INCONEL® alloy 617

INCONEL® alloy 617 (UNS N06617/W.Nr. 2.4663a) is a solid-solution, strengthened, nickel-chromium-cobalt- molybdenum alloy with an exceptional combination of high-temperature strength and oxidation resistance. The alloy also has excellent resistance to a wide range of corrosive environments, and it is readily formed and welded by conventional techniques.

The limiting chemical composition of INCONEL alloy 617 is listed in Table 1. The high nickel and chromium contents make the alloy resistant to a variety of both reducing and oxidizing media. The aluminum, in conjunction with the chromium, provides oxidation resistance at high temperatures. Solid-solution strengthening is imparted by the cobalt and molybdenum.

The combination of high strength and oxidation resistance at temperatures over 1800°F (980°C) makes INCONEL alloy 617 an attractive material for such components as ducting, combustion cans, and transition liners in both aircraft and land-based gas turbines. Because of its resistance to high-temperature corrosion, the alloy is used for catalyst-grid supports in the production of nitric acid, for heat-treating baskets, and for reduction boats in the refining of molybdenum. INCONEL alloy 617 also offers attractive properties for components of power-generating plants, both fossil- fueled and nuclear.

Property values are given in both United States customary units and the International System of Units (SI). The SI unit of stress is the pascal (Pa), which is equivalent to newton per square metre. The approximate relationship between the pascal and the pound per square inch (psi) is 1 Pa = 0.0001450 psi, or 1 psi = 6895 Pa.

Table 1 - Limiting Chemical Composition, %, of INCONEL alloy 617

Nickel	44.5 min.
Chromium	20.0-24.0
Cobalt	10.0-15.0
Molybdenum	8.0-10.0
Aluminum	0.8-1.5
Carbon	0.05-0.15
Iron	3.0 max.
Manganese	1.0 max.
Silicon	1.0 max.
Sulfur	0.015 max.
Titanium	0.6 max.
Copper	0.5 max.
Boron	0.006 max.

Table 2 - Physical Constants

Density, lb/in³	0.302
Mg/m³	8.36
Melting Range, °F	2430-2510
°C	1332-1380
Specific Heat at 78°F (26°C)	
Btu/lb-°F	0.100
J/kg-°C	419
Electrical Resistivity at 78°F (26°C)	
ohm-circ mil/ft	736
μΩ-m	1.22

Physical Constants and Thermal Properties

Melting range and some physical constants at room temperature are shown in Table 2. The alloy's low density, compared with tungsten-containing alloys of similar strength, is significant in applications such as aircraft gas turbines where high strength-to-weight ratio is desirable.

Thermal properties of alloy 617 at temperatures to 2000°F (1095°C) are given in Table 3. Values for thermal conductivity and specific heat were calculated; other values were measured. Thermal expansion of INCONEL alloy 617 is lower than that of most other austenitic alloys, reducing stresses from differential expansion when the alloy is coupled with carbon steels or low-alloy steels.

Modulus of elasticity of INCONEL alloy 617 is shown along with Poisson's ratio (calculated from moduli of elasticity) in Table 4. The modulus values were determined by a dynamic method.

Publication Number SMC-029

Table 3 - Electrical and Thermal Properties

Temperature	Electrical Resistivity	Thermal Conductivity[a]	Coefficient of Expansion[b]	Specific Heat[c]
°F	ohm-circ mil/ft	Btu-in./ft²-h-°F	10^{-6} in./in./°F	Btu/lb-°F
78	736	94	-	0.100
200	748	101	7.0	0.104
400	757	113	7.2	0.111
600	764	125	7.4	0.117
800	770	137	7.6	0.124
1000	779	149	7.7	0.131
1200	793	161	8.0	0.137
1400	807	173	8.4	0.144
1600	803	185	8.7	0.150
1800	824	197	9.0	0.157
2000	-	209	9.2	0.163
°C	μΩ-m	W/m-°C	μm/m-°C	J/kg-°C
20	1.222	13.4	-	419
100	1.245	14.7	11.6	440
200	1.258	16.3	12.6	465
300	1.268	17.7	13.1	490
400	1.278	19.3	13.6	515
500	1.290	20.9	13.9	536
600	1.308	22.5	14.0	561
700	1.332	23.9	14.8	586
800	1.342	25.5	15.4	611
900	1.338	27.1	15.8	636
1000	1.378	28.7	16.3	662

[a]Calculated from electrical resistivity.
[b]Mean coefficient of linear expansion between 78°F (26°C) and temperature shown.
[c]Calculated values.

Table 4 - Modulus of Elasticity[a]

Temperature	Tensile Modulus	Shear Modulus	Poisson's Ratio[b]
°F	10^3 ksi	10^3 ksi	
74	30.6	11.8	0.30
200	30.0	11.6	0.30
400	29.0	11.2	0.30
600	28.0	10.8	0.30
800	26.9	10.4	0.30
1000	25.8	9.9	0.30
1200	24.6	9.5	0.30
1400	23.3	9.0	0.30
1600	21.9	8.4	0.30
1800	20.5	7.8	0.31
2000	18.8	7.1	0.32
°C	GPa	GPa	Poisson's Ratio[b]
25	211	81	0.30
100	206	80	0.30
200	201	77	0.30
300	194	75	0.30
400	188	72	0.30
500	181	70	0.30
600	173	66	0.30
700	166	64	0.30
800	157	61	0.30
900	149	57	0.30
1000	139	53	0.31
1100	129	49	0.32

[a]Determined by dynamic method.
[b]Calculated from moduli of elasticity.

Mechanical Properties

INCONEL alloy 617 has high mechanical properties over a broad range of temperatures. One of the alloy's outstanding characteristics is the strength level it maintains at elevated temperatures. The resistance of the alloy to high-temperature corrosion enhances the usefulness of its strength.

Tensile Properties

Typical room-temperature tensile properties of various product forms are listed in Table 5. All values are for material in the solution-annealed condition. Properties shown for sheet, strip, and plate are for the transverse direction.

Tensile properties at high temperatures of solution-annealed, hot-rolled rod are shown in Figure 1. The test specimens were from rod of 0.50-in (13-mm) or 0.62-in (16-mm) diameter. High-temperature tensile properties of solution-annealed, cold-rolled sheet are presented in Figure 2. The tests were performed in the transverse direction on sheet of 0.187-in. (4.75-mm) thickness.

Fatigue Strength

High-cycle fatigue strength of INCONEL alloy 617 at room temperature and 1600°F (870°C) is indicated by the curves in Figure 3. The data are from rotating-beam tests on coarse-grain, solution-annealed, hot-rolled rod of 0.56-in. (14-mm) diameter.

The results of low-cycle fatigue tests on coarse-grain, solution-annealed plate are shown in Figure 4. Included for comparison are test results for welded joints. The specimens were from joints welded by the gas-metal-arc process using matching-composition filler metal.

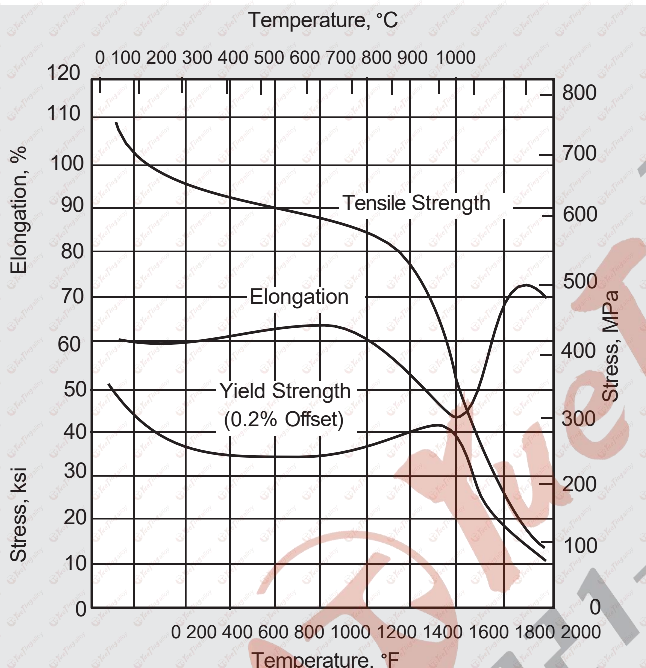


Figure 1. High-temperature tensile properties of solution-annealed, hot-rolled rod.

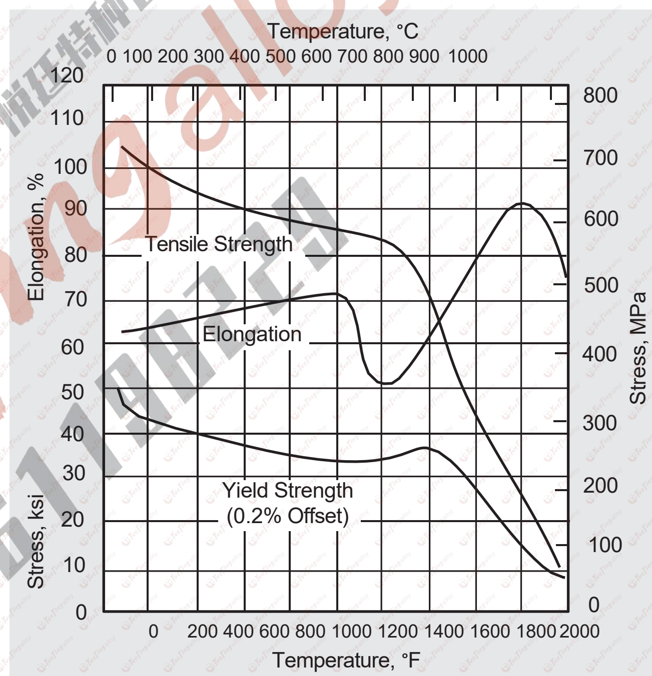


Figure 2. High-temperature tensile properties of solution-annealed, cold-rolled sheet.

Table 5 - Typical Room-Temperature Mechanical Properties of Solution-Annealed Material

Product Form	Production Method	Yield Strength (0.2% Offset)		Tensile Strength		Elongation, %	Reduction of Area, %	Hardness BHN
		ksi	MPa	ksi	MPa			
Plate	Hot Rolling	46.7	322	106.5	734	62	56	172
Bar	Hot Rolling	46.1	318	111.5	769	56	50	181
Tubing	Cold Drawing	55.6	383	110.0	758	56	-	193
Sheet or Strip	Cold Rolling	50.9	351	109.5	755	58	-	173

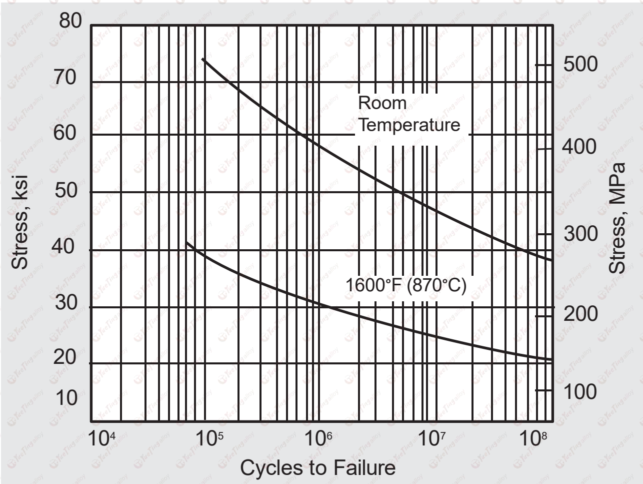


Figure 3. Rotating-beam fatigue strength of solution-annealed INCONEL alloy 617.

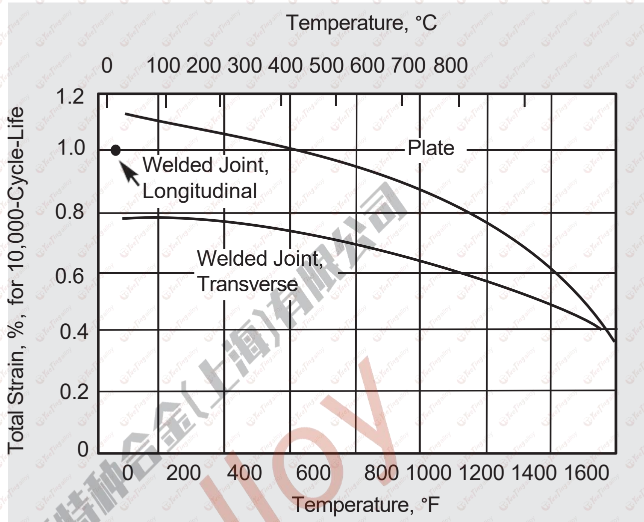
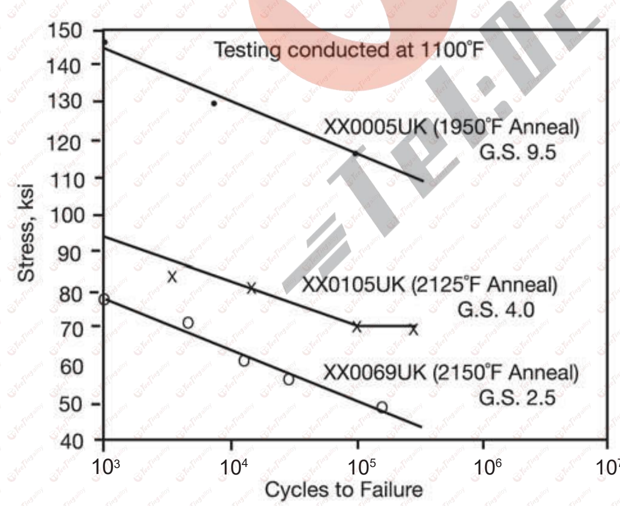


Figure 4. Low-cycle fatigue strength of solution-annealed plate and as-welded joints. Welds were made with INCONEL Filler Metal 617 and the gas-metal-arc process.

LCF Considerations

The development of alloy 617 centered on the desire for maximum creep strength at elevated temperatures. Solution annealing temperatures were selected to provide the coarse grains necessary for the best high temperature creep resistance. In recent years, designers of turbine hot gas path structures have realized the need for optimization of both low cycle fatigue (LCF) strength as well as creep. A development program was initiated to achieve this optimization. The results of the program are detailed in Reference 1.

Tension-tension axial load controlled LCF test data acquired at 1100°F (593°C) and 1400°F (760°C) are shown in Figure 5 and Table 6. The improvement in LCF performance with ASTM grain sizes of 4 and 5 is significant. After extensive thermomechanical processing experimentation, a controlled practice was developed which restricts the grain size of production plate to ASTM 3 to 6. Slight alloy composition modifications permit better grain size control and improved stress rupture properties. The combination of alloy composition optimization and closely controlled thermomechanical processing results in an alloy which demonstrates much improved LCF performance with little or no loss of creep resistance in comparison with coarse grain material. The improved LCF performance extends to higher temperatures as well, as shown in Figure 6.



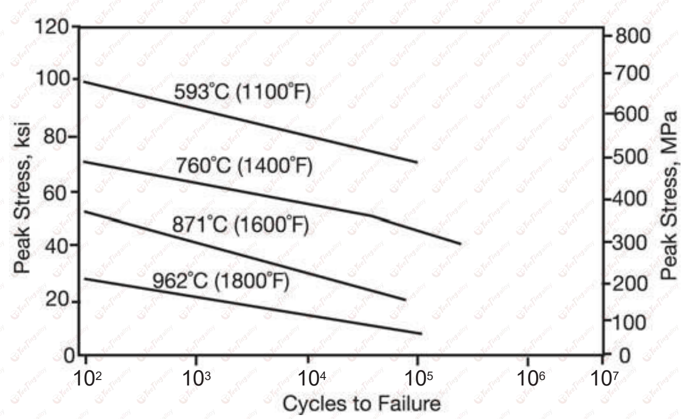


Figure 5. Effect of grain size on the tension-tension axial stress controlled LCF properties of alloy 617 (R=0.1).

Figure 6. Effect of temperature on the tension-tension axial stress controlled fatigue strength of alloy 617 (R=0.1).

Figure 6a shows results of fully-reversed (R=-1) axial low-cycle fatigue testing (frequency = 30 cycles per minute) of INCONEL alloy 617 sheet. Cycles to failure are shown as a function of total cyclic strain range at room temperature, 1000°F and 1600°F. Curves were fitted to the data using the methodology developed by Coffin and Manson.

Table 6 - Effect of grain size on the tension-tension axial stress controlled LCF properties of alloy 617 at 760°C (1400°F)

Alloy 617 Heat Number	ASTM G. S. Size No.	Tension-Tension Axial Stress 34.5-413.7 MPa (5-60 ksi) Cycles to failure
XX0023UK	2.5	500
XX0015UK	5.0	64,391
XX0005UK	9.5	93,440

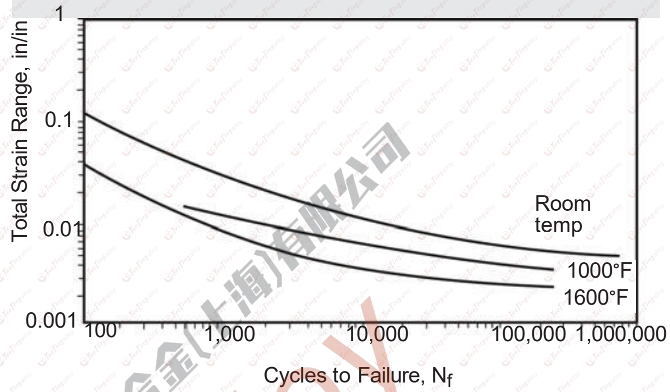


Figure 6a. Axial low-cycle fatigue testing of INCONEL alloy 617 sheet. R=1, frequency=30 cpm

Stability of Properties

Alloy 617 exhibits good metallurgical stability for an alloy of its strength level. Table 7 shows changes in tensile and impact properties after exposures extending to 12,000 h at elevated temperatures. All samples were in the solution-annealed condition before exposure. The strengthening is attributable to carbide formation and, at exposure temperatures of 1200°F (650°C) to 1400°F (760°C), to precipitation of gamma prime phase.

Creep and Rupture Properties

INCONEL alloy 617 displays exceptionally high levels of creep-rupture strength, even at temperatures of 1800°F (980°C) and above. That characteristic, combined with good resistance to oxidizing and carburizing atmospheres, makes the alloy especially suitable for long-term, high-stress use at elevated temperatures.

Figure 7 shows the creep strength of solution-annealed alloy 617 at temperatures to 2000°F (1095°C). Rupture strength of solution-annealed material over the same temperature range is shown in Figure 8. The tests were performed on bar, tubing, and sheet specimens.

Table 7 - Mechanical Properties After Exposure to Elevated Temperatures

Exposure Temperature		Exposure Time, h	Yield Strength (0.2% Offset)		Tensile Strength		Elongation, %	Impact Strength	
°F	°C		ksi	MPa	ksi	MPa		ft-lb	J
No exposure			46.3	319	111.5	769	68	171	232
1100	595	100	46.5	321	111.5	769	69	213	289
		1 000	51.8	357	116.5	803	67	223	302
		4 000	55.7	384	117.5	810	67	181	245
		8 000	59.5	410	121.5	838	61	98	133
		12 000	67.6	466	132.0	910	34	69	94
1200	650	100	51.8	357	114.5	789	69	191	259
		1 000	66.6	459	133.5	920	37	35	47
		3 640	76.3	526	142.0	979	33	35	47
		8 000	76.5	527	144.0	993	28	40	54
		12 000	77.5	534	144.0	993	32	38	52
1300	705	100	58.7	405	126.5	872	38	57	77
		1 000	70.5	486	138.0	952	33	48	65
		4 000	70.6	487	138.0	952	36	48	65
1400	760	100	58.3	402	126.5	872	35	56	76
		1 000	56.3	388	126.0	879	37	63	85
		4 000	58.1	401	128.5	886	38	62	84
		8 000	58.5	403	130.0	896	40	64	87
		12 000	56.4	389	129.5	893	38	67	91

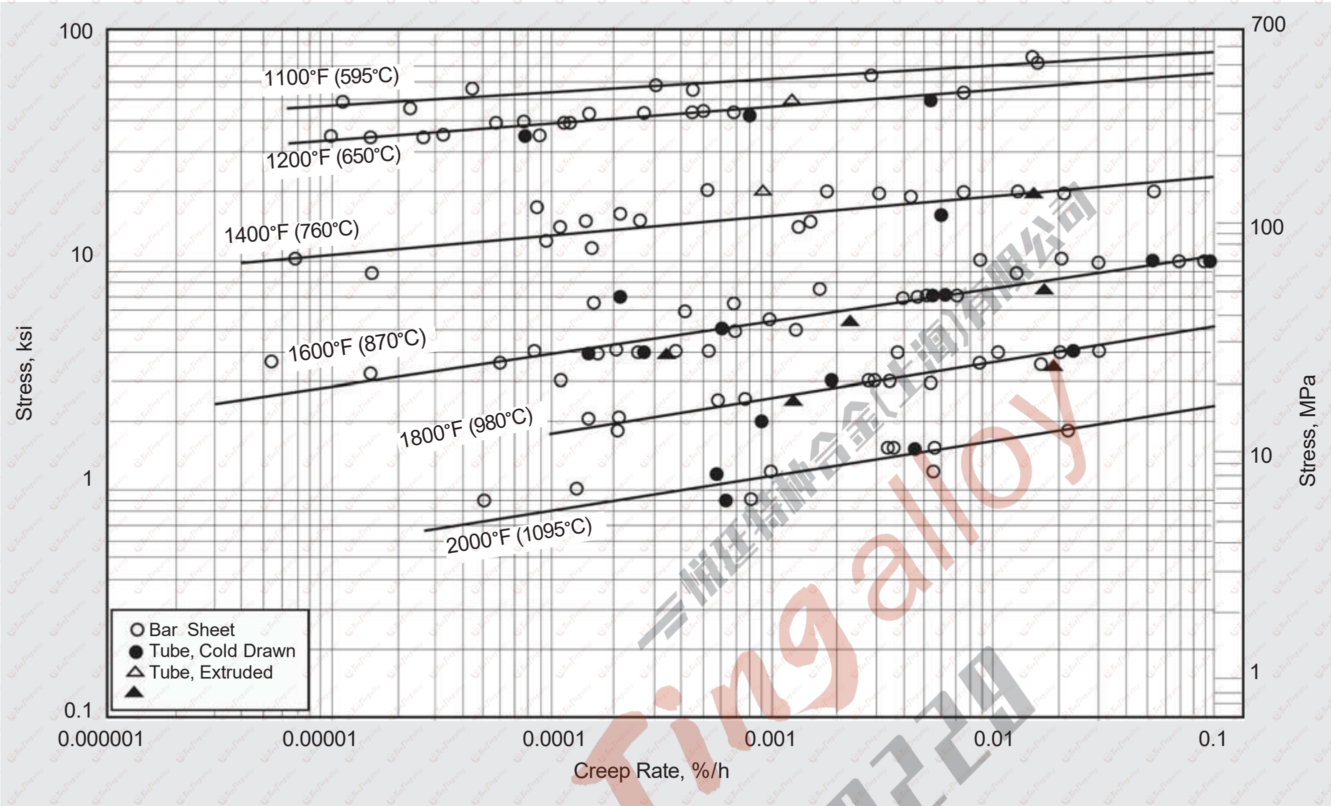


Figure 7. Creep strength of solution-annealed INCONEL alloy 617.

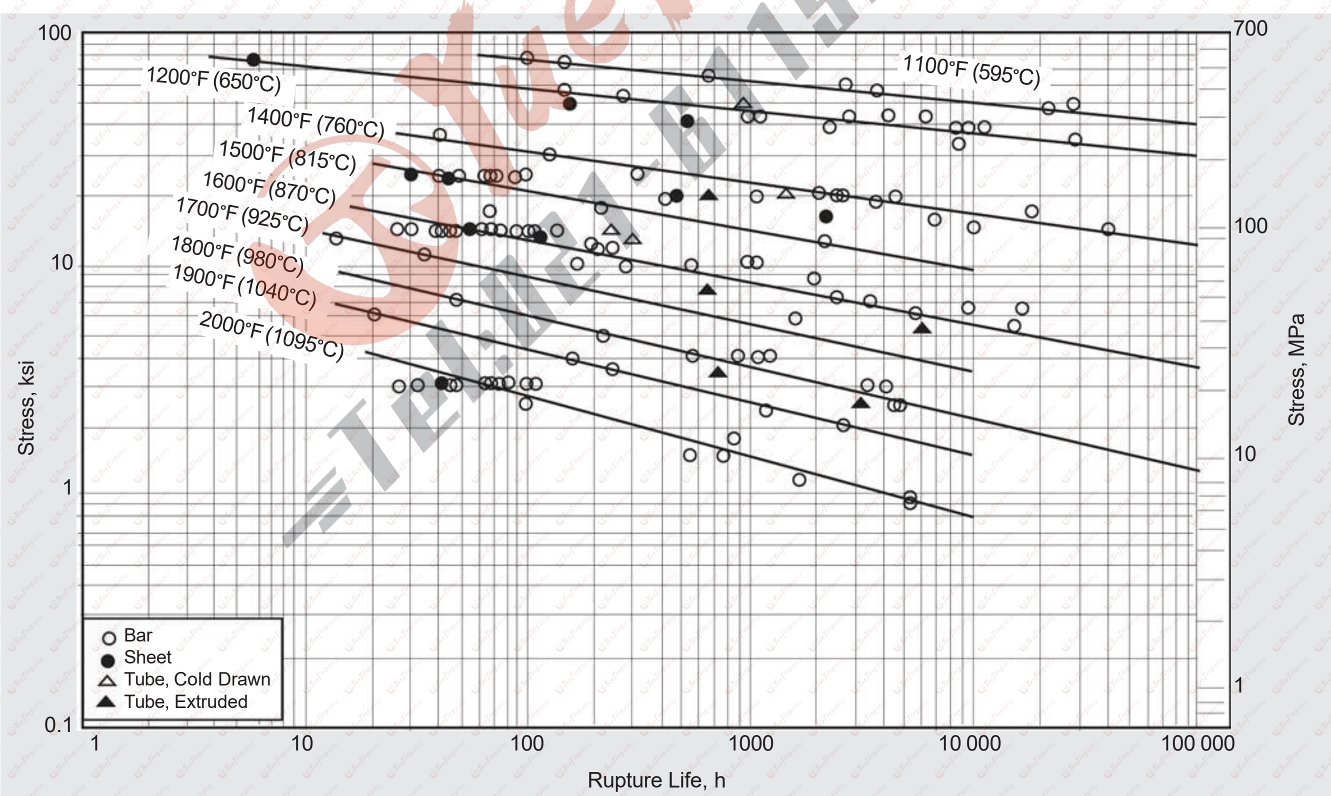


Figure 8. Rupture strength of solution-annealed INCONEL alloy 617. Arrows denote tests discontinued before fracture.

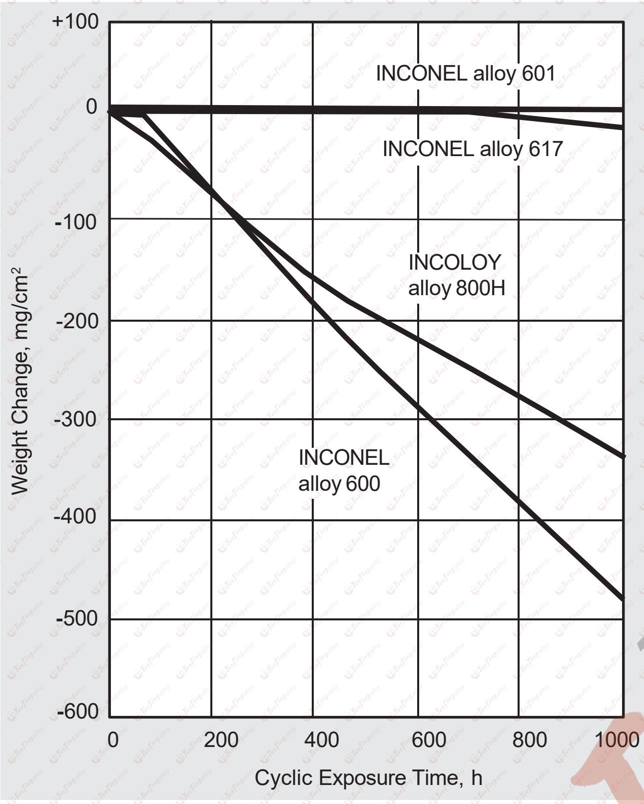


Figure 9. Resistance to cyclic oxidation at 2000°F (1095°C). Cycles consisted of 15 minutes heating and 5 minutes cooling in air.

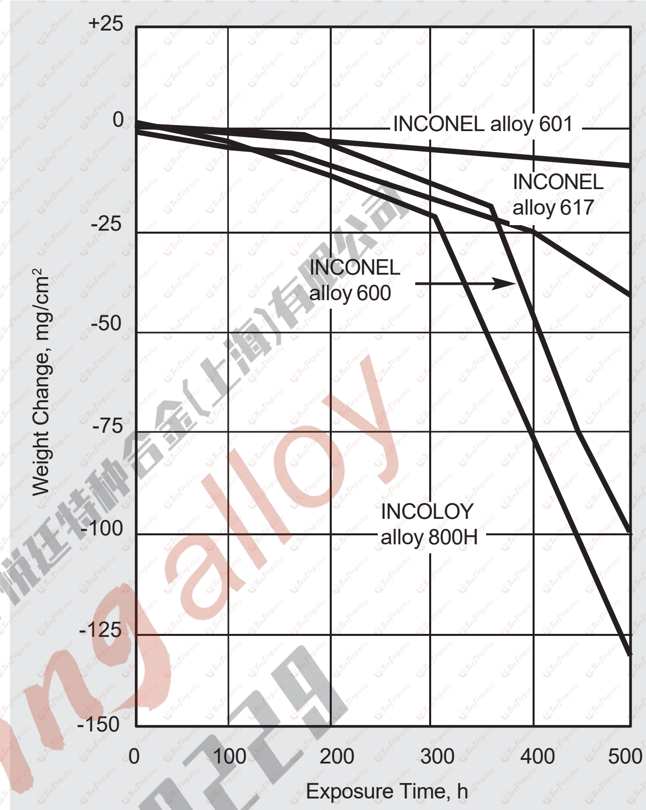


Figure 10. Resistance to cyclic oxidation at 2100°F (1150°C). Samples were exposed to temperature in 50-h cycles.

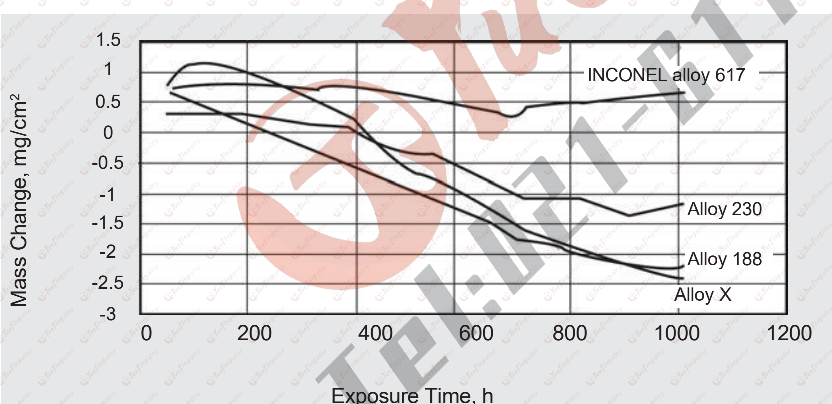


Figure 11. Resistance to oxidation of heat-resistant alloys at 1832°F (1000°C). Samples were exposed in air with 20% water. Cycle period was once per week.

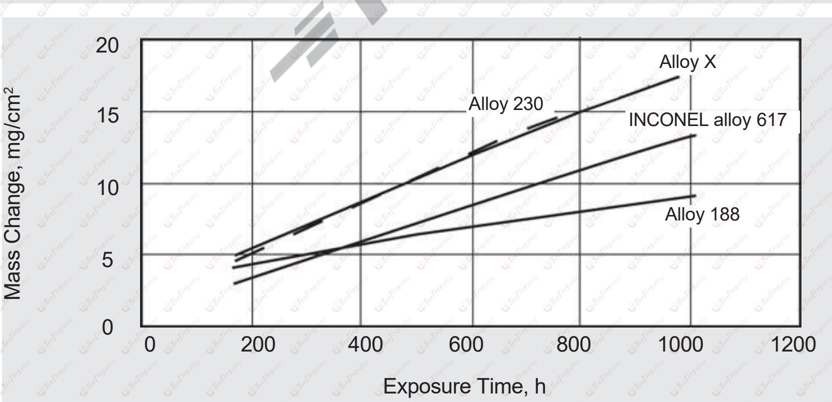


Figure 12. Carburization resistance of heat-resistant alloys at 1832°F (1000°C). Samples were exposed to H_2-5.5% CO_2-4.5% CH_4.

Design Considerations

Allowable design stresses for INCONEL alloy 617 products are found in Table 1B of Section II, Part D of the ASME Boiler and Pressure Vessel Code. Alloy 617 is one of the few materials covered by the ASME Code with design stresses up to 1800°F. Allowable design stresses from the 2005 edition for the common temperatures of application are compared with those for UNS N06230 in Table 8. It is seen that alloy 617 permits increasingly higher design stresses over UNS N06230 as temperature increases in the range where these alloys are typically employed.

Table 8 - ASME SC VIII, Div. 1 Allowable Design Stresses

	INCONEL alloy 617	UNS N06230
Temperature, °F	Allowable Stress, ksi	Allowable Stress, ksi
1000	15.5	20.9
1050	15.4	20.9
1100	15.4	20.9
1150	15.3	19.0
1200	15.3	15.6
1250	14.5	12.9
1300	11.2	10.6
1350	8.7	8.5
1400	6.6	6.7
1450	5.1	5.3
1500	3.9	4.1
1550	3.0	2.9
1600	2.3	2.1
1650	1.8	1.5
1700	1.4	1.1
1750	1.1	0.70
1800	0.73	0.45

Corrosion Resistance

The composition of INCONEL alloy 617 includes substantial amounts of nickel, chromium, and aluminum for a high degree of resistance to oxidation and carburization at high temperatures. Those elements, along with the molybdenum content, also enable the alloy to withstand many wet corrosive environments.

Oxidation and Carburization

The resistance of INCONEL alloy 617 to cyclic oxidation at 2000°F (1095°C) is shown in Figure 9. The tests were performed on specimens of thin strip and consisted of cycles of exposure to temperature for 15 minutes followed by cooling in still air for 5 minutes. The results demonstrate the ability of the alloy to form and retain a protective surface oxide under conditions of extremely severe thermal cycling. The results of a similar test at 2100°F (1150°C) are shown in Figure 10. The specimens of thin strip were exposed to the test temperature in 50-hour cycles with weight loss determined after each cycle. The resistance of alloy 617 and other high strength, heat-resistant alloys to static oxidation in moist air at 1832°F (1000°C) is shown in Figure 11.

The excellent resistance of alloy 617 to oxidation results from the alloy's chromium and aluminum contents. At elevated temperatures, those elements cause the formation of a thin, subsurface zone of oxide particles. The zone forms rapidly upon exposure to high temperatures until it reaches a thickness of 0.001 to 0.002 in. (0.025 to 0.05 mm). The oxide zone provides the proper diffusion conditions for the formation of a protective chromium oxide layer on the surface of the metal. It also helps to prevent spalling of the protective layer.

INCONEL alloy 617 has excellent resistance to carburization. Table 9 compares alloy 617 and some other carburization-resistant alloys in a gaseous carburizing environment at 2000°F (1095°C). The weight-gain measurements indicate the amount of carbon absorbed during the test period. Table 10 shows the superiority of alloy 617 over alloys of similar strength in a gas-carburization test at 1800°F (980°C).

Aqueous Corrosion

While alloy 617 exhibits excellent resistance to aqueous corrosion by many media, the alloy is normally only used at high temperatures. For information about the resistance of alloy 617 in specific wet environments, visit the website, www.yttzhj.com.

Table 9-Results of 25-h Carburization Tests in Hydrogen/2% Methane at 2000°F (1095°C)

Material	Weight Gain, g/m^2
Alloy 617	10
Alloy 600	28
Alloy 625	37
Alloy 800	53
Alloy X	71

Table 10-Results of 100-h Carburization Tests in Hydrogen/2% Methane at 1800°F (980°C)

Material	Weight Gain, g/m^2
Alloy 617	35
Alloy 263	82
Alloy 188	86
Alloy L-605	138

Fabrication

INCONEL alloy 617 has good fabricability. Forming, machining, and welding are carried out by standard procedures for nickel alloys. Techniques and equipment for some operations may be influenced by the alloy's strength and work-hardening rate. Information on fabricating is available in the Special Metals publication "Fabricating" on the website, www.yttzhj.com.

Hot and Cold Forming

Alloy 617 has good hot formability, but it requires relatively high forces because of its inherent strength at elevated temperatures. In general, the hot-forming characteristics of alloy 617 are similar to those of INCONEL alloy 625. The temperature range for heavy forming or forging is 1850 to 2200°F (1010 to 1205°C). Light working can be done at temperatures down to 1700°F (925°C).

INCONEL alloy 617 is readily cold formed by conventional procedures although its work-hardening rate, shown in Figure 13, is high. For best results, the alloy should be cold formed in the fine-grain condition, and frequent intermediate anneals should be used. Annealing for cold forming should be done at 1900°F (1040°C).
Further information on general hot-forming and cold-forming can be obtained from Special Metals.

Heat Treatment

INCONEL alloy 617 is normally used in the solution-annealed condition. That condition provides a coarse grain structure for the best creep-rupture strength. It also provides the best bend ductility at room temperature. Solution annealing is performed at a temperature of 2150°F(1175°C) for a time commensurate with section size. Cooling should be by water quenching or rapid air cooling.

Machining

Information on machining of alloy 617 can be obtained from Special Metals. Cutting tools should be sharp and have positive rake angles to minimize work hardening of the material. Cutting feed and depth of cut must be sufficient to prevent burnishing of the workpiece surface. Additional information on machining is available in the Special Metals publication 'Machining' on the company website, www.yttzhj.com.

Joining

INCONEL alloy 617 has excellent weldability. INCONEL Filler Metal 617 is used for gas-tungsten-arc and gas-metal-arc welding while INCONEL Welding Electrode 117 is used for shielded metal-arc welding. The composition of the filler metal matches that of the base metal, and deposited weld metal is comparable to the wrought alloy in strength and corrosion resistance. Tensile properties at high temperatures of all-weld-metal specimens are shown in Figure 14. As indicated by Figure 15, rupture strength of the weld metal is equivalent to that of the wrought alloy. Low-cycle fatigue strength of welded joints is shown in Figure 4. Additional information on joining is available in the Special Metals publication "Joining" on the company website, www.yttzhj.com.

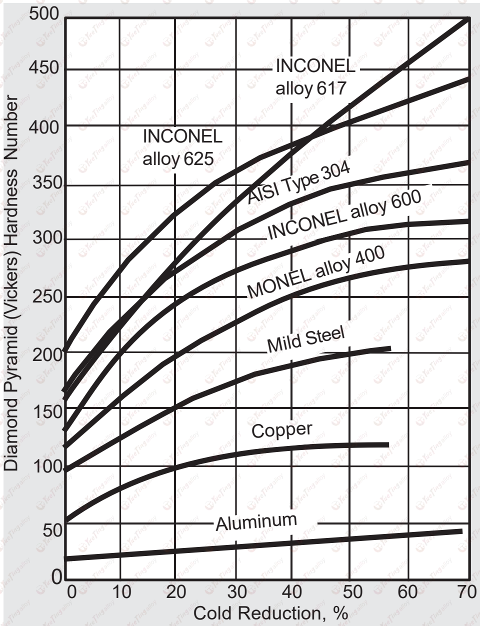


Figure 13. Effect of cold reduction on hardness.

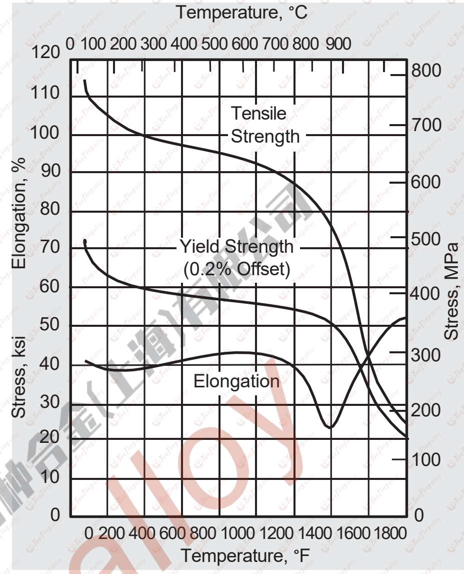


Figure 14. High-temperature tensile properties of all-weld metal specimens from gas-metal-arc welds made with INCONEL Filler Metal 617.

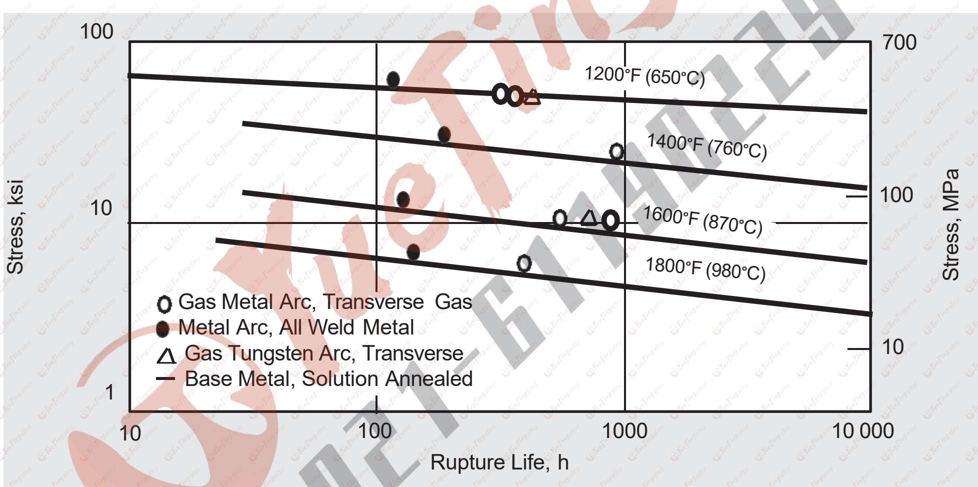


Figure 15. Rupture-strength comparison for base metal and joints welded with INCONEL Filler Metal 617.

LCF Fabrication Considerations

It has been shown that small residual amounts of cold work, such as that which results from even mild forming operations, can have a pronounced effect on the creep or rupture performance of superalloys, including alloy 617[2]. While re-solution annealing at 2150°F (1177°C) followed by water quenching would remove the effects of cold work and restore creep properties, laboratory and production data show that a re-anneal at this temperature would result in grain coarsening and thereby reduce LCF performance. Lower annealing temperatures were investigated on samples cold worked 10 and 20%. Samples of as solution annealed material were included in the investigation, as some areas of complex shapes receive essentially no cold work in the part forming process. The data (Figure 16) show that a re-solution anneal of 2050°F (1121°C) followed by air cooling is optimum for achieving recrystallization of the cold worked structure while not promoting grain growth in areas that received little or no cold work. Subsequent tests on production components have confirmed the appropriateness of this re-solution annealing treatment.[3]

Based on these considerations the following recommendations are suggested: beginning with mill solution annealed material (2150°F [1177°C], water quench), cold form, weld and re-solution anneal at 2050°F (1121°C) followed by air-cooling. An acceptable alternative procedure, if the fabrication is too large to re-anneal as an assembly, would be to re-solution anneal the individual pieces after forming but before assembly (welding).

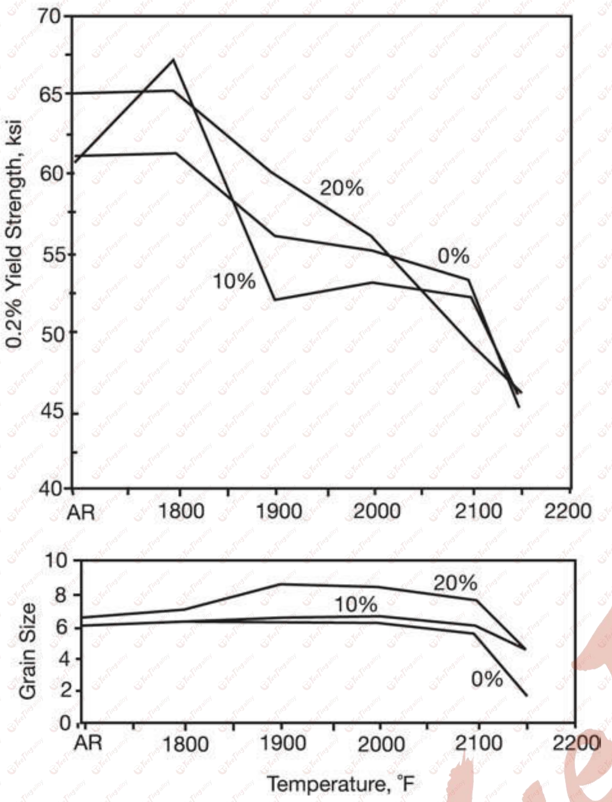


Figure 16. Effect of cold work and subsequent annealing temperature (annealed for 1 hour and air cooled) on the yield strength and grain size of alloy 617.

Available Products and Specifications

INCONEL alloy 617 is designated as UNS N06617 and Werkstoff Nr. 2.4663a. Allowable design stresses for ASME Boiler and Pressure Vessel Code construction are defined in ASME Code Cases 1956 and 1982.

Rod, Bar, Wire, and Forging Stock - ASTM B 166/ASME SB 166 (Rod, Bar and Wire), ASTM B 564/ASME SB 564 (Forgings), SAE AMS 5887 (Bars, Forgings and Rings), VdTÜV 485 (Sheet, Plate, Bar and Tubing), ISO 9724 (Wire), DIN 17752 (Rod and Bar), DIN 17753 (Wire), DIN 17754 (Forgings)

Plate, Sheet, and Strip - ASTM B 168/ASME SB 168 (Plate, Sheet and Strip), SAE AMS 5888 (Plate), SAE AMS 5889 (Sheet and Strip), VdTÜV 485 (Sheet, Plate, Bar and Tubing), ISO 6208 (Plate, Sheet and Strip), DIN 17750 (Plate, Sheet and Strip)_

Pipe and Tube - VdTÜV 485 (Sheet, Plate, Bar, and Tubing), ISO 6207 (Tubing), ASTM B 546/ASME SB 546 (Pipe), DIN 17751 (Pipe and Tube)

Composition - DIN 17744

Welding Products - INCONEL Filler Metal 617 - AWS A5.14/ERNiCrCoMo-1; INCONEL Welding Electrode 117 - AWS A5.11 / ENiCrCoMo-1

References

1.G.D. Smith and D.H. Yates, "Optimization of the Fatigue Properties of INCONEL alloy 617", Paper No. 91-GT-161 ASME International Gas Turbine and Aeroengine Congress and Exhibition, Orlando, FL (1991).

2.H.-J. Breuer, H. Breitling, W. Dietz, "Internal Pressure Experiments on Heat-Exchanger Tubes made from NiCr22Co12Mo at 950°C", 8th Meeting on Long Term Behavior of Creep Resistant Steels and High Temperature Materials, Association for Creep-Resistant Steels and Association for High-Temperature Materials, Duesseldorf (1985).

3.D.H. Yates, P. Ganesan and G.D. Smith, "Recent Advances in the Enhancement of INCONEL alloy 617 Properties to Meet the Needs of the Gas Turbine Industry", *Advanced Materials and Coatings for Combustion Turbines,* Proceedings of ASM 1993 Materials Congress, Pittsburgh, PA, V.P. Swaminathan and N.S. Chevuru, Editors, pp. 89-97 (1993).