INCONEL® alloy 690

INCONEL® alloy 690 (UNS N06690/W. Nr. 2.4642) is a high-chromium nickel alloy having excellent resistance to many corrosive aqueous media and high-temperature atmospheres. In addition to its corrosion resistance, alloy 690 has high strength, good metallurgical stability, and favorable fabrication characteristics.

The chemical composition of INCONEL alloy 690 is listed in Table 1. The substantial chromium content gives the alloy outstanding resistance to oxidizing chemicals and to high-temperature oxidizing gases. The high level of nickel imparts resistance to stress-corrosion cracking in chloride-containing environments as well as to sodium hydroxide solutions.

The properties of INCONEL alloy 690 are useful for various applications involving nitric or nitric/hydrofluoric acid solutions. Examples are tail-gas reheaters used in nitric acid production and heating coils and tanks for nitric/hydrofluoric solutions used in pickling of stainless steels and reprocessing of nuclear fuels.

The alloy's resistance to sulfur-containing gases makes it an attractive material for such applications as coal-gasification units, burners and ducts for processing sulfuric acid, furnaces for petrochemical processing, recuperators, incinerators, and glass vitrification equipment for radioactive waste disposal.

In various types of high-temperature water, alloy 690 displays low corrosion rates and excellent resistance to stress-corrosion cracking. Thus, alloy 690 is widely used for steam generator tubes, baffles, tubesheets, and hardware in nuclear power generation.

Table 1 - Limiting Chemical Composition, %, of INCONEL alloy 690[a]

Nickel	58.0 min.
Chromium	27.0-31.0
Iron	7.0-11.0
Carbon	0.05 max.
Silicon	0.50 max.
Manganese	0.50 max.
Sulfur	0.015 max.
Copper	0.50 max.

[a]Amendments for nuclear applications: 28-31 Cr, 0.04 max. C, 0.10 max. Co.

Physical Constants and Thermal Properties

Table 2 gives melting range and some physical constants at room temperature for INCONEL alloy 690. Table 3 contains values for thermal and electrical properties over a range of temperatures. Values for specific heat were calculated; other values were measured. Modulus of elasticity in tension, determined by a dynamic method, is shown for temperatures to 1600°F (870°C) in Table 4. All measurements of physical properties were done on annealed specimens.

Table 2 - Physical Constants

Density, lb/in.^{3}	0.296
Mg/m^3	8.19
Melting Range, °F	2450-2510
°C	1343-1377
Specific Heat, Btu/lb-°F	0.107
J/kg-°C	450
Electrical Resistivity, ohm-circ mil/ft	691
µΩ-m	1.148
Permeability at 200 oersteds (15.9 kA/m)	1.001
Young's Modulus, 10^3 ksi	30.6
GPa	211
Poisson's Ratio	0.289

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Table 3 - Thermal and Electrical Properties

Temperature	Thermal Conductivity	Coefficient of Expansion[a]	Specific Heat	Electrical Resistivity
°F	Btu-in./ft²-h-°F	10^{-6} in./in./°F	Btu/lb-°F	ohm-circ mil/ft
75	-	-	0.107	691
200	93	7.80	0.112	698
400	107	7.97	0.119	710
600	122	8.11	0.126	723
800	136	8.29	0.133	736
1000	151	8.53	0.140	745
1200	165	8.87	0.148	745
1400	179	9.14	0.155	749
1600	194	9.38	0.162	753
1800	207	9.63[b]	0.169	760
2000	-	9.87[b]	0.176	768
°C	W/m-°C	µm/m/°C	J/kg-°C	µΩ-m
25	-	-	450	1.148
100	13.5	14.06	471	1.162
200	15.4	14.31	497	1.180
300	17.3	14.53	525	1.199
400	19.1	14.80	551	1.219
500	21.0	15.19	578	1.235
600	22.9	15.70	604	1.239
700	24.8	16.18	631	1.241
800	26.6	16.60	658	1.247
900	28.5	17.01[b]	684	1.255
1000	30.1	17.41[b]	711	1.265
1100	-	17.79[b]	738	1.278

[a]Between 75°F (24°C) and temperature shown.
[b]Extrapolated values.

Table 4 - Modulus Data (Annealed)

Temperature, °F	°C	Young's Modulus, 10^3 ksi	GPa	Shear Modulus 10^3 ksi	GPa	Poisson's Ratio
70	21	30.0	206.9	11.5	79.3	0.30
200	93	29.3	202.0	11.35	78.3	0.29
400	204	28.5	196.5	10.95	75.5	0.30
600	316	27.6	190.3	10.5	72.4	0.31
800	427	26.6	183.4	10.15	70.0	0.31
1000	538	25.3	174.4	9.75	67.2	0.30
1200	619	23.9	164.8	9.35	64.5	0.28
1400	760	22.5	155.1	8.8	60.7	0.28
1600	871	21.3	146.9	8.2	56.5	0.30
1800	982	19.8	136.5	7.35	50.7	0.33
2000	1093	18.2	125.5	6.70	46.2	0.36*

* Extrapolated value.

Mechanical Properties

INCONEL alloy 690 has high strength over a broad range of temperatures. Mechanical properties of the alloy vary with product form and temper. Alloy 690 is normally used in the annealed temper, and strength characteristics described below are representative of annealed material. The usual annealing temperature is approximately 1900°F (1040°C). The effect of different annealing temperatures on the tensile properties of cold-worked material is shown under "Fabrication" in Figure 8.

Tensile Properties

At room and elevated temperatures, INCONEL alloy 690 displays high yield and ultimate strengths along with good ductility. Table 5 lists results of room-temperature tensile tests on annealed material. As indicated by the values, tensile properties may vary with product form and size. At high temperatures, alloy 690 retains a substantial level of tensile properties with temperatures of over 1000°F (540°C) required to produce significant declines in strength. Figure 1 shows the results of short-time tensile tests performed at temperatures to 1800°F (982°C). The curves represent average values for both cold-worked and hot-worked products in the annealed temper.

Fatigue Strength

The results of low-cycle fatigue tests performed at room temperature are shown in Figure 2. The specimens were tested under axial strain with fully reversed loading.

Table 5 - Room-Temperature Tensile Properties of Annealed[a] INCONEL alloy 690

Form	Size		Yield Strength (0.2% Offset)		Tensile Strength		Elongation
	in.	mm	ksi	MPa	ksi	MPa	%
Tube[b], cold drawn	0.50 x 0.050	12.7 x 1.27	66.8	461	110.0	758	39
	0.75 x 0.065	19.0 x 1.65	55.0	379	101.5	700	46
	3.50 x 0.216	88.9 x 5.49	40.9	282	94.0	648	52
Flat, hot rolled	0.5 x 2.0	13 x 51	51.0	352	102.0	703	46
Rod, hot rolled	2.0 dia.	51 dia.	48.5	334	100.0	690	50
Rod, hot rolled	0.62 dia.	16 dia.	54.0	372	107.0	738	44
Strip, cold rolled	0.150 thick	3.81	50.5	348	105.0	724	41

[a]1900°F (1040°C).
[b]Dimensions are outside diameter and wall thickness.

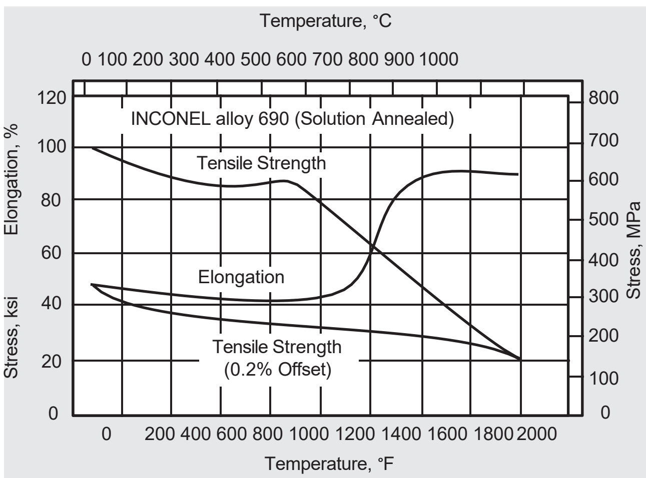

Figure 1. High-temperature tensile properties of annealed INCONEL alloy 690. Data are a composite of cold worked and hot worked product.

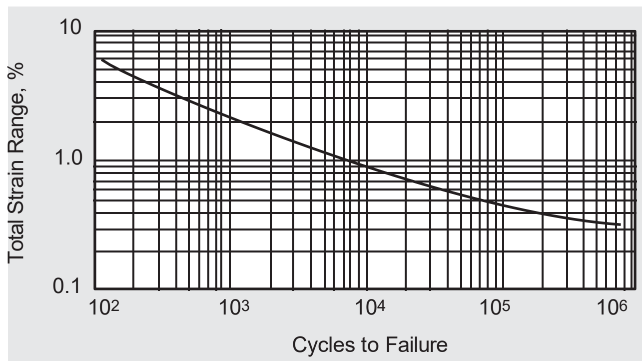

Figure 2. Low-cycle fatigue strength at room temperature of annealed INCONEL alloy 690.

Creep and Rupture Properties

INCONEL alloy 690 offers attractive properties for applications involving extended service at elevated temperatures. The alloy has good creep-rupture strength along with metallurgical stability and resistance to high-temperature corrosion.

Time-dependent strength levels for INCONEL alloy 690 are indicated by Figures 3 and 4, which respectively show creep rate and rupture life as functions of stress and temperature. The tests were performed on material annealed at 1900°F (1040°C).

Stability of Properties

Alloy 690 has a high degree of metallurgical stability, forming no embrittling phases during long-time exposure to elevated temperatures. As shown in Table 6, room-temperature tensile properties and impact strength are not significantly changed by exposure to critical intermediate temperatures for 12,000 h and longer. The samples were in the annealed condition prior to exposure.

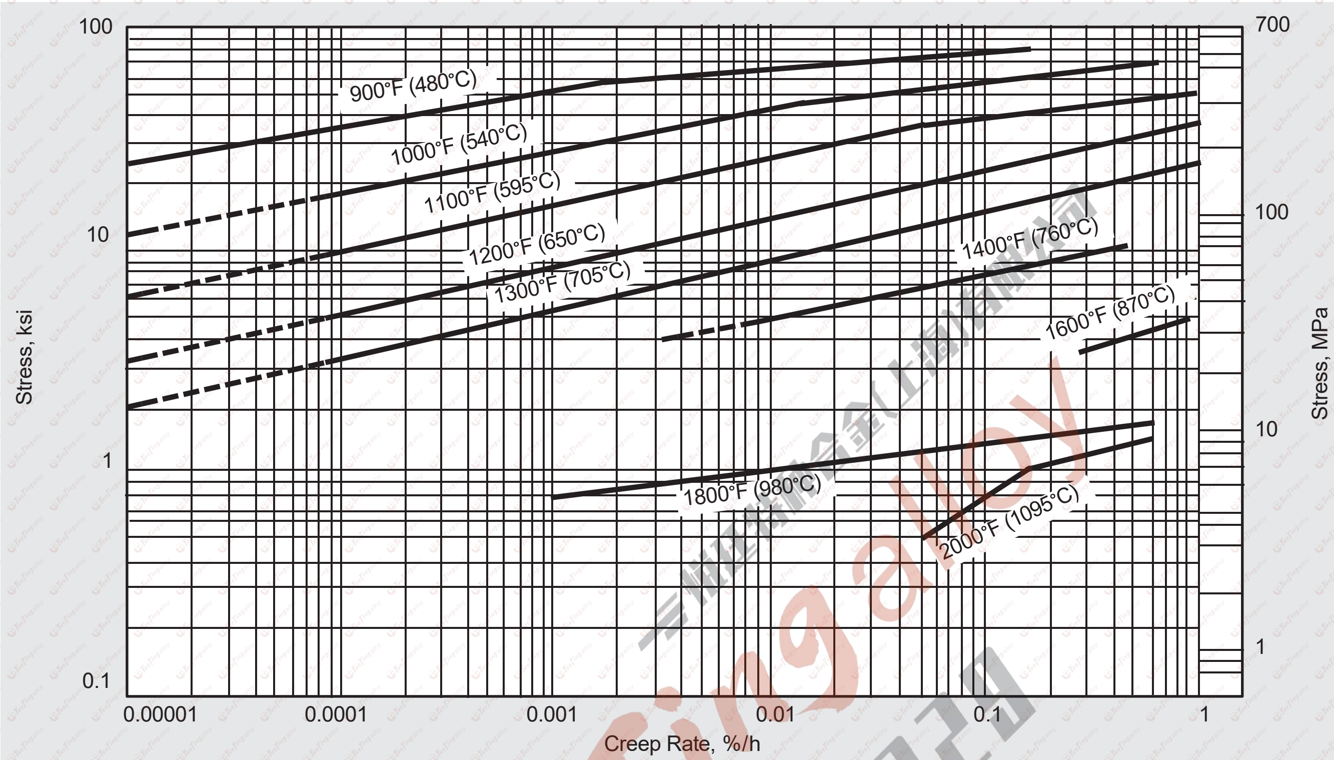

Figure 3. Creep strength of annealed INCONEL alloy 690.

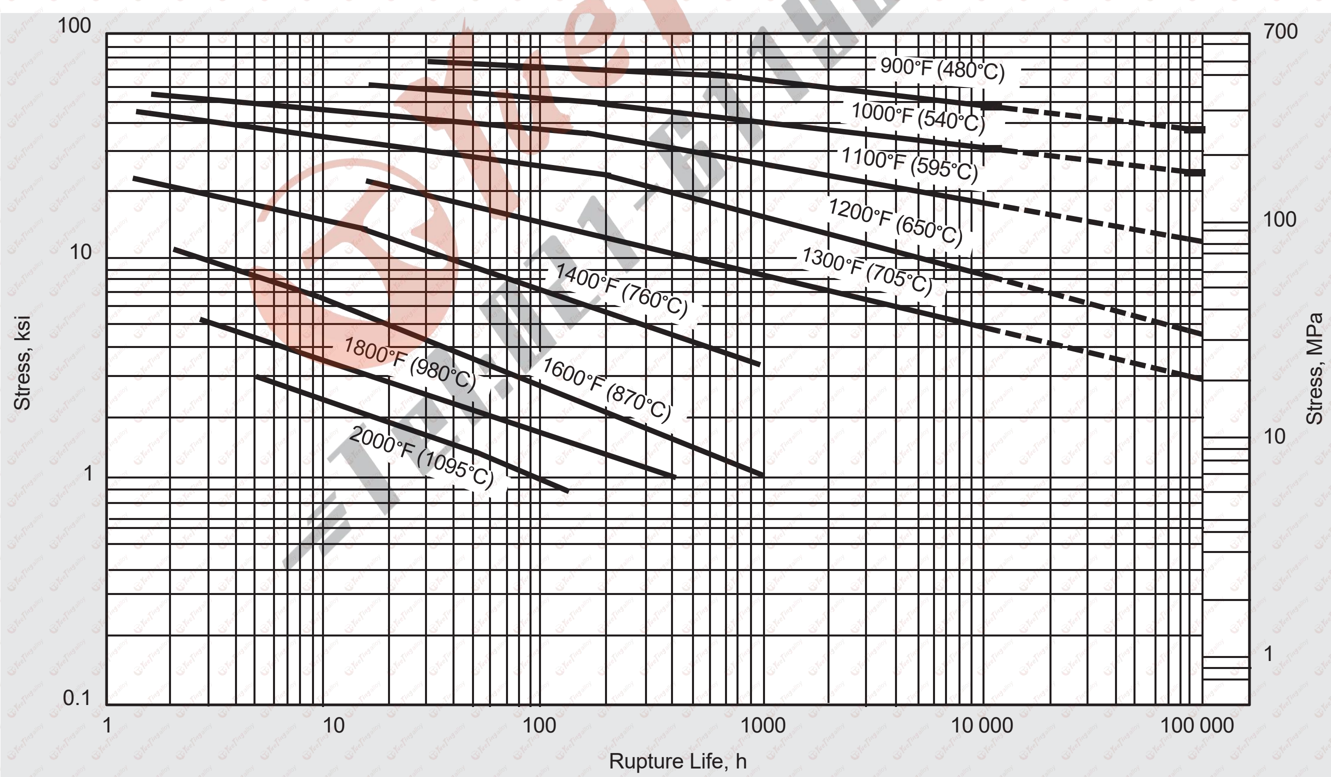

Figure 4. Rupture strength of annealed INCONEL alloy 690.

Table 6 - Effect of High-Temperature Exposure on Room-Temperature Properties of INCONEL alloy 690

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		-	41.0	283	103.5	714	48	140	190
1050	565	1 000	48.5	334	105.5	727	45	115	156
		4 000	47.0	324	105.0	724	45	126	171
		12 000	45.5	314	105.5	727	44	121	164
1100	595	1 000	62.5	431	107.0	738	45	144	195
		4 000	46.5	321	106.0	731	43	125	170
		13 428	45.5	314	105.5	727	44	125	170
1200	650	1 000	46.8	323	105.5	727	46	146	198
		4 000	48.5	334	106.0	731	54	132	179
		12 000	46.1	318	108.5	748	41	127	172
1400	760	1 000	50.0	345	107.0	738	44	158	214
		4 000	44.4	306	103.5	714	44	148	201
		12 000	46.5	321	103.5	714	46	136	184

Corrosion Resistance

INCONEL alloy 690 has excellent resistance to corrosion in a broad range of aqueous and high temperature environments. Because of its high chromium content, the alloy is particularly resistant to oxidizing conditions. Alloy 690 also offers excellent resistance to attack by sulfur at high temperatures.

Corrosion by Acids

Alloy 690 has good resistance to many oxidizing acid solutions. It is especially useful for handling nitric and nitric/hydrofluoric acids. In nitric acid, laboratory tests have shown the alloy to corrode at rates less than 1 mpy (0.03 mm/a) in concentrations through 70% at room temperature and at 176°F (80°C). In mixtures of nitric and hydrofluoric acids such as those used in pickling of stainless steels and reprocessing of nuclear fuel elements, INCONEL alloy 690 has displayed excellent corrosion resistance. Table 7 gives corrosion rates in three acid mixtures obtained from laboratory tests at 140°F (60°C). The tests were performed on specimens of annealed sheet.

INCONEL alloy 690 is highly resistant to phosphoric acid at room and moderate temperatures. Laboratory tests have shown the alloy to have corrosion rates of less than 1 mpy (0.03 mm/y) in concentrations of phosphoric acid through 85% at temperatures to 176°F (80°C). At boiling temperatures, alloy 690 is resistant to lower acid concentrations. Tests exposed in boiling acid exhibit general corrosion rates of 30 mpy (0.8 mm/a) in 20% acid and greater than 100 mpy (2.5 mm/a) at higher concentrations.

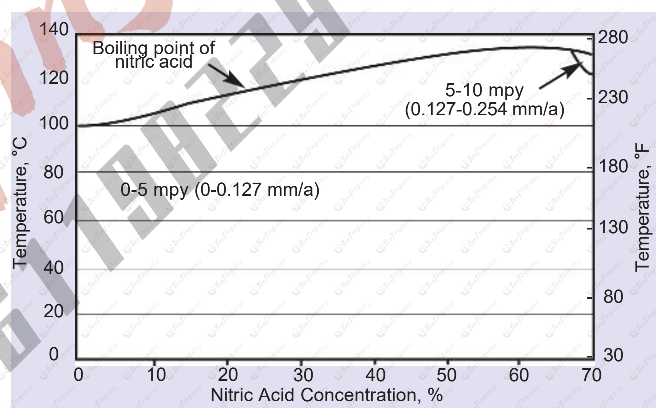

Figure 5. Isocorrosion curve of INCONEL alloy 690 in nitric acid.

Table 7 - Corrosion Rates in Nitric/Hydrofluoric Acid Mixtures

Acid Solution	Corrosion Rate[a]	
	mpy	mm/a
10% Nitric/ 3% Hydrofluoric	6	0.15
15% Nitric/ 3% Hydrofluoric	10	0.25
20% Nitric/ 2% Hydrofluoric	6	0.15

[a]Average for duplicate specimens tested at 140°F (60°C)

Metal Dusting

INCONEL alloy 690 has good resistance to metal dusting. It is compared with other heat resistant alloys in Figure 6.

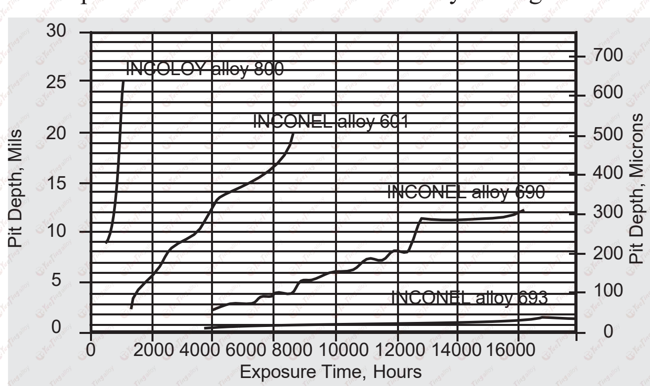

Figure 6. Maximum pitting depth as a function of time after exposure in CO-20% H_2 at 1150°F (621°C) for 120-grit ground samples.

Stress-Corrosion Cracking

INCONEL alloy 690 has good resistance to stress-corrosion cracking in many environments including chloride-containing solutions, high-temperature water, polythionic acid, and moderate concentrations of sodium hydroxide.

In boiling 45% magnesium chloride, stressed U-bend specimens of alloy 690 did not crack in 30 days of exposure.

Alloy 690 has been tested extensively for resistance to stress-corrosion cracking in high-temperature water such as encountered in nuclear steam generators. The results show the alloy to be highly resistant to cracking in chloride-containing water, oxygen-containing water under crevice conditions, and deaerated (oxygen of 0.02 ppm or less) water.

In polythionic acid, stressed U-bends of alloy 690 showed no cracking after exposure for 720 h to a solution that cracked sensitized Type 304 stainless steel within 1 h. The specimens of alloy 690 were tested both in the annealed condition and after being exposed to 600°F (315°C) for up to 1000 h.

The results of stress-corrosion-cracking tests in sodium hydroxide are given in Table 8. The tests were performed on U-bend specimens in nondeaerated sodium hydroxide. Testing at 500°F (260°C) and 610°F (320°C) was done in autoclaves having air in the head space. The results indicate that alloy 690 resists cracking in boiling sodium hydroxide at concentrations up to about 50%. Severe general corrosion occurred at 500°F (260°C) and 610°F (320°C) in concentrations of 30% and greater.

In deaerated 1% sodium hydroxide at 600°F (316°C), U-bend specimens did not crack in 9400 h.

Additional tests in sodium hydroxide were performed on bent-beam specimens stressed at 50%, 90%, and 100% of yield strength (0.2% offset). No cracking occurred in 100 h of exposure to boiling 80% sodium hydroxide.

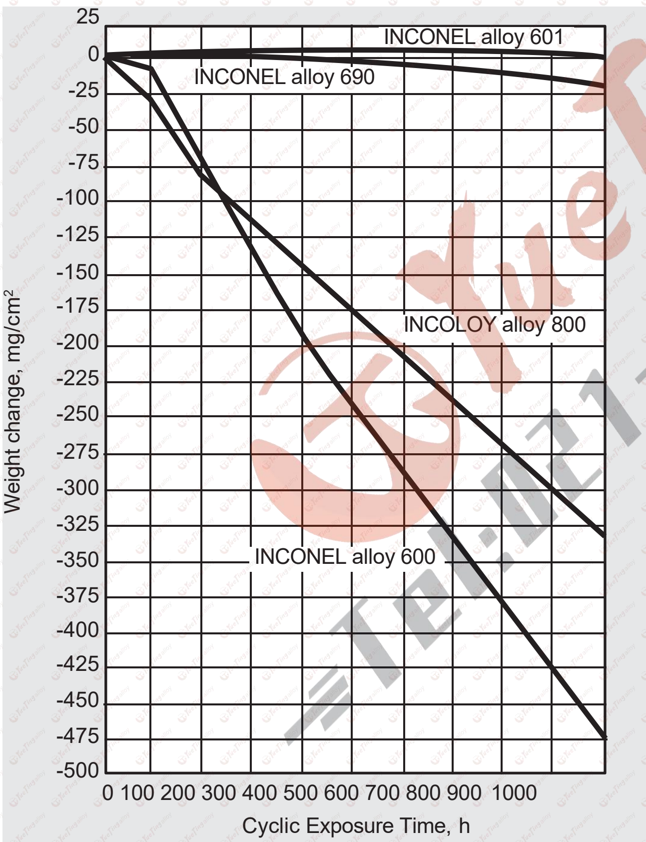

Figure 7. Cyclic oxidation resistance at 2000°F (1095°C). Cycles consisted of 15 min heating and 5 min cooling in air.

Table 8 - Stress-Corrosion-Cracking Tests in Sodium Hydroxide

Concentration, %	Temperature °F	Temperature °C	Results
10	610	321	No cracking in 100 h.
20	500	260	No cracking in 1000 h.
20	610	321	No cracking in 1000 h.
30	500	260	Cracking in 1000 h.
40	500	260	Cracking in 1000 h.
40	610	321	Cracking in 100 h.
50	500	260	Cracking in 100 h.
50	302[a]	150[a]	No cracking in 1000 h.
60	322[a]	161[a]	Cracking in 1000 h.

[a]Atmospheric boiling point.

Oxidation and Sulfidation

INCONEL alloy 690 has good resistance to oxidation and sulfidation in high-temperature gaseous environments. Figure 7 shows the alloy's resistance to cyclic oxidation at 2000°F (1095°C). The results of similar tests performed at 1800°F (980°C) on specimens coated with sodium sulfate are given in Figure 8. The specimens were recoated with sodium sulfate at 65-h intervals throughout the test period.

Corrosion rates for INCONEL alloy 690 in oxidizing and reducing sulfidizing atmospheres are given in Table 9. The tests were performed on rod specimens. Corrosion rates were derived from weight-loss measurements on completely descaled specimens. Test duration was 96 h.

Table 9 - Corrosion Rates in Sulfidizing Atmospheres at 1340°F (727°C)

Alloy	1.5% H_2S/3% O_2/36.5% H_2/59% Ar		1.5% H_2S/98.5% H_2	
	mpy	mm/a	mpy	mm/a
INCOLOY alloy 800	55	1.4	724	18.4
Type 310 Stainless Steel	71	1.8	709	18.0
INCONEL alloy 690	91	2.3	1366	34.7
INCONEL alloy 625	228	5.8	744	18.9
INCONEL alloy 617	280	7.1	1409	35.8
INCONEL alloy 601	382	9.7	685	17.4
INCONEL alloy 600	1453	36.9	1413	35.9

Fabrication

INCONEL alloy 690 is readily fabricated by conventional techniques for high-nickel alloys. In most working operations, alloy 690 exhibits characteristics similar to those of INCONEL alloy 600. More information on procedures for heating, forming, pickling, and finishing is contained in the Special Metals publication "Fabricating" on the website, www.yttzhj.com.

Heating and Pickling

Like other nickel alloys, alloy 690 should be clean before it is heated and should be heated in a low-sulfur atmosphere. Furnace atmospheres for open heating should also be slightly reducing to prevent excessive oxidation of the material.

INCONEL alloy 690 is a solid-solution alloy and is not hardenable by heat treatment. The alloy is normally used in the annealed condition. Figure 8 shows the effects of various annealing temperatures on the tensile properties of cold-rolled (45% reduction) sheet. The specimens were annealed for 30 minutes and tested at room temperature.

Pickling of alloy 690 is performed by procedures given for nickel-chromium alloys in the Special Metals publication "Fabricating" on the website www.yttzhj.com. Pretreatment in a fused-salt bath is recommended to aid pickling.

Joining

INCONEL alloy 690 exhibits excellent weldability. Alloy 690 components are joined to other alloy 690 components using INCONEL Filler Metal 52 and INCONEL Welding Electrode 152. The compositions of the deposits of these welding products are near-matching to that of the alloy 690 base metal. INCONEL Filler Metal 82, INCONEL Welding Electrode 182, and INCO-WELD A Welding Electrode may be used to join alloy 690 to carbon steel, stainless steel, and most dissimilar nickel- chromium and iron-nickel-chromium alloys. For welding alloy 690 components for service in highly corrosive aqueous environments, particularly mixtures of nitric and hydrofluoric acids as are commonly used in alloy pickling operations, INCONEL Filler Metal 625 and INCONEL Welding Electrode 112 should be considered. Additional information on joining may be found in the Special Metals publication "Joining" on the website.

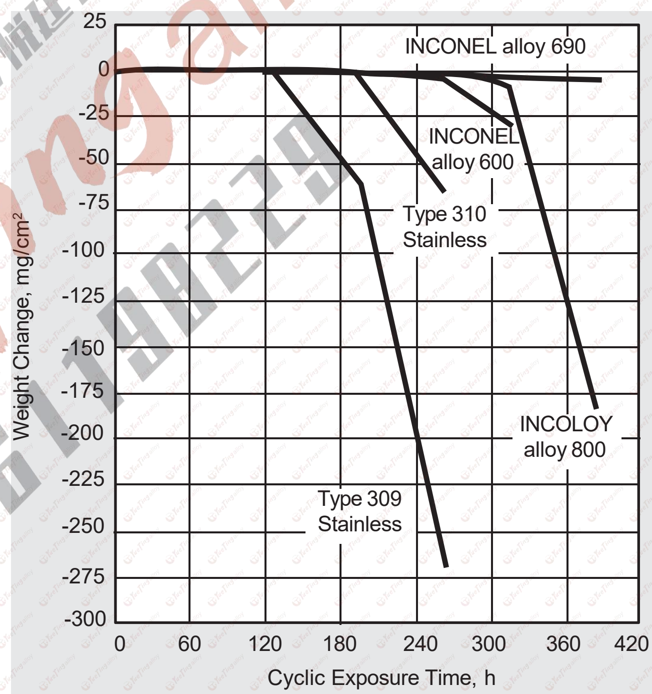

Figure 8. Cyclic oxidation resistance at 1800°F (980°C) of specimens coated with sodium sulfate. Cycles consisted of 15 min heating and 5 min cooling in air.

Machining

Alloy 690 should be machined by the procedures given for Group C alloys in the Special Metals publication, "Machining" on the website www.yttzhj.com. Sharp tools, positive rake angles, and steady cutting feeds are required to minimize work hardening of the material.

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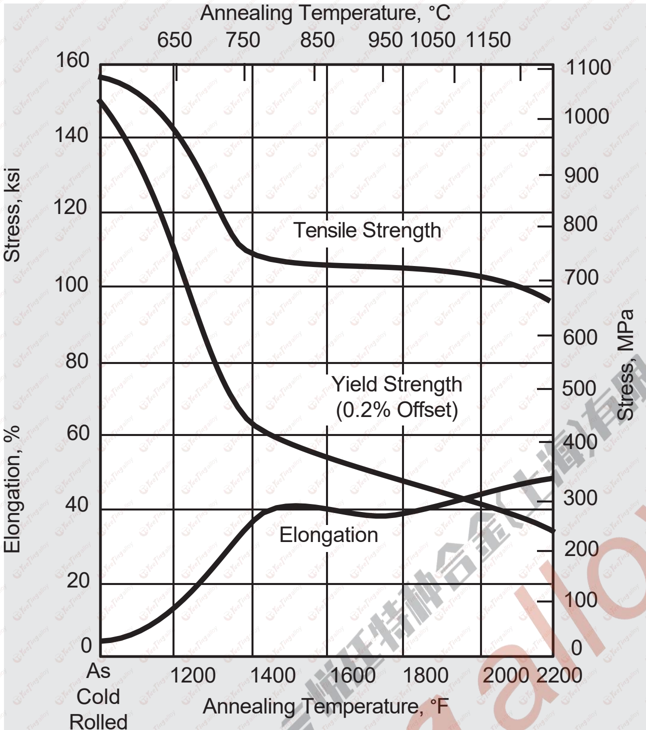

Figure 9. Effect of annealing temperature on tensile properties of cold-rolled sheet.

Forming

The temperature range for heavy hot forming of INCONEL alloy 690 is 1900 to 2250°F (1040 to 1230°C). Light forming can be done at temperatures down to 1600°F (870°C).

The alloy's behavior during cold forming is similar to that of INCONEL alloy 600. Somewhat higher forces, however, are required for alloy 690. Figure 10 compares the work-hardening rates of INCONEL alloy 690 and other materials.

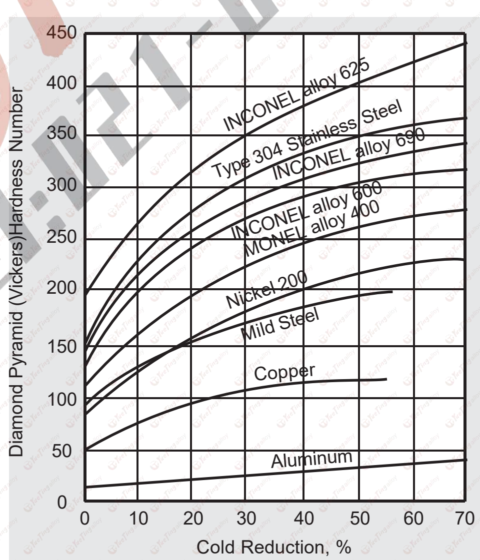

Figure 10. Work-hardening rates for INCONEL alloy 690 and other materials.

Microstructure

INCONEL alloy 690 is an austenitic, solid-solution alloy with a high degree of metallurgical stability. The alloy has a low solubility for carbon, and its microstructure normally contains carbides. The major carbide present in the alloy is $M_{23}C_6$; the abundance of the phase varies with carbon content and thermal exposure of the material. Other phases normally present are titanium nitrides and carbonitrides. No embrittling intermetallic phases such as sigma phase have been identified in alloy 690.

Available Products and Specifications

INCONEL alloy 690 is available in a wide range of standard mill forms including rod, bar, wire, pipe, tube, plate, sheet, strip and forging stock.

Alloy 690 is designated as UNS N06690, W. Nr. 2.4642 and ISO NW6690.

Rod, Bar, Wire and Forging Stock - ASTM B / ASME SB 166, ASTM B 564 /ASME SB 564, ASME Code Case N-525, ISO 9723, MIL-DTL-24801

Seamless Pipe and Tube - ASTM B / ASME SB 163, ASTM B 167 / ASME SB 829, ASTM B 829 /ASME SB 829, ASME Code Cases 2083, N-20, N-525, ISO 6207, MIL-DTL-24803

Plate, Sheet, and Strip - ASTM B / ASME SB 168 / 906, ASME N-525, ISO 6208, MIL-DTL-24802

Welding Products - INCONEL Filler Metal 52 - AWS A5.14 / ERNiCrFe-7; INCONEL Welding Electrode 152 - AWS A5.11 / ENiCrFe-7