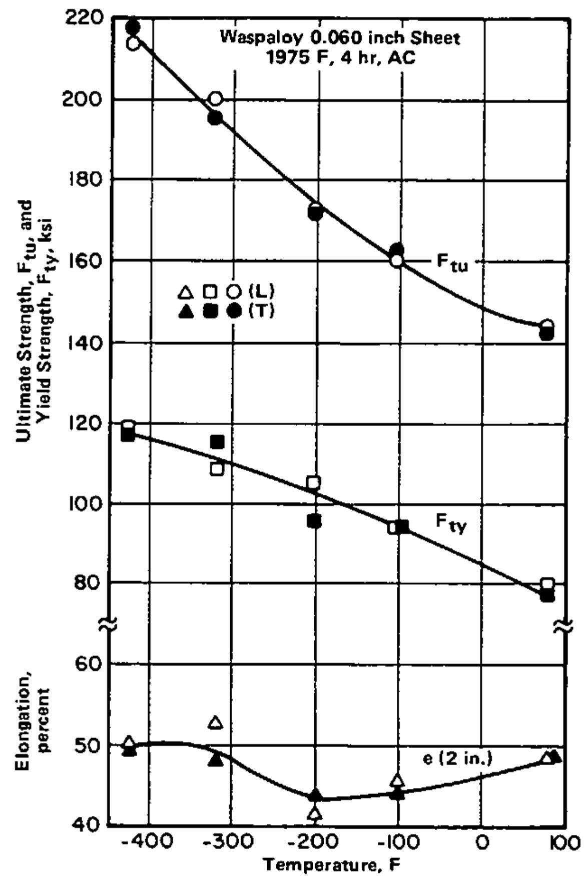


FIGURE 3.0312. EFFECT OF LOW TEMPERATURES ON TENSILE PROPERTIES OF ANNEALED SHEET (19)

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

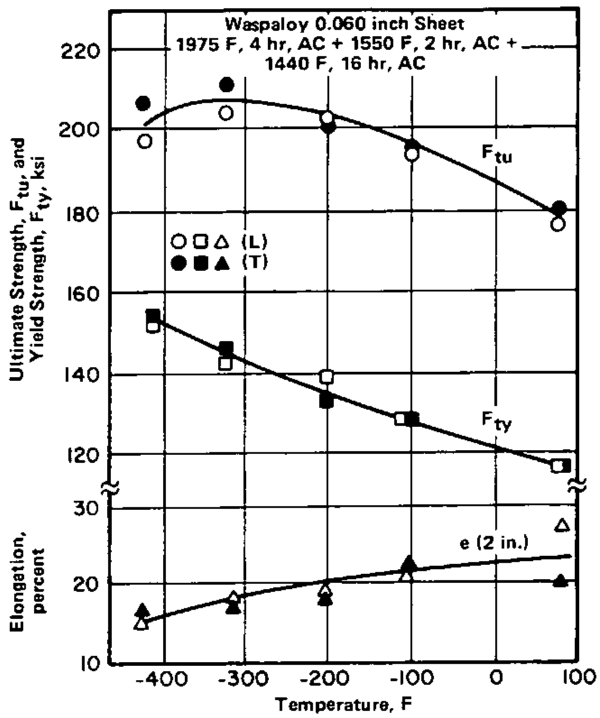


FIGURE 3.0313. EFFECT OF LOW TEMPERATURES ON TENSILE PROPERTIES OF ANNEALED PLUS AGED SHEET (19)

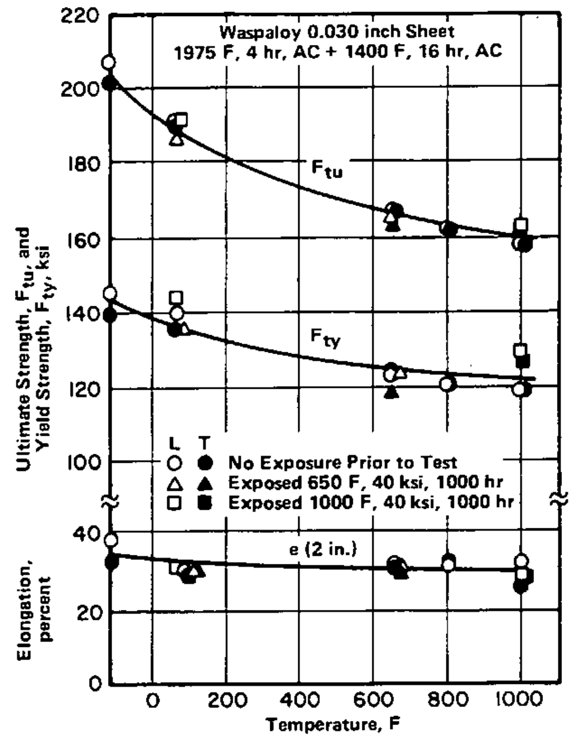


FIGURE 3.0314. EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ANNEALED PLUS AGED SHEET WITH AND WITHOUT PRIOR EXPOSURE TO STRESS AND TEMPERATURE (27)

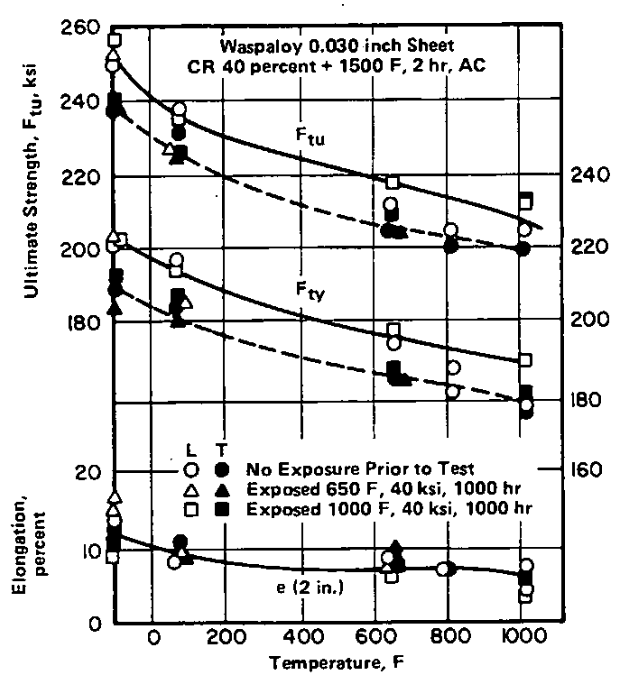


FIGURE 3.0315. EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF COLD WORKED AND AGED SHEET WITH AND WITHOUT PRIOR EXPOSURE TO STRESS AND TEMPERATURE (27)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

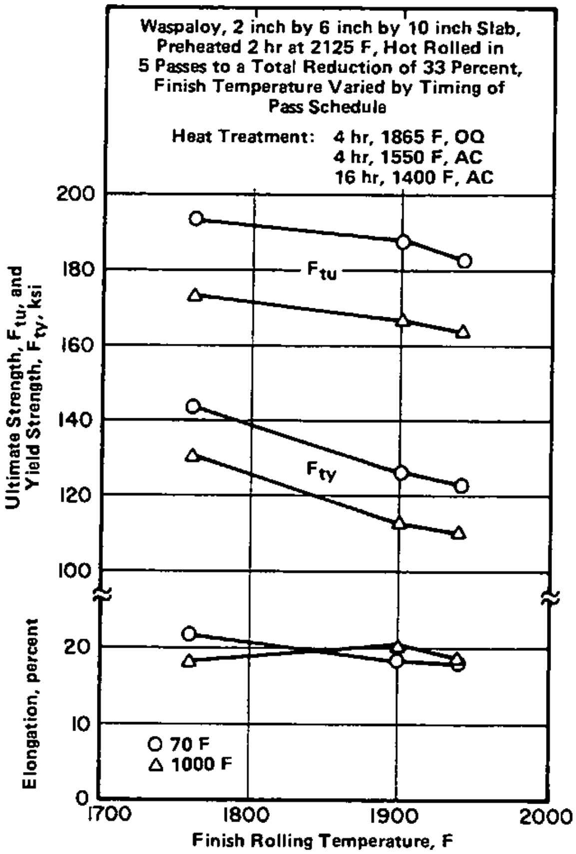


FIGURE 3.0316. EFFECT OF FINISH ROLLING TEMPERATURE ON TENSILE PROPERTIES OF WASPALOY AT 70 AND 1000 F (51)

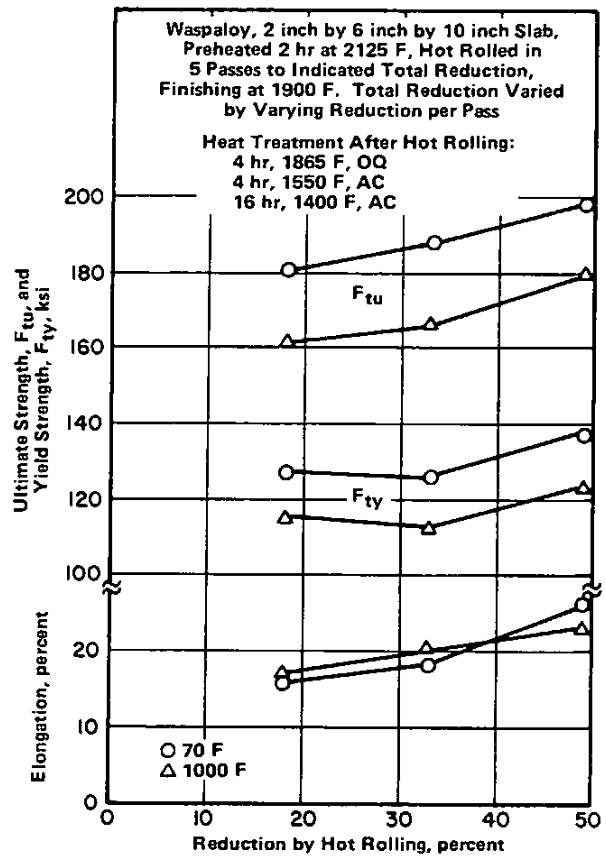


FIGURE 3.0317. EFFECT OF HOT ROLLING REDUCTION ON TENSILE PROPERTIES OF WASPALOY AT 70 AND 1000 F (51)

Alloy	Waspaloy, Forged					
		Tensile Properties				
Material(a)	Test Temp, F	0.2 Percent F_{ty}, ksi	F_{tu}, ksi	Elongation, percent	Reduction in Area, percent
Waspaloy	70	140	194	23	28
	1000	130	180	20	23
	1250	114	150	19	22
Super Waspaloy(b)	70	161	212	23	38
	1000	146	199	17	24
	1250	140	171	30	47

(a) Heat treated after forging: 4 hours, 1840 F, OQ
4 hours, 1550 F, AC
16 hours, 1400 F, AC.

(b) See 4.014 for description of Super Waspaloy.

TABLE 3.0318. TYPICAL TENSILE PROPERTIES OF WASPALOY AND SUPER WASPALOY AT 70 TO 1250 F (52)

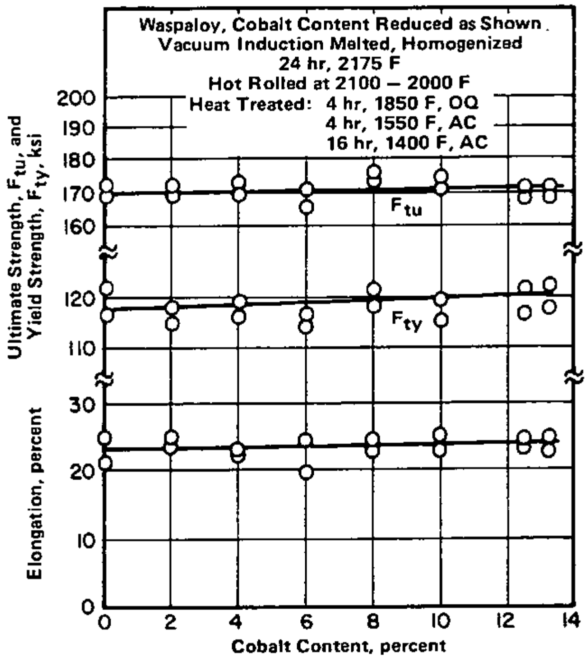


FIGURE 3.0319. EFFECT OF COBALT CONTENT ON TENSILE PROPERTIES OF WASPALOY AT 1000 F (39)

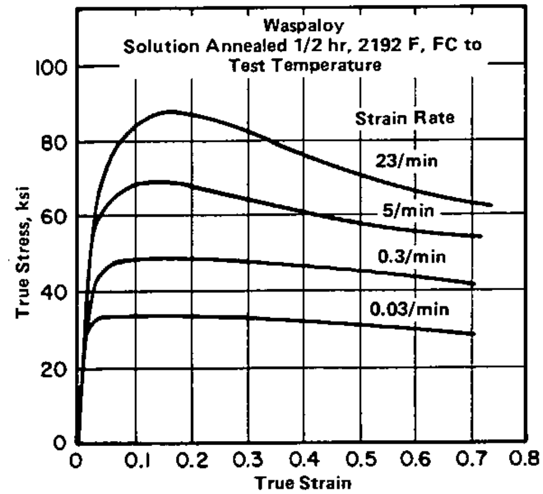


FIGURE 3.0322. EFFECT OF STRAIN RATE ON COMPRESSIVE FLOW CURVES FOR WASPALOY AT 1742 F (53)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

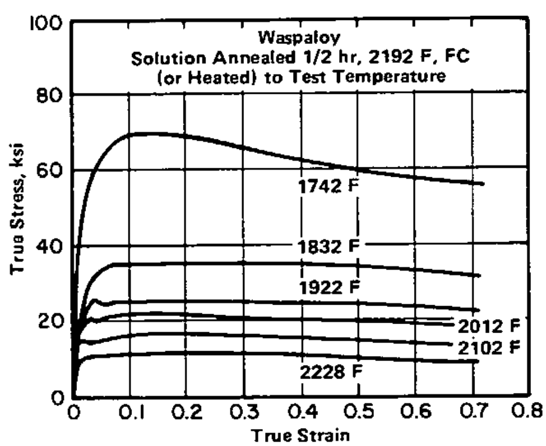


FIGURE 3.0323. EFFECT OF TEMPERATURE ON COMPRESSIVE FLOW CURVES FOR WASPALOY AT A STRAIN RATE OF 5/MIN (53)

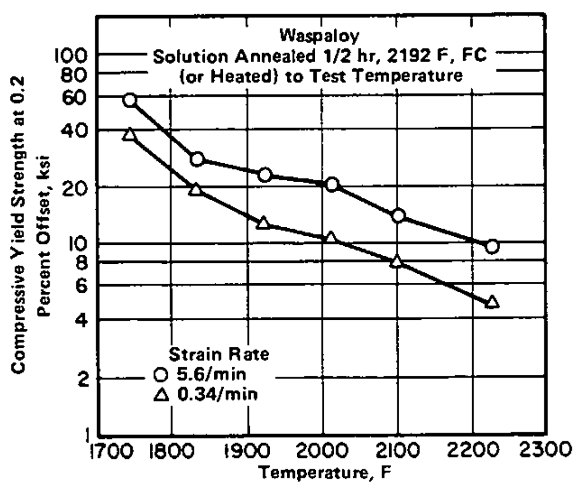


FIGURE 3.0324. TEMPERATURE DEPENDENCE OF YIELD STRENGTH OF WASPALOY IN COMPRESSION (53)

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

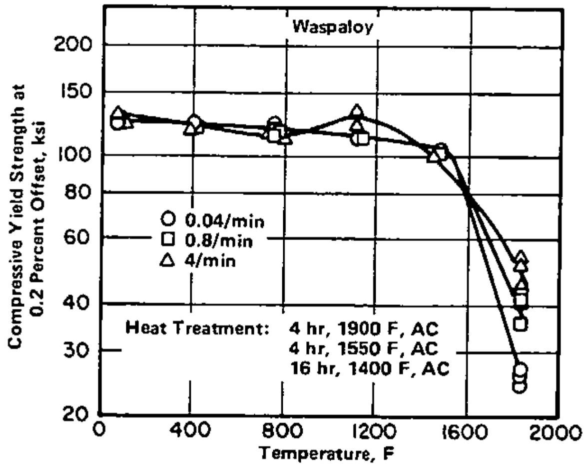


FIGURE 3.0325. EFFECT OF TEMPERATURE AND STRAIN RATE ON THE COMPRESSIVE YIELD STRENGTH OF WASPALOY (54)

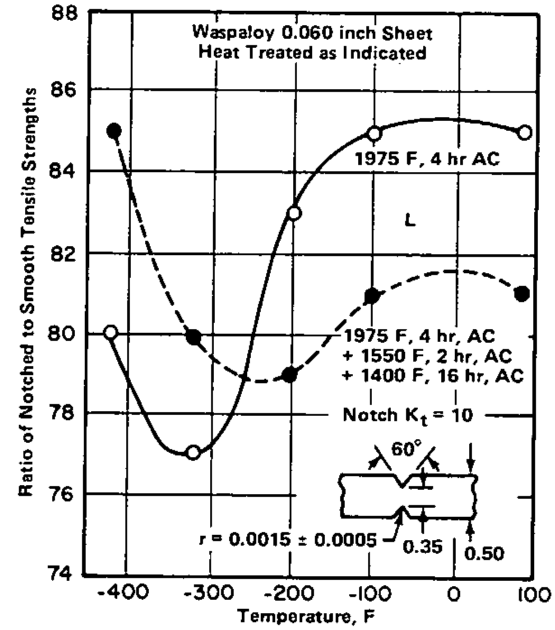


FIGURE 3.03711. EFFECT OF LOW TEMPERATURES ON NOTCH STRENGTH RATIO OF ANNEALED AND OF ANNEALED PLUS AGED SHEET (19)

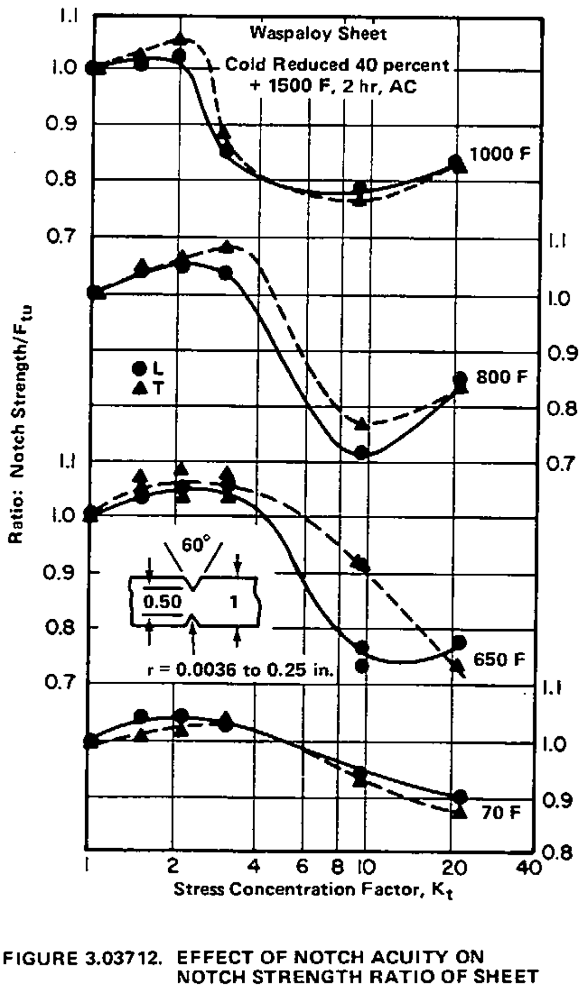


FIGURE 3.03712. EFFECT OF NOTCH ACUITY ON NOTCH STRENGTH RATIO OF SHEET AT ROOM AND ELEVATED TEMPERATURES (20)

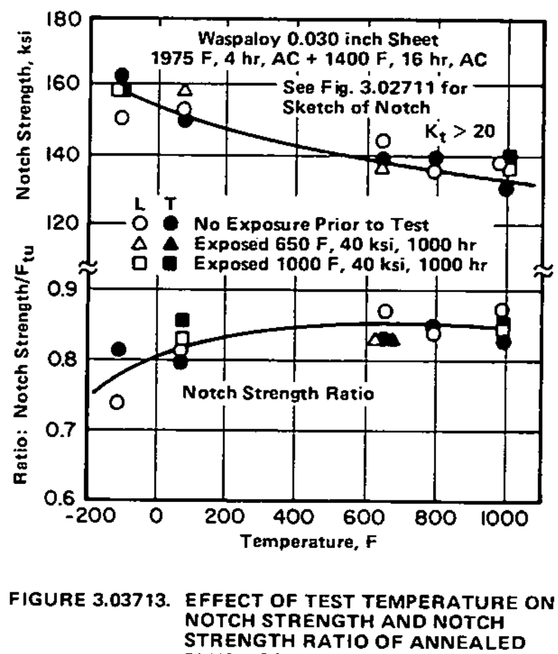


FIGURE 3.03713. EFFECT OF TEST TEMPERATURE ON NOTCH STRENGTH AND NOTCH STRENGTH RATIO OF ANNEALED PLUS AGED SHEET WITH AND WITHOUT PRIOR EXPOSURE TO STRESS AND TEMPERATURE (27)

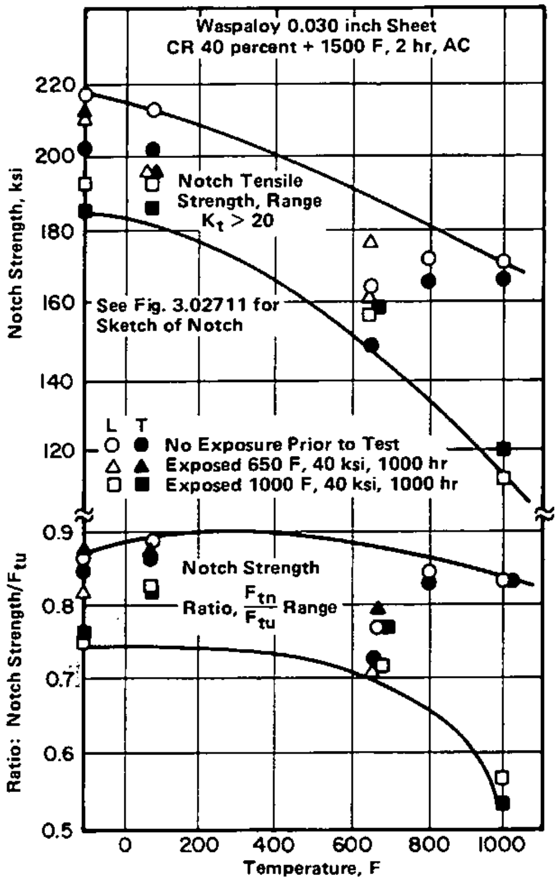


FIGURE 3.03714. EFFECT OF TEST TEMPERATURE ON NOTCH STRENGTH AND NOTCH STRENGTH RATIO OF COLD WORKED AND AGED SHEET WITH AND WITHOUT EXPOSURE TO STRESS AND TEMPERATURE (27)

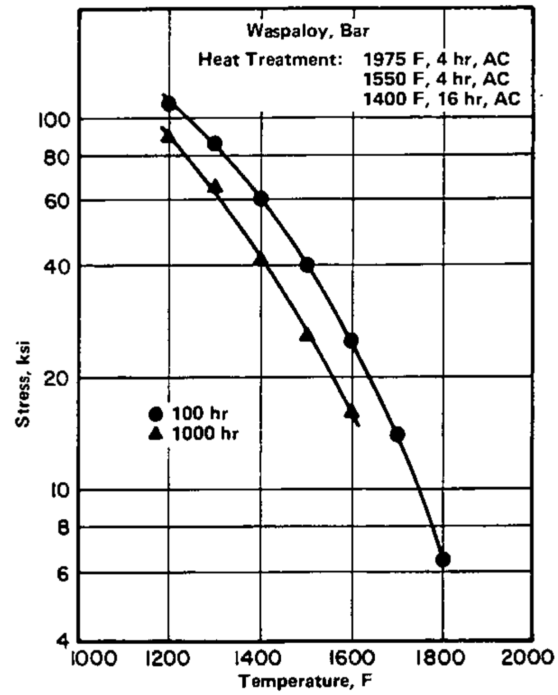


FIGURE 3.041. CREEP-RUPTURE LIFE AS A FUNCTION OF TEMPERATURE FOR WASPALOY (43)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

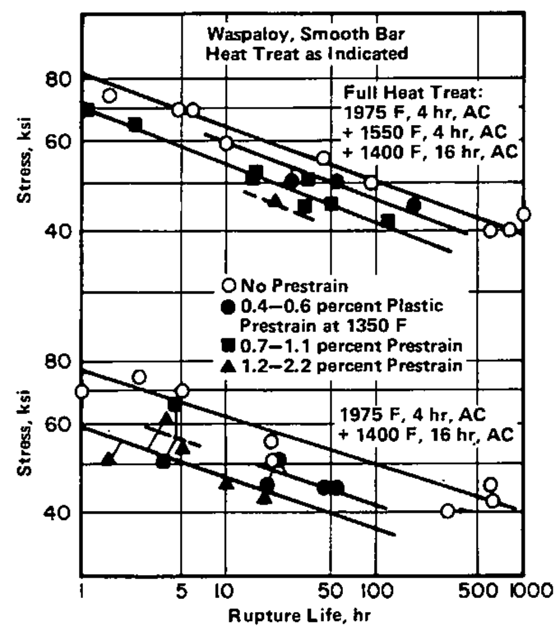


FIGURE 3.042. EFFECT OF PLASTIC PRESTRAIN ON CREEP-RUPTURE BEHAVIOR OF BAR AT 1350 F (11)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

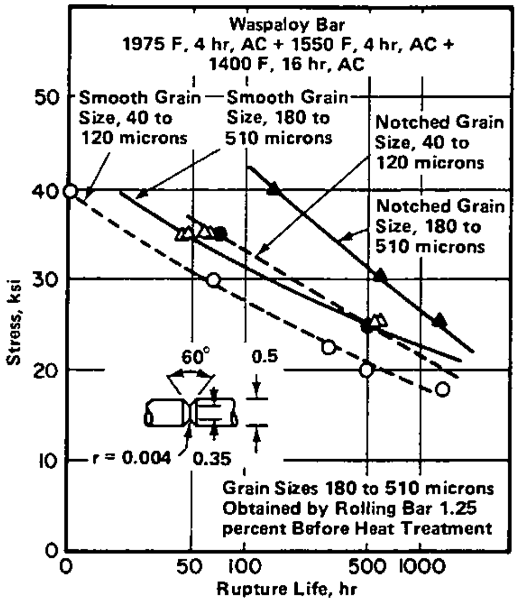


FIGURE 3.043. EFFECT OF GRAIN SIZE ON CREEP-RUPTURE PROPERTIES OF NOTCHED AND SMOOTH BAR AT 1500 F (18)

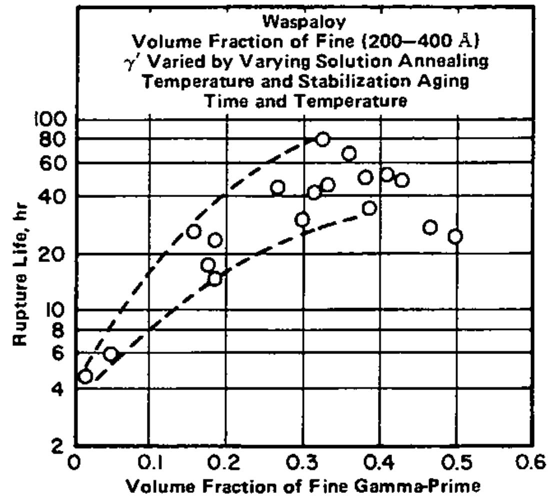


FIGURE 3.045. CREEP-RUPTURE LIFE OF WASPALOY AT 1350 F AND 75 KSI AS A FUNCTION OF VOLUME FRACTION OF FINE GAMMA-PRIME PRECIPITATE FORMED DURING STABILIZATION AGING (37)

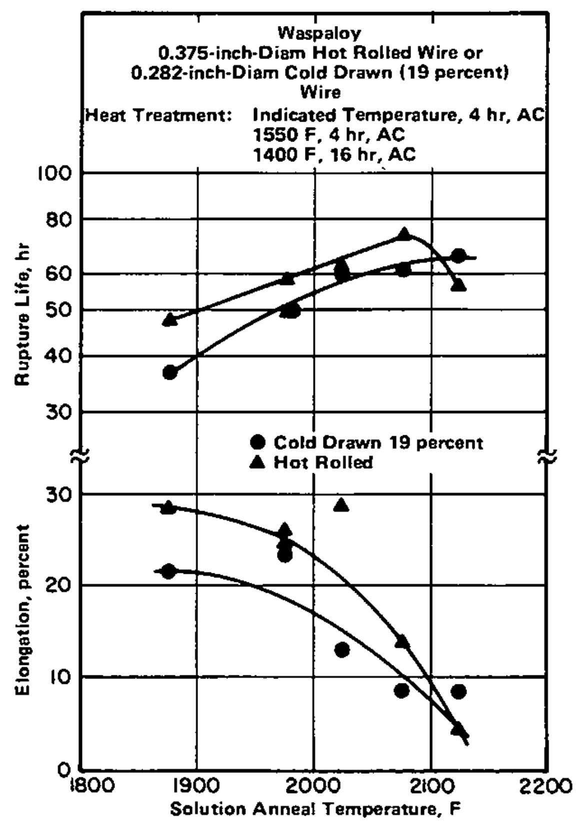


FIGURE 3.046. EFFECT OF SOLUTION ANNEALING TEMPERATURE ON RUPTURE LIFE AND ELONGATION OF HOT ROLLED AND COLD DRAWN WIRE AT 1300 F AND 40 KSI (14)

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

Alloy	Waspaloy			
Forging Schedule		Creep Rupture Properties(c)		
2-hr Forge Preheat Temperature, F	Number of Forge Cycles and Deformation per Cycle, percent(a)	Rupture Life, hr	Elongation, percent	Reduction in Area, percent
2150	3 at 40 percent	58	14	40
	3 at 20 percent	28	12	29
	2 at 20 percent(b)	47	9	14
1975	3 at 40 percent	34	18	42
	3 at 20 percent	48	23	36
	2 at 20 percent(b)	40	26	40
1800	3 at 40 percent	43	22	43
	3 at 20 percent	52	17	37
	2 at 20 percent(b)	61	23	34

(a) Heat treated after forging as follows:
- Gamma-prime solution — 4 hours at 1975 F, AC
- Carbide stabilize — 24 hours at 1550 F, AC
- Gamma-prime age — 16 hours at 1400 F, AC.

(b) Plus reheat to forge temperature without subsequent deformation.

(c) Average of two tests.

TABLE 3.047. EFFECTS OF FORGING TEMPERATURE AND DEFORMATION ON CREEP-RUPTURE PROPERTIES OF WASPALOY AT 1500 F AND 47 KSI (50)

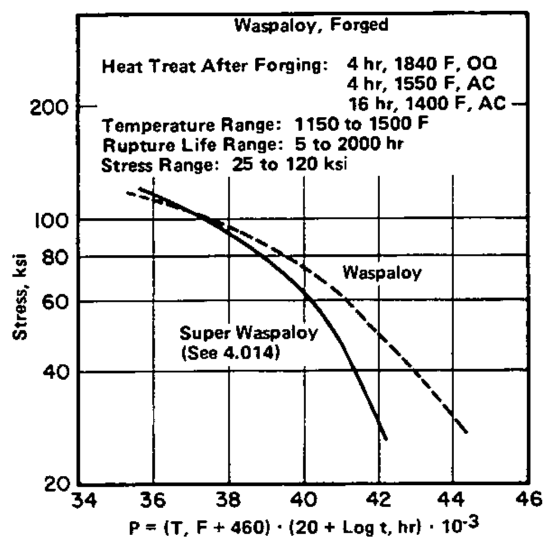


FIGURE 3.048. LARSON-MILLER PLOT OF CREEP-RUPTURE STRENGTH OF WASPALOY AND SUPER WASPALOY (52)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

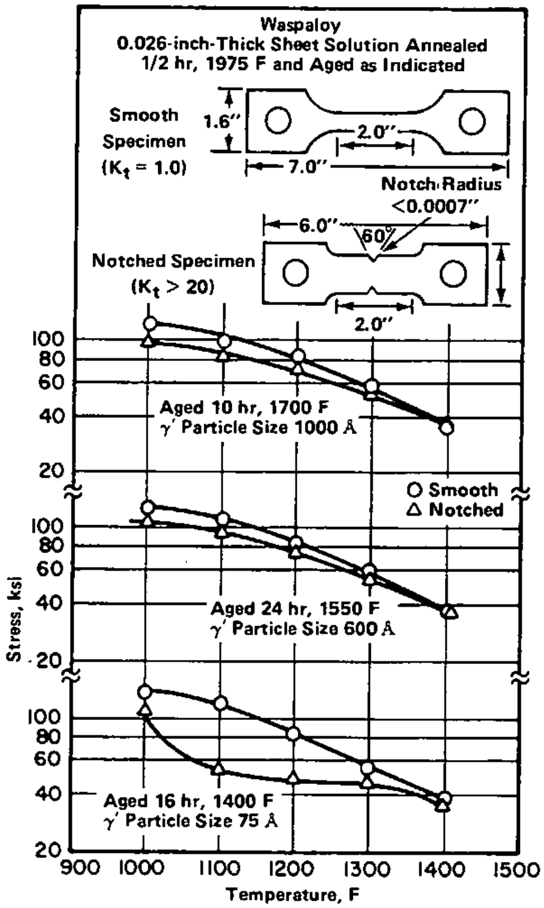


FIGURE 3.0410. STRESS FOR RUPTURE IN 1000 HOURS AS A FUNCTION OF TEMPERATURE FOR SMOOTH AND NOTCHED WASPALOY SHEET (35)

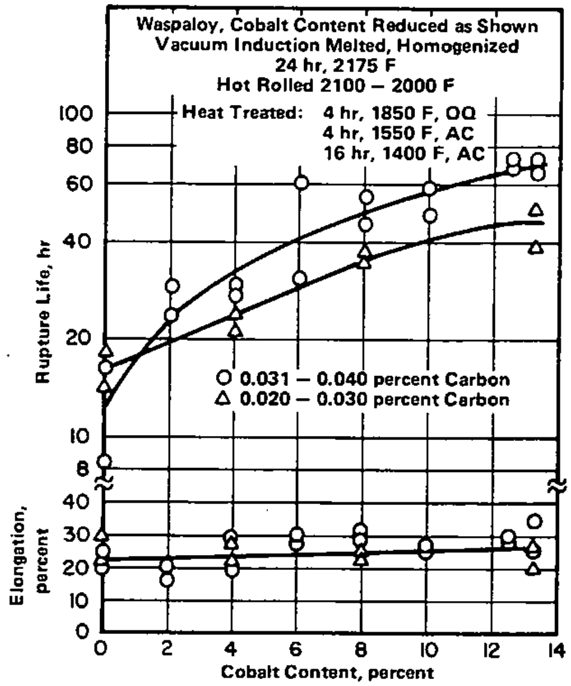


FIGURE 3.0411. EFFECT OF COBALT CONTENT ON CREEP-RUPTURE PROPERTIES OF WASPALOY AT 1350 F AND 80 KSI (39)

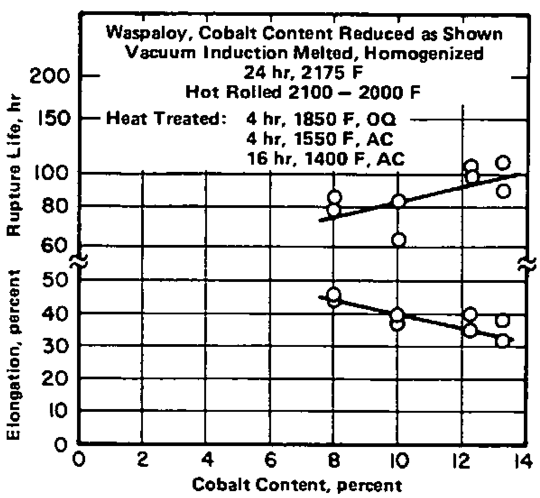


FIGURE 3.0412. EFFECT OF COBALT CONTENT ON CREEP-RUPTURE PROPERTIES OF WASPALOY AT 1500 F AND 42.5 KSI (39)

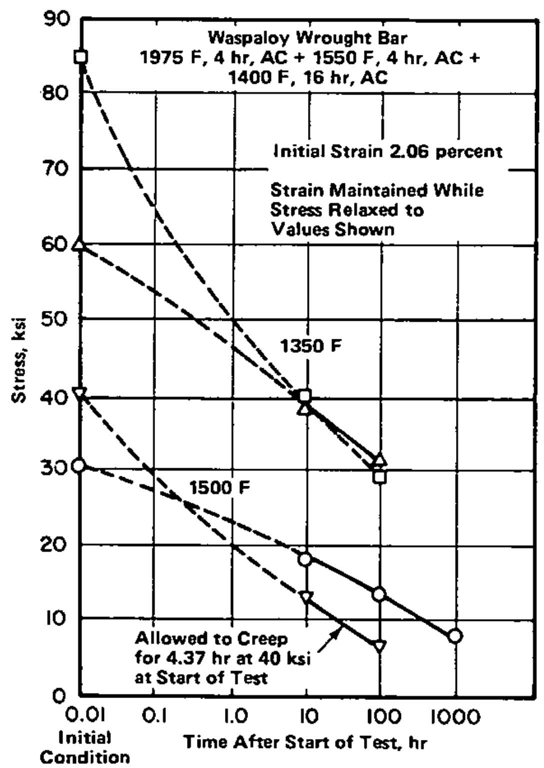


FIGURE 3.0413. STRESS RELAXATION FOR APPLIED STRAIN OF 2.06 PERCENT AT 1350 AND 1500 F (16)

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

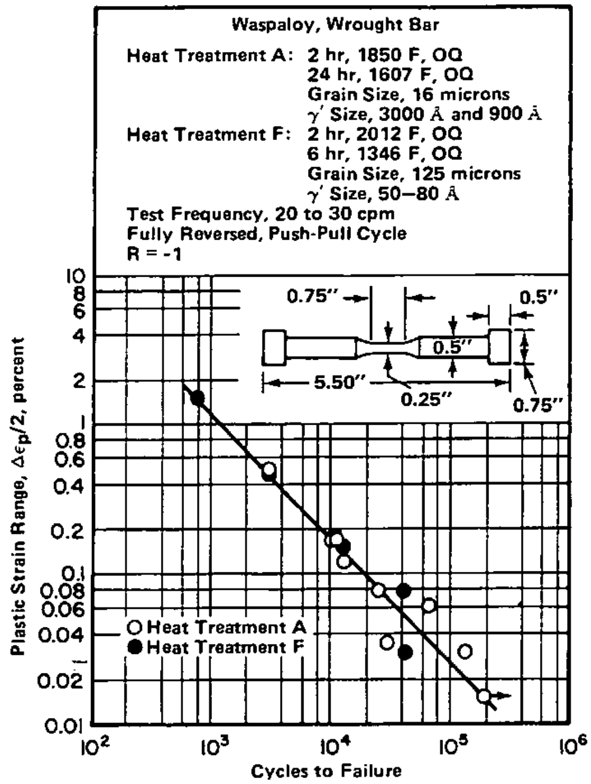


FIGURE 3.0511. LOW-CYCLE FATIGUE BEHAVIOR OF WASPALOY AT ROOM TEMPERATURE (57)

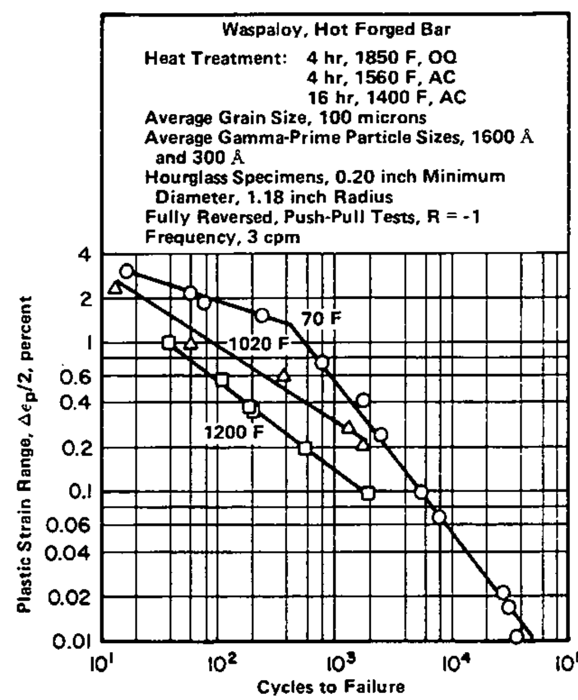


FIGURE 3.0513. LOW-CYCLE FATIGUE BEHAVIOR OF WASPALOY AT 70, 1020, AND 1200 F (58, 59)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

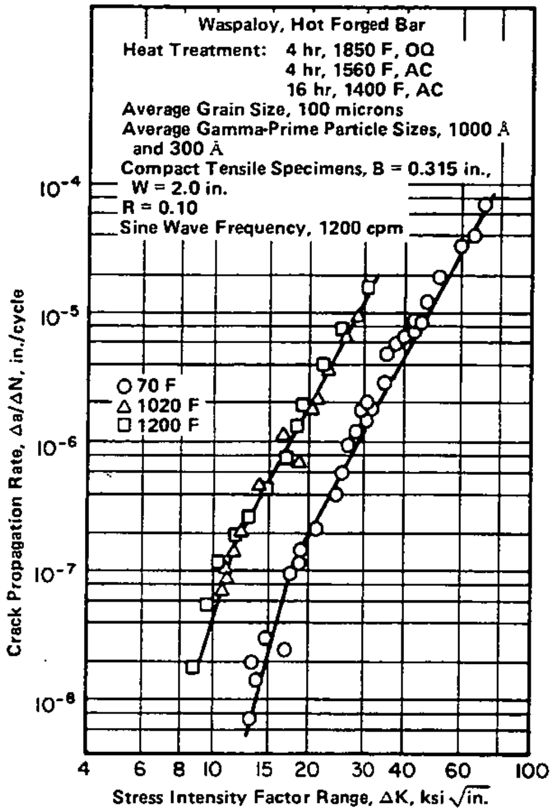


FIGURE 3.0514. LOW-CYCLE FATIGUE CRACK PROPAGATION RATES FOR WASPALOY AT 70, 1020, AND 1200 F (59)

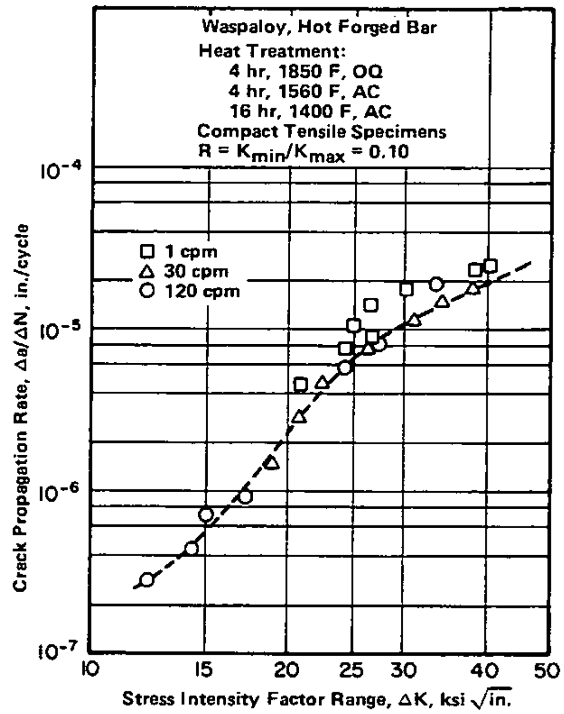


FIGURE 3.0315. LOW-CYCLE FATIGUE CRACK PROPAGATION RATES FOR WASPALOY AT 1200 F AT FREQUENCIES FROM 1 TO 120 CPM (58)

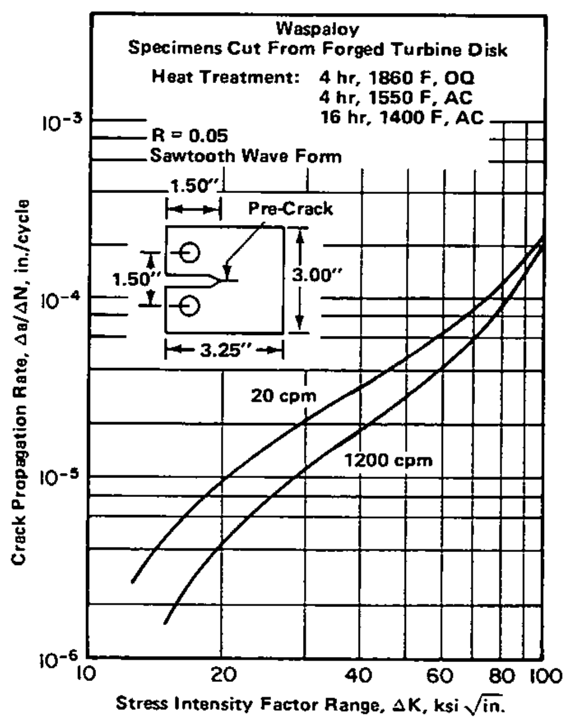


FIGURE 3.0516. LOW-CYCLE FATIGUE CRACK PROPAGATION RATES FOR WASPALOY AT 1200 F (60)

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

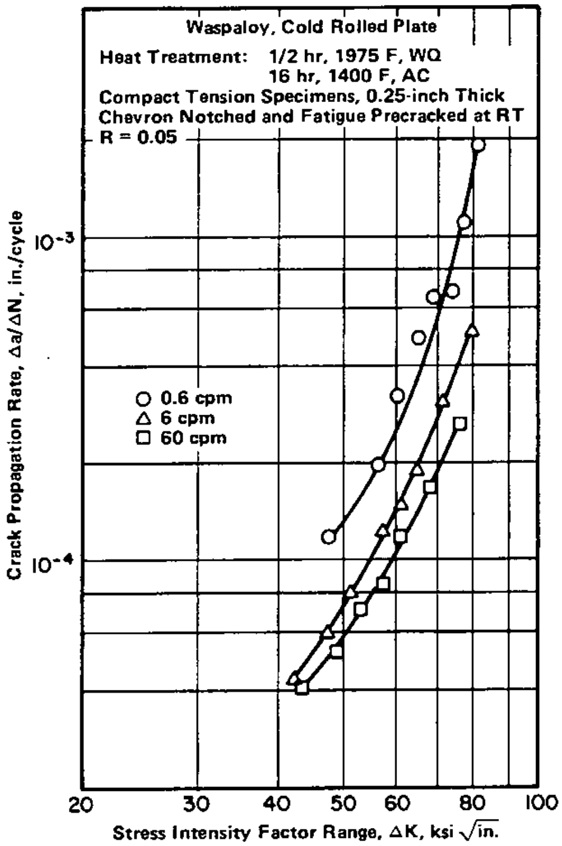


FIGURE 3.0517. LOW-CYCLE FATIGUE CRACK PROPAGATION RATES AT THREE CYCLIC FREQUENCIES FOR WASPALOY AT 1200 F (61)

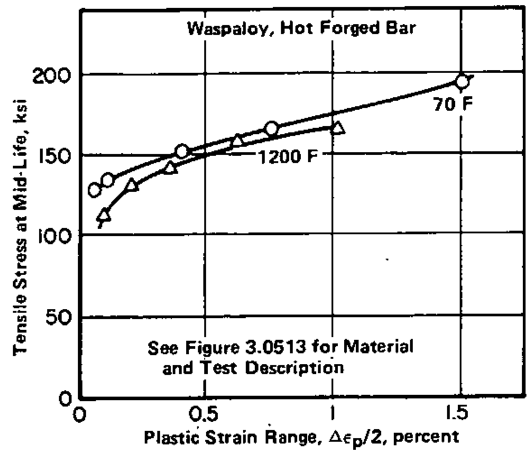


FIGURE 3.0518. LOW-CYCLE FATIGUE STRESS-STRAIN CURVES FOR WASPALOY AT 70 AND 1200 F (58)

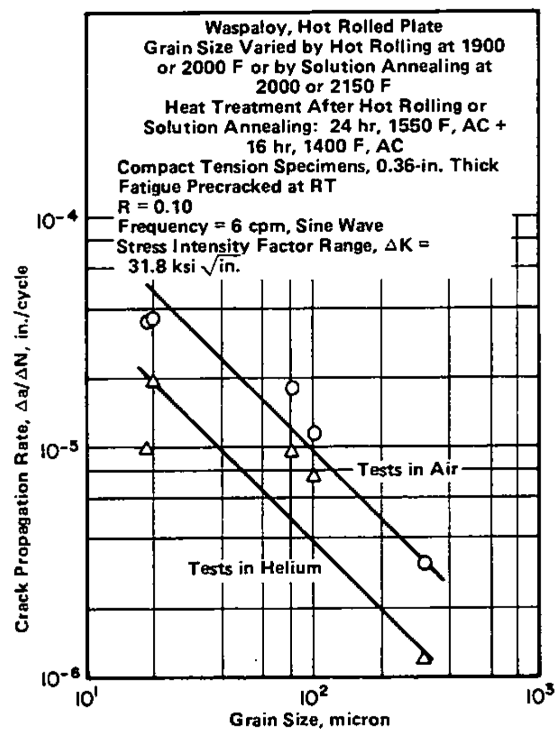


FIGURE 3.05110. LOW-CYCLE FATIGUE CRACK PROPAGATION RATE AS A FUNCTION OF GRAIN SIZE FOR WASPALOY IN AIR OR IN HELIUM AT 1200 F (62)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

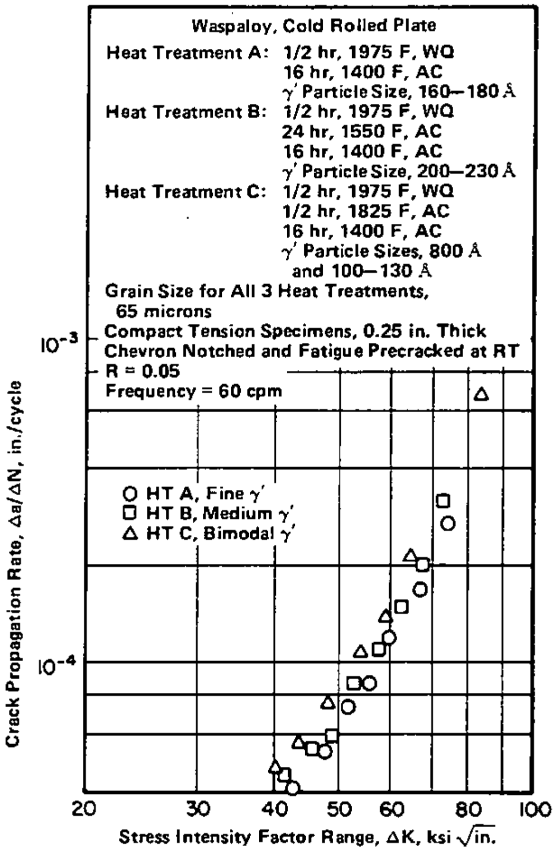


FIGURE 3.05111. EFFECT OF GAMMA-PRIME PARTICLE SIZE ON LOW-CYCLE FATIGUE CRACK PROPAGATION RATE IN WASPALOY AT 1200 F (61)

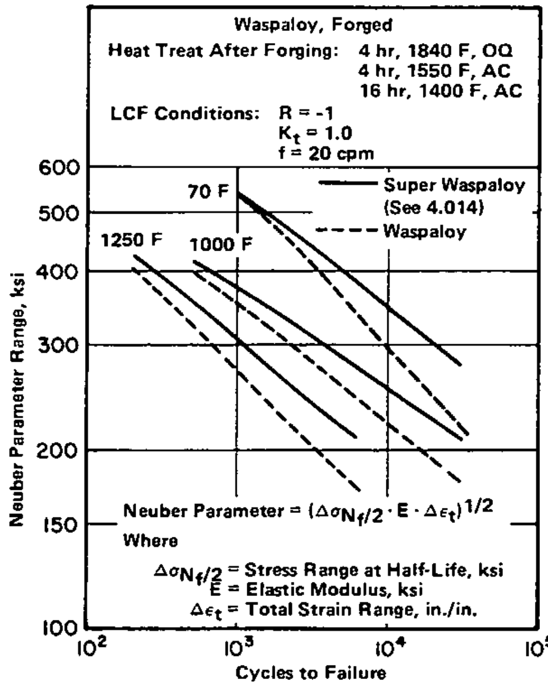
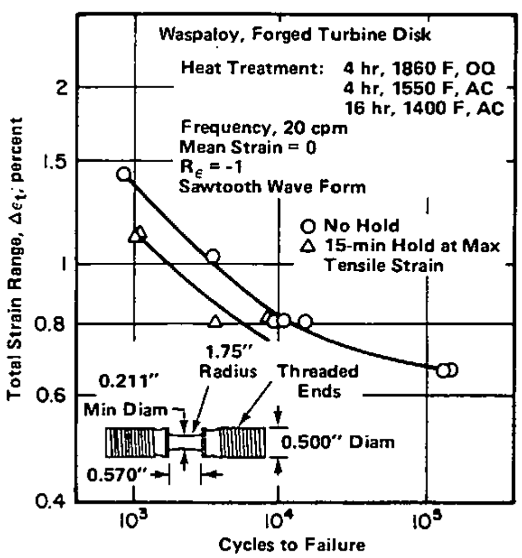
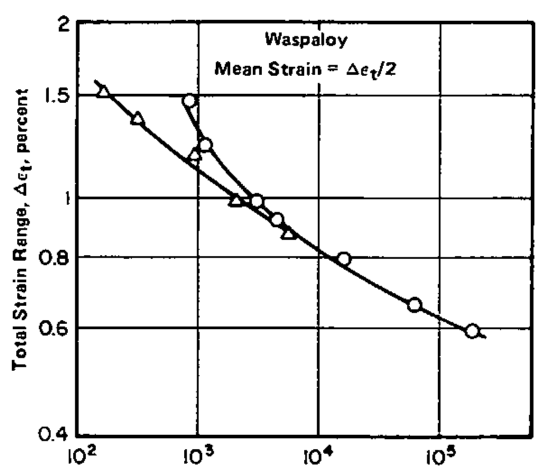


FIGURE 3.05112. STRAIN-CONTROLLED LOW-CYCLE FATIGUE BEHAVIOR OF FORGED WASPALOY AND SUPER WASPALOY AT 70, 1000, AND 1250 F (52)



(a) $R_\epsilon = -1$

FIGURE 3.05114. LOW-CYCLE FATIGUE LIFE AS A FUNCTION OF TOTAL STRAIN RANGE FOR WASPALOY AT 1200 F (60)



(b) $R_\epsilon = 0$

FIGURE 3.05114. (CONTINUED)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

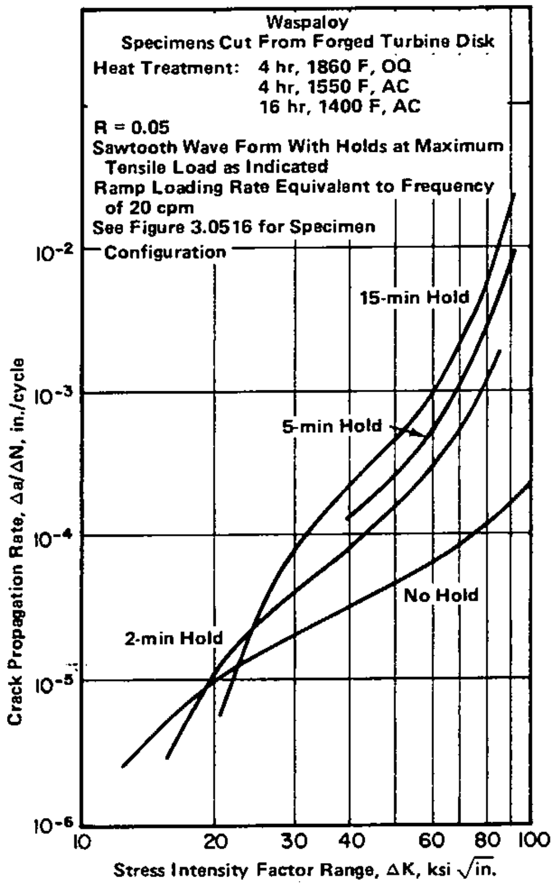


FIGURE 3.05115. EFFECT OF HOLD TIME ON CRACK PROPAGATION RATES FOR WASPALOY AT 1200 F (60)

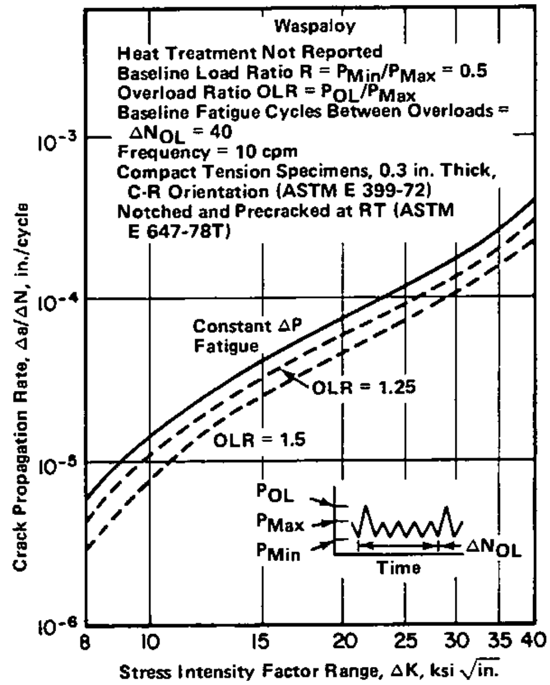


FIGURE 3.05117. EFFECT OF OVERLOAD RATIO ON LOAD-CONTROLLED LOW-CYCLE FATIGUE CRACK PROPAGATION RATE OF WASPALOY AT 1200 F (65)

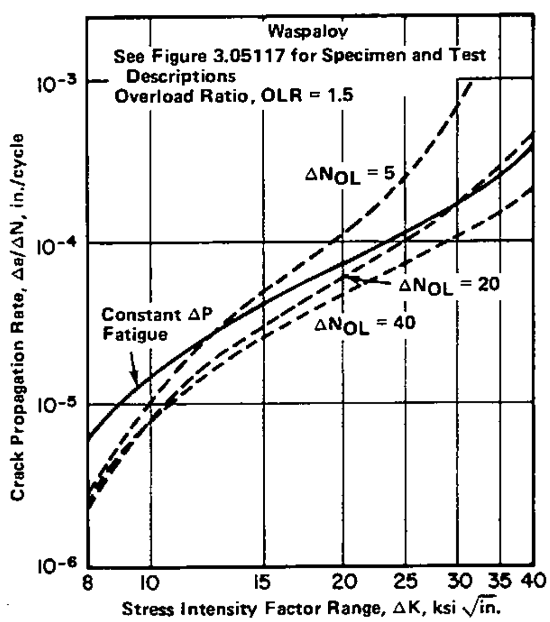
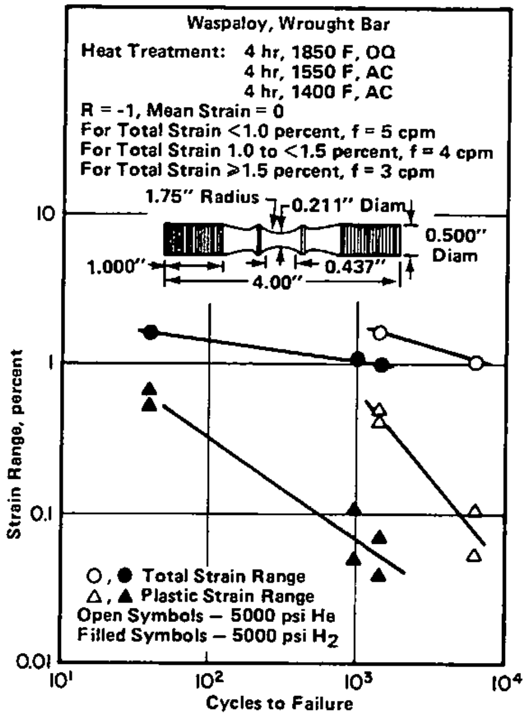


FIGURE 3.05118. EFFECT OF CYCLES BETWEEN OVERLOADS ON LOAD-CONTROLLED LOW-CYCLE FATIGUE CRACK PROPAGATION RATE OF WASPALOY AT 1200 F (65)

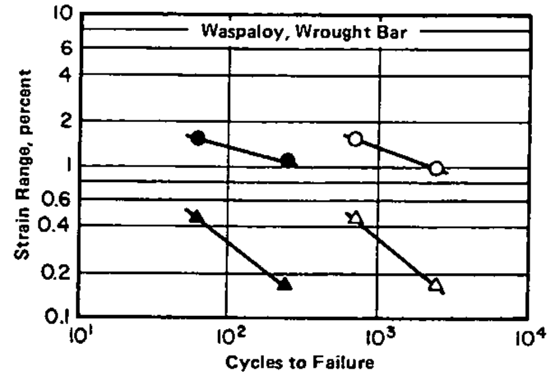
Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy



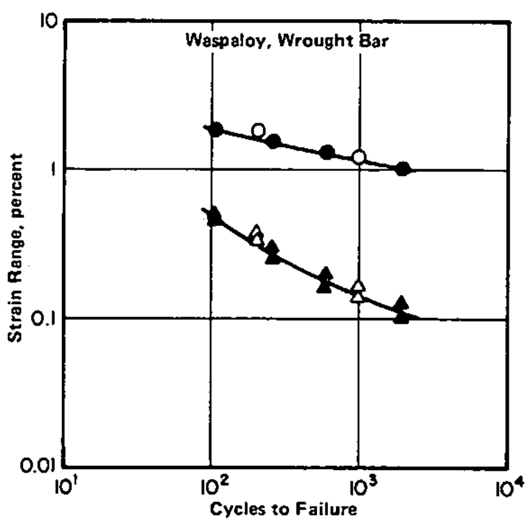
(a) Room Temperature

FIGURE 3.05120. EFFECTS OF HIGH PRESSURE HYDROGEN ON LOW-CYCLE FATIGUE LIFE OF WASPALOY (66, 67)



(b) 540 F

FIGURE 3.05120. (CONTINUED)



(c) 1250 F

FIGURE 3.05120. (CONTINUED)

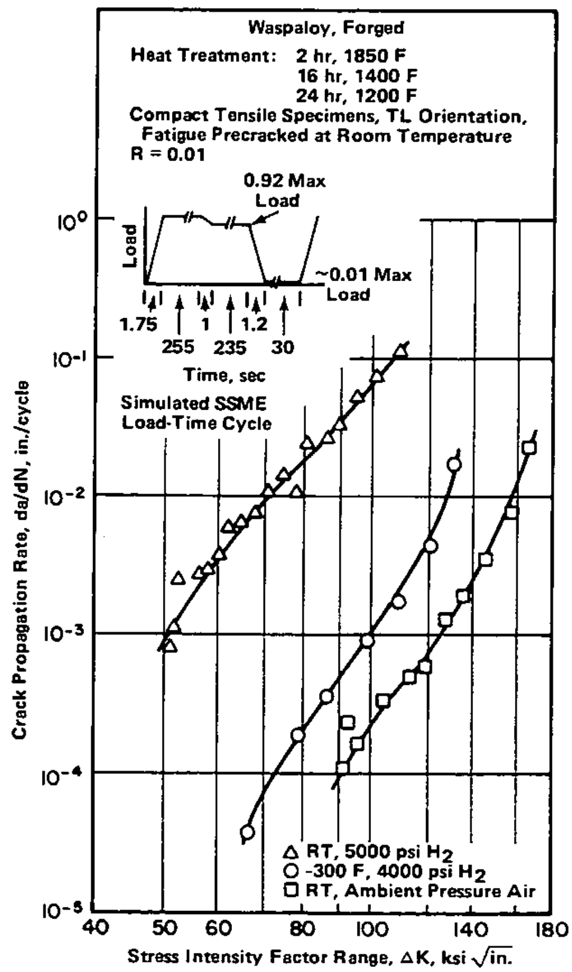


FIGURE 3.05122. EFFECTS OF HYDROGEN ON SIMULATED SPACE SHUTTLE MAIN ENGINE (SSME) CYCLE CRACK PROPAGATION RATE OF WASPALOY AT ROOM TEMPERATURE AND -300 F (68)

	Ni
20	Cr
14	Co
4	Mo
3	Ti
1	Al

Waspaloy

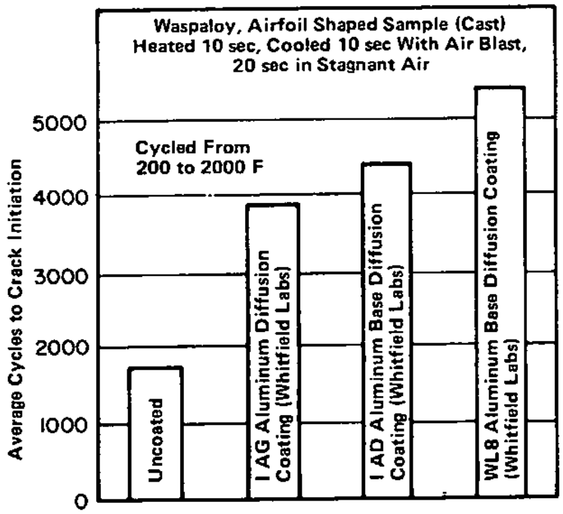


FIGURE 3.0521. COMPARISON IN THERMAL SHOCK OF UNCOATED AIRFOIL SECTION WITH CORRESPONDING SAMPLES COATED WITH PROPRIETARY ALUMINUM AND ALUMINUM-BASE DIFFUSION COATINGS (10)

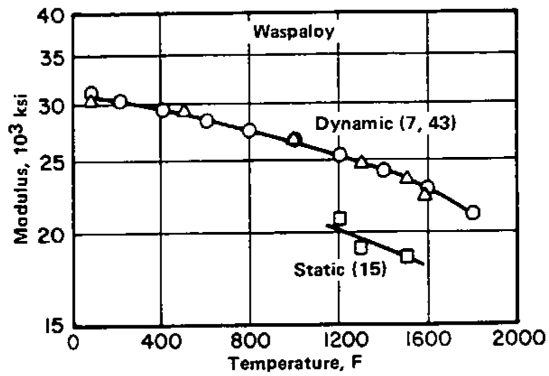


FIGURE 3.062. MODULUS OF ELASTICITY (7, 15, 43)

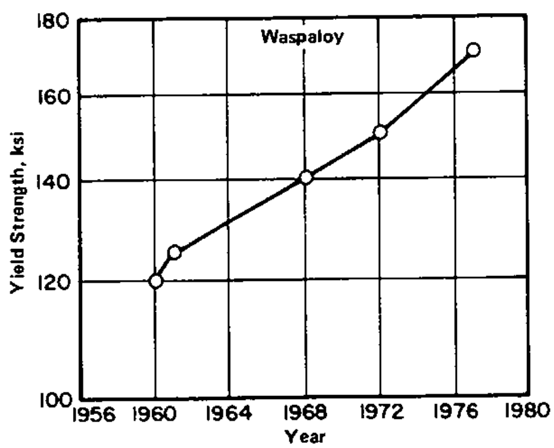


FIGURE 4.012. ROOM-TEMPERATURE YIELD STRENGTH OF WASPALOY (1960—1977) (69)

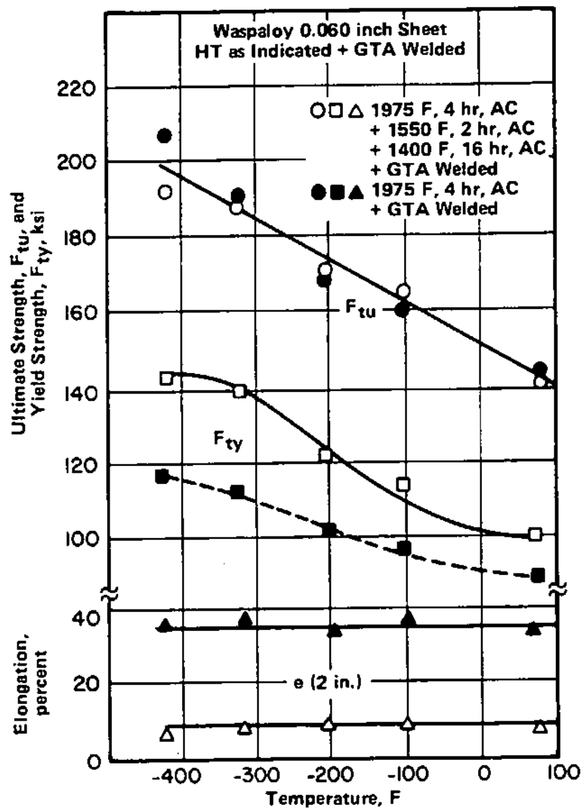


FIGURE 4.032. EFFECT OF GTA WELDING ON TENSILE PROPERTIES AT LOW TEMPERATURE OF ANNEALED AND OF ANNEALED PLUS AGED SHEET (19)

Ni
20 Cr
14 Co
4 Mo
3 Ti
1 Al

Waspaloy

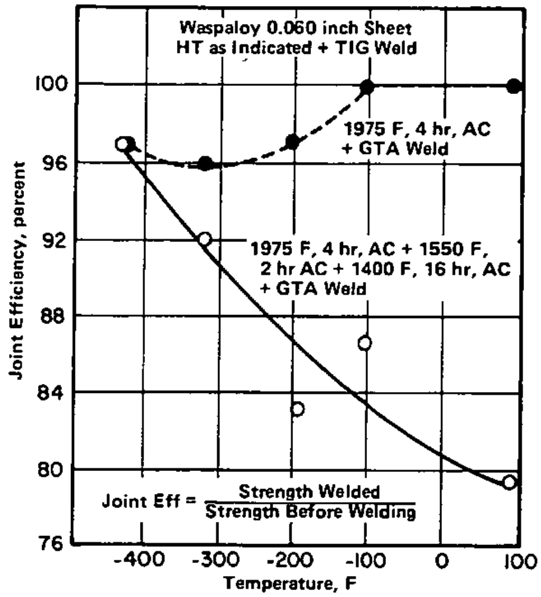


FIGURE 4.033. JOINT EFFICIENCY AT LOW TEMPERATURES OF ANNEALED AND OF ANNEALED PLUS AGED SHEET AFTER GTA WELDING (19)

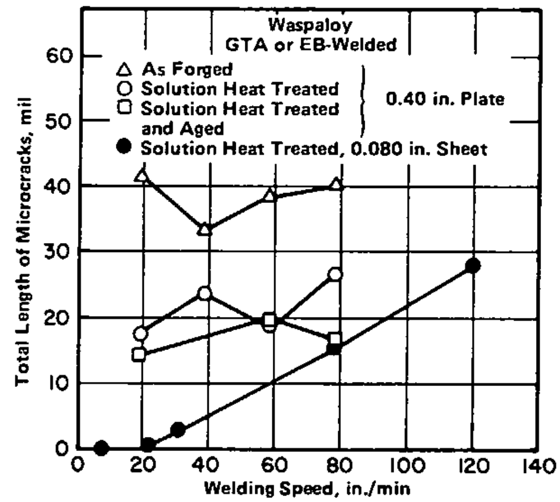


FIGURE 4.035. EFFECTS OF WELDING SPEED, HEAT TREATMENT, AND SHEET THICKNESS ON WELD MICROCRACKING (75)

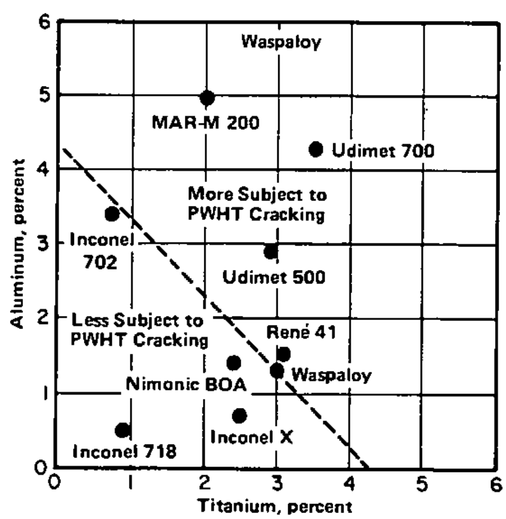


FIGURE 4.037. EFFECT OF ALUMINUM AND TITANIUM CONTENT ON POST-WELD HEAT TREATMENT CRACKING TENDENCY IN WASPALOY AND SEVERAL OTHER SUPERALLOYS (76)

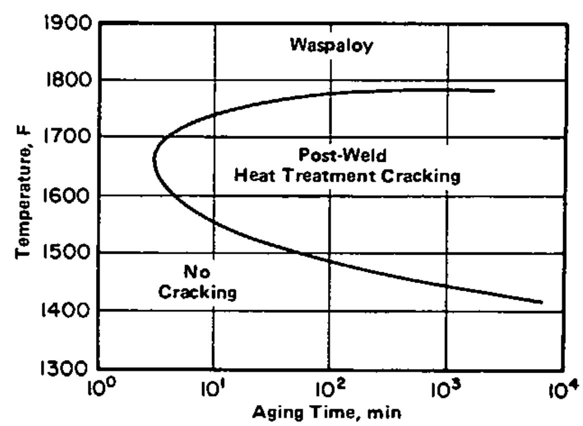


FIGURE 4.038. POST-WELD HEAT TREATMENT CRACKING TENDENCY AS A FUNCTION OF AGING TIME AND TEMPERATURE FOR WASPALOY (76)