INCONEL® alloy 693 - Excellent Resistance to Metal Dusting and High Temperature Corrosion

INCONEL alloy 693 (UNS N06693) is a new alloy from Special Metals which offers resistance to high temperature corrosion mechanisms not previously available from a nickel-based alloy. Of particular interest to the designer is the alloy's resistance to metal dusting. INCONEL® alloy 693 offers the best resistance to metal dusting in chemical and petrochemical processing environments of any conventional alloy currently manufactured. Alloy 693 typically contains 60.5% nickel, 29% chromium, and 3.1% aluminum. The limiting composition is presented in Table 1. Like its predecessor, INCONEL alloy 690, the alloy's high chromium content gives it excellent resistance to oxidation and sulfidation. However, the addition of 3.1% aluminum to alloy 693 vastly improves resistance to other forms of high temperature corrosion as well. Alloy 693 is protected by U.S. Patent Number 4,882,125.

Table 1 - Limiting Chemical Composition, %

Nickel	Remainder[a]
Chromium	27.0-31.0
Iron	2.5-6.0
Aluminum	2.5-4.0
Niobium	0.5-2.5
Manganese	1.0 max.
Titanium	1.0 max.
Copper	0.5 max.
Silicon	0.5 max.
Carbon	0.15 max.
Sulfur	0.01 max.

[a]Element determined arithmetically by difference.

Physical and Thermal Properties

Some physical properties for INCONEL alloy 693 are given in Table 2. Thermal properties for the alloy from room-temperature to 2100°F and 1150°C are found in Table 3. Values for the Modulus of Elasticity (Young's Modulus) were determined by a dynamic method from room-temperature to 1500°F and 800°C and are presented in Table 4.

Table 2 - Physical constants

Density, lb/in³	0.280
g/cm³	7.77
Melting Range, °F	2403-2493
°C	1317-1367
Electrical Resistivity, ohm•circ mil/ft	702.7
µΩ•m	1.168

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Table 3 - Thermal Properties

Temperature °F	Thermal Conductivity Btu•in./ft²•h•°F	Coefficient of Expansion[a] 10⁻⁶in./in./°F	Specific Heat Btu/lb•°F
73	64.3	-	0.109
200	73.1	7.22	0.115
400	87.8	7.57	0.121
600	102.8	7.84	0.127
800	117.2	8.09	0.131
1000	130.8	8.28	0.135
1200	143.2	8.60	0.140
1400	154.6	9.02	0.145
1600	165.2	9.38	0.151
1800	175.5	-	0.156
2000	186.3	-	0.159
2100	192.2	-	0.160
°C	W/m•°C	µm/m/°C	J/kg•°C
23	9.1	-	455
100	10.7	13.04	484
200	12.6	13.61	505
300	14.2	14.05	525
400	16.1	14.42	548
500	17.8	14.80	560
600	19.5	15.22	579
700	21.6	15.72	598
800	22.8	16.32	616
900	23.6	17.01	642
1000	25.2	-	662
1100	26.8	-	674
1150	27.5	-	678

[a]Mean coefficient of linear expansion between 78°F (26°C) and temperature shown.

Mechanical Properties

INCONEL alloy 693 exhibits excellent mechanical properties. Nominal tensile properties are given in Table 5. Typical tensile properties of annealed bar from room-temperature to 2000°F (1093°C) are found in Figure 1.

Table 4 - Modulus at Elevated Temperatures

Temperature, °F	Modulus of Elasticity, Tension, 10³ ksi
70	28.5
200	28.2
400	27.3
600	26.6
800	25.6
1000	24.8
1400	23.2
1500	22.5
°C	GPa
21	196
100	194
200	188
300	180
400	172
500	165
600	157
700	148
800	137

Table 5 - Nominal Room-Temperature Mechanical Properties

Product Form	Yield Strength (0.2% Offset)		Tensile Strength		Elongation, %
	ksi	MPa	ksi	MPa	
Hot-Rolled and Annealed Plate	71	489.5	128	882.6	45
Cold-Drawn and Annealed Tubing	77	530.9	136	937.7	42

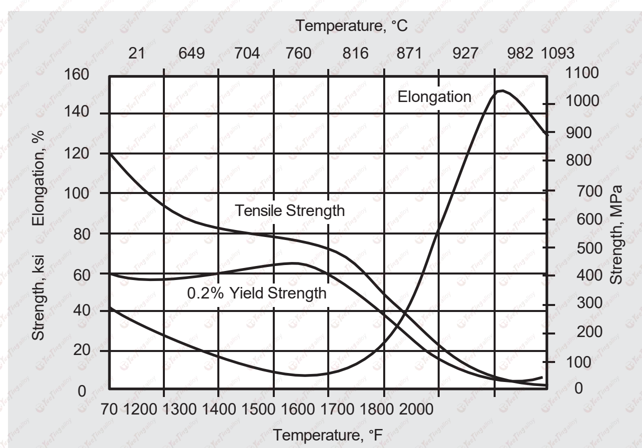

Figure 1. Elevated temperature tensile properties of annealed bar.

Creep and Rupture Properties

Alloy 693 exhibits excellent rupture strength at elevated temperatures. A comparison of the rupture properties of INCONEL alloy 693 with those of other alloys commonly used for high temperature service can be seen in the Larson-Miller plot in Figure 2. The creep rupture strength of alloy 693 at temperatures from 1200°F (649°C) to 1800°F (982°C) is seen in Figure 3.

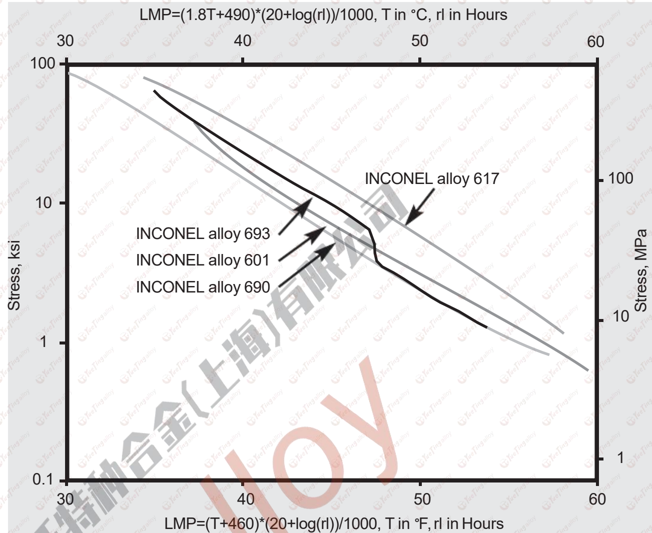

Figure 2. Larson-Miller comparison of creep-rupture properties of INCONEL alloys 693, 617, 601, and 690.

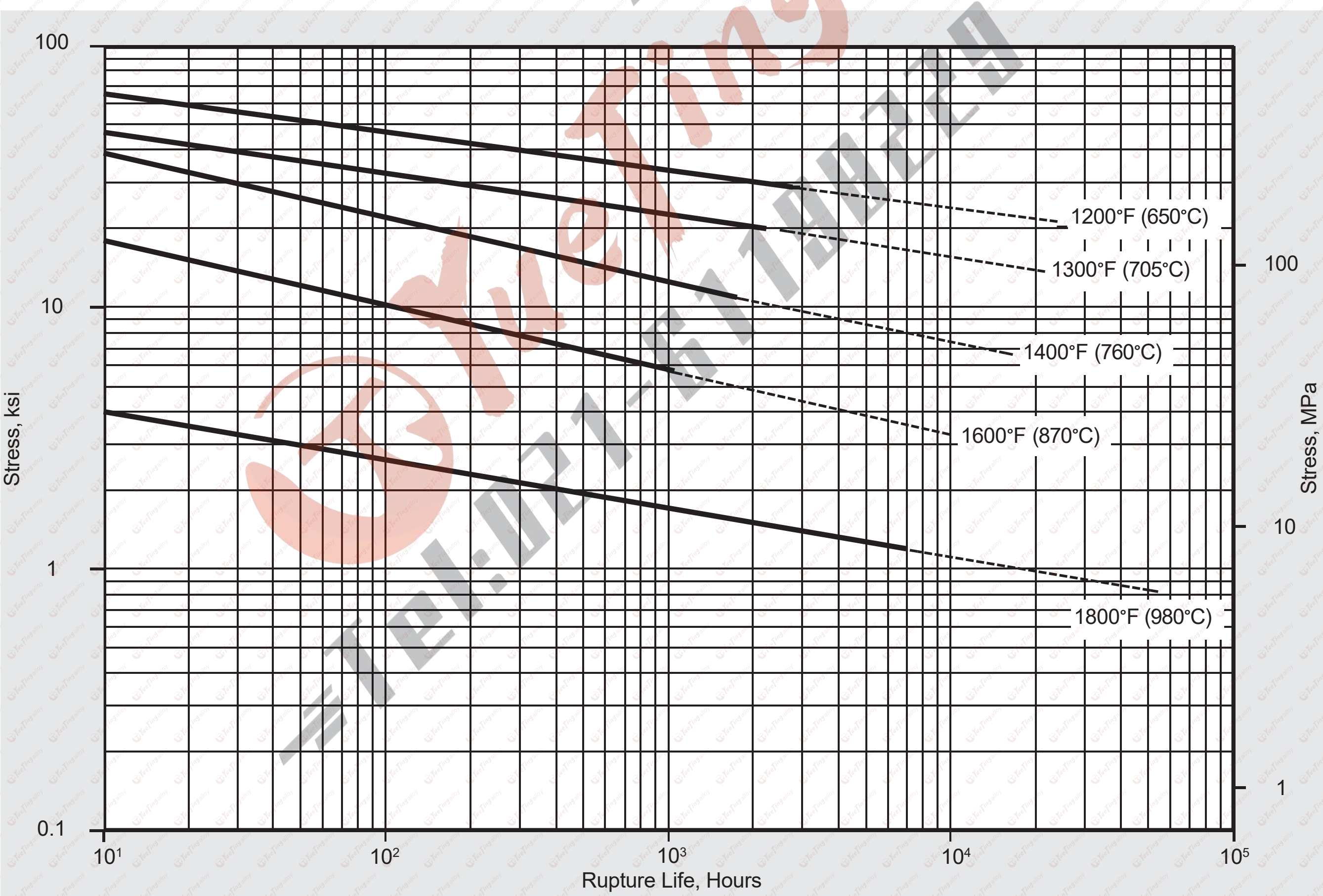

Figure 3. Stress rupture life of INCONEL alloy 693.

Thermal Stability

INCONEL alloy 693 is commonly used for service at temperatures between 1000° and 1400°F (538° and 760°C). The alloy exhibits good thermal stability as evidenced by the mechanical and impact properties reported in Tables 6, 7 and 8. The alloy 693 rod used to generate these data was produced by hot rolling followed by annealing at 1850°F (1010°C) for 30 minutes and water quenched. The test samples were then heated in a furnace to the exposure temperature, exposed for the time noted and cooled in air to room temperature. The samples tested at elevated temperature were reheated to the test temperature.

Table 6 - Room-Temperature Charpy (CVN) Impact Toughness of Exposed Rod

Exposure Temperature		Exposure Time	Impact Energy	
°F	°C	h	ft-lb	J/cm²
1100	593	1000	40.5	68.6
1200	649	1000	16.3	27.5
1300	704	1000	15.5	26.3
1400	760	1000	23.0	39.0

Table 7 - Room-Temperature Tensile Properties of Exposed Rod

Exposure Temperature		Exposure Time	0.2% Yield Strength		Ultimate Tensile Strength		Elongation	Reduction of Area
°F	°C	h	ksi	MPa	ksi	MPa	°%	%
1100	593	1000	107.5	741.2	166.0	1144.6	31	48
1200	649	1000	120.0	827.4	175.5	1210.1	28	47
1300	704	1000	117.0	806.7	170.5	1175.6	31	50
1400	760	500	101.5	699.8	160.0	1103.2	32	56

Table 8 - Elevated-Temperature Tensile Properties of Exposed Rod

Test Temperature		Exposure Temperature		Exposure Time	0.2% Yield Strength		Ultimate Tensile Strength		Elongation	Reduction of Area
°F	°C	°F	°C	h	ksi	MPa	ksi	MPa	°%	%
1100	593	1100	593	1000	89.0	613.7	132.0	910.1	28	37
1200	649	1200	649	1000	92.9	640.5	128.9	888.8	9	22
1300	704	1300	704	1000	80.7	556.1	111.6	769.5	20	24
1400	760	1400	760	1000	46.7	322.0	78.6	541.9	32	48

Resistance to Corrosion at Elevated Temperatures

Alloy 693 offers superior resistance to metal dusting, a particularly aggressive form of carburization that can cause failure after very short exposures. Atmospheres containing reducing media (e.g. carbon monoxide and hydrogen) are known to induce metal dusting at elevated temperatures. Figures 4 and 5 show that alloy 693 offers vastly superior resistance to attack when compared with other alloys which are commonly used in such environments.

Alloy 693 offers good resistance to sulfidation in both oxidizing and reducing environments containing sulfur. Also, the alloy performed well when exposed to oxide-rich media such as glass frit and fluxing compounds at temperatures up to 1100°C (2012°F).

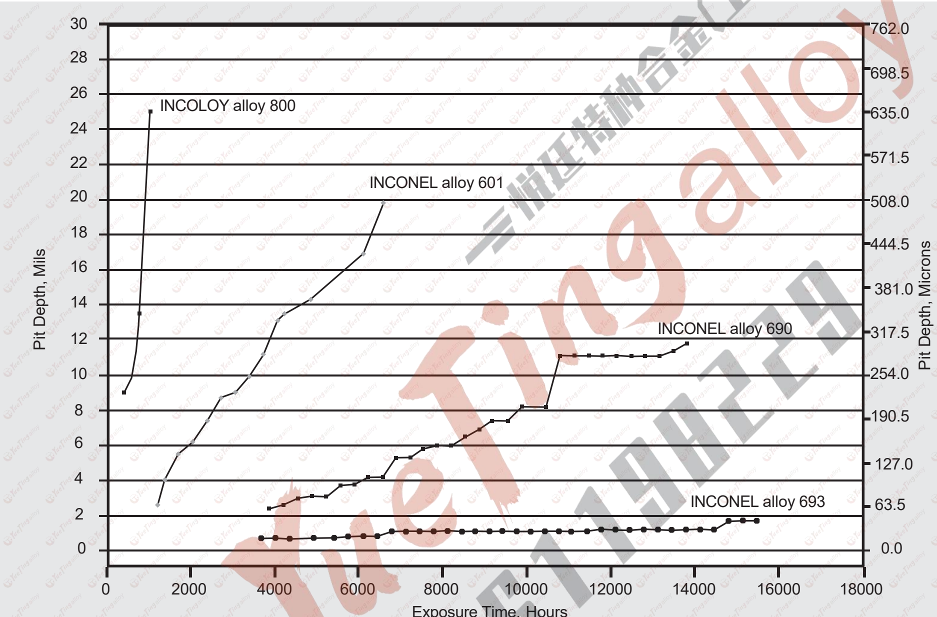

Figure 4. Pitting depth resulting from exposure in CO-20% H_2 at 1150°F (621°C).

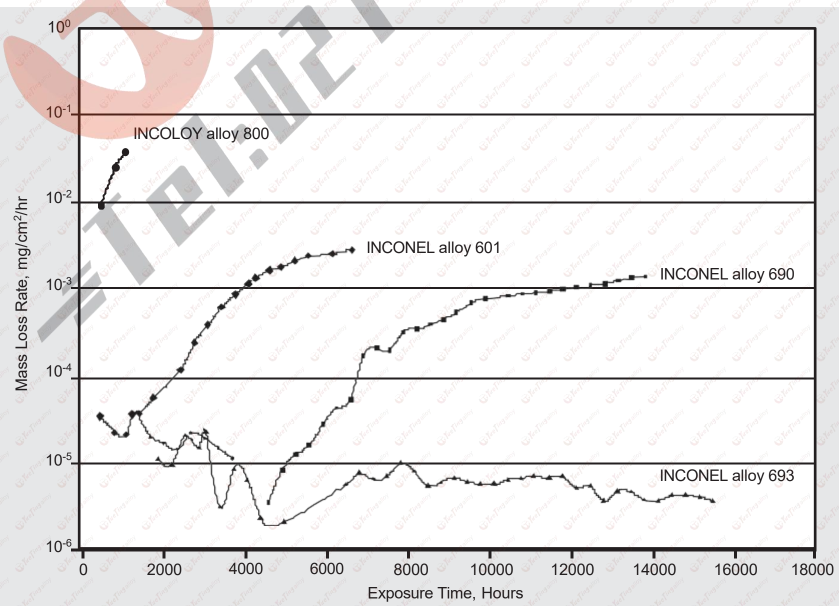

Figure 5. Rate of mass loss resulting from exposure to CO-20% H_2 at 1150°F (621°C).

INCONEL alloy 693 offers excellent resistance to corrosive attack at elevated temperatures in a variety of media. The alloy offers excellent resistance to oxidation in air at temperatures up to 1200°C (2192°F) as seen in Figure 6. The alloy also resists oxidation in moist air (Figure 7). Alloy 693 demonstrated excellent resistance to carburization when exposed in a medium containing hydrogen, methane, and carbon dioxide at 1000°C (1832°F) as shown in Figure 8.

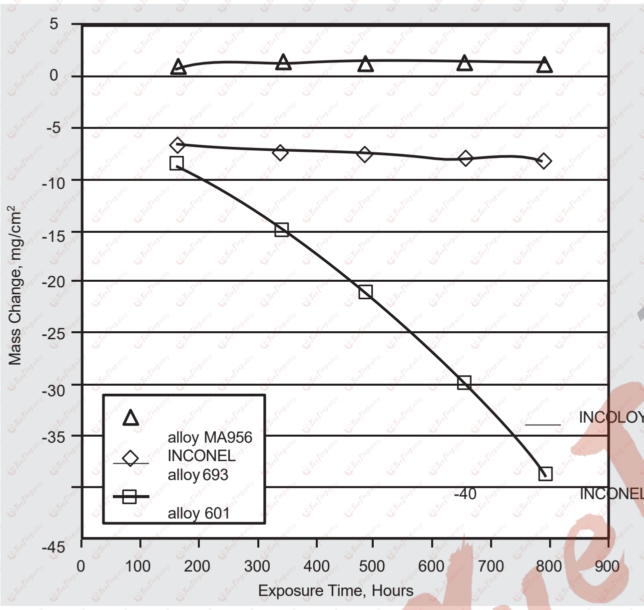

Figure 6. Oxidation resistance at 1200°C (2192°F).

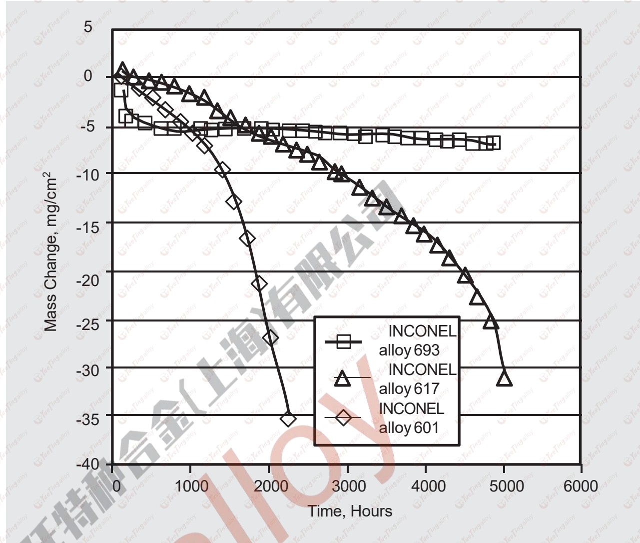

Figure 7. Oxidation resistance in air + 5% water at 1100°C (2012°F).

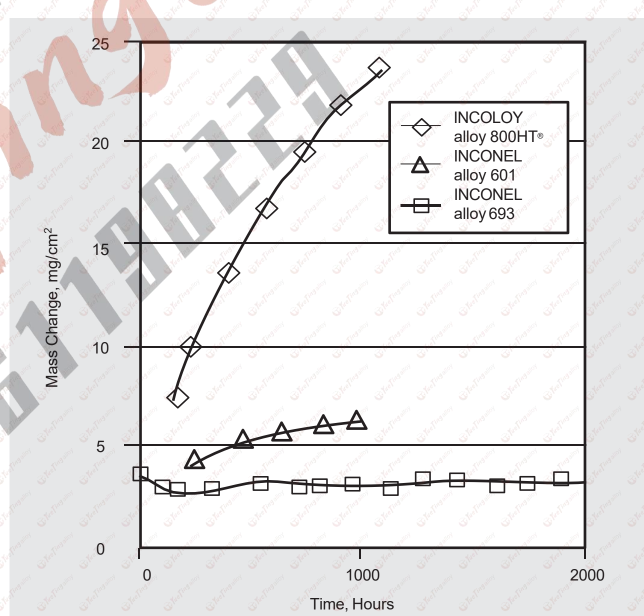

Figure 8. Mass change resulting from exposure in H_2-5.5% CH_4-4.5% CO_2 at 1000°C (1832°F).

Aqueous Corrosion Resistance

Table 9 - Comparison of Aqueous Corrosion Properties of INCONEL alloy 690 and INCONEL alloy 693

Environment	INCONEL alloy 693, mpy (mm/a)	INCONEL alloy 690, mpy (mm/a)
10% HNO_3+ 3% HF 60°C(140°F)	27.5 (0.699)	11 (0.279)
10% Sulfuric 60°C (140°F)	No attack	19.5 (0.495)
3% HCl at room temperature	1.2 (0.030)	1.0 (0.025)
3% HCl at 45°C (113°F)	8 (0.203)	10 (0.254)
10% HCl at room temperature	2.8 (0.071)	6 (0.152)
10% HCl at 45°C (113°F)	39.5 (1.003)	130 (3.302)
15% HCl at room temperature	8 (0.203)	14.7 (0.373)
15% HCl at 45°C (113°F)	120 (3.048)	368 (9.347)
65% boiling Nitric acid (Huey)	10 (0.254)	3 (0.076)

Fabrication

INCONEL alloy 693 is readily fabricated by conventional techniques. Its forming and machining characteristics are similar to those of INCONEL alloy 600 or 690. The work hardening response of alloy 693 is shown in Figure 9.

Alloy 693 can precipitate second phases when exposed to intermediate temperatures (1000°to 1400°F, 538° to 760°C). The presence of these phases can decrease the ductility and impact properties of the alloy. Therefore, care must be taken to avoid extended exposure within this temperature range during fabrication and forming. Alloy 693 components exposed to intermediate temperatures for extended periods should be annealed prior to subsequent forming or service as described under “Heat Treatment” to re-solution these deleterious phases.

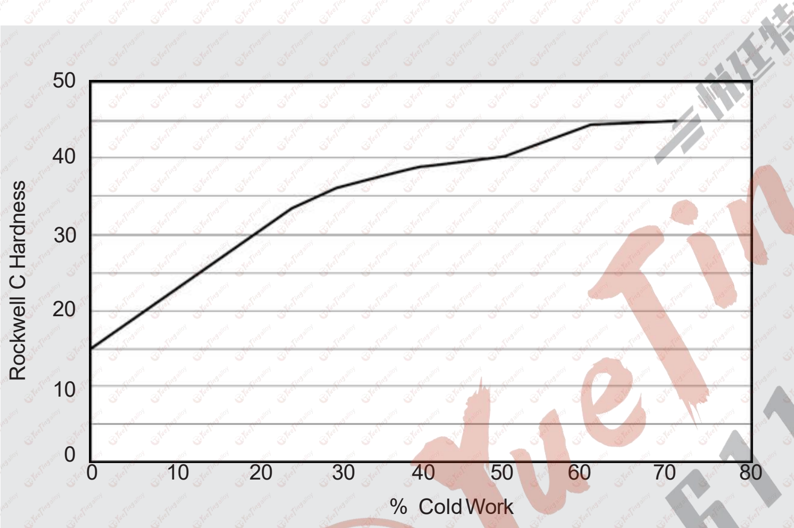

Figure 9. Work Hardening Curve for INCONEL alloy 693

Heat Treatment

INCONEL alloy 693 is a solid-solution, single-phase alloy and as such is supplied in the annealed condition. Annealing of alloy 693 can be accomplished by heating to 1850° to 1950°F (1010° to 1066°C), and holding for a time commensurate with section thickness, followed by rapid cooling in air or water quenching (recommended quenching method dependent upon section thickness - consult the manufacturer).

Table 10 - Room-Temperature Mechanical properties of an INCONEL filler metal 53MD GMA Weldment in ½-in Plate (All Weld Metal Longitudinal Tensile Test Specimen)

Tensile strength, ksi (MPa)	108.3 (746)
0.2% Yield Strength, ksi (MPa)	70.1 (483)
Elongation, %	48.1
Reduction of area, %	58.7
2T side bend tests	No fissures

Joining

INCONEL alloy 693 exhibits good weldability for matching and dissimilar joints.

Alloy 693 components are best joined in the annealed condition. Gas Tungsten Arc-Welding (GTAW or "TIG") and Gas Metal-Arc Welding (GMAW or "MIG") are the most commonly used processes. Argon or argon / helium mixtures are suitable as shielding gases. Preheat is not normally required.

INCONEL Filler Metal 53MD, a near-matching composition welding product, is normally used for joining alloy 693 products. This consumable is suitable for similar metal joints in light to moderate sections (generally up to ½ inch dependent upon joint design and the resulting welding stresses). The properties of an INCONEL Filler Metal 53MD weldment deposited in ½ inch plate using the GMAW process are reported in Table 10. Welding parameters were 170 amps (DCEP), 29 Volts, and 100% argon shielding gas flowing at 35 CFH.

For heavier sections or highly stressed joints or when welding dissimilar materials, it may be preferable to use either INCONEL Filler Metal 52 or INCONEL Filler Metal 617 for the structural portion of the weldment. The welding process is completed by overlaying the portion of the joint exposed to the service environment with two layers of either INCONEL Filler Metal 53MD or INCONEL Filler Metal 72.

Alloy 693 welded components to be exposed to high temperatures (e.g, temperatures greater than 1400°F or 760°C) do not normally require post weld heat treatment. Welded and/or formed components to be exposed to intermediate service temperatures (1000° to 1400°F, 538 to 760°C) should be stress relieved after forming and welding for 2 to 3 hours at a temperature in the range of 1742 to 1922°F (950° to 1050°C), followed by air cooling. If an alloy 693 component is to be pre-oxidized prior to service to improve its resistance to high temperature corrosion, the treatment should be done after welding so that the weldment develops the same protective oxide film as the base metal.

INCONEL Filler Metal 53MD may also be used for overlaying purposes. For example, carbon or stainless steel tubesheets may be overlaid with Filler Metal 53MD for some applications as an alternative to solid alloy 693 construction.

The application, joint design, and material thickness must be considered in development of the optimum welding procedure.

General welding information for INCONEL alloy 693 and the other nickel-base alloys manufactured by Special Metals is available on the websites, www.yttzhj.com and www.specialmetalswelding.com.

Applications

Petrochemical: Synthesis gas production

Applications for alloy 693 are found in the petrochemical processing industry. Of special interest is the production of synthesis gas for production of ammonia, methanol and hydrogen. Typical products are reformer tubes, thermowells, thermocouple sheathing, tube ferrules, baffle plates and valve components. INCONEL alloy 693 has been successfully used in a reactor for syngas production. Tube ferrules and baffle plates have also been fabricated from alloy 693. Alloy 693 wire has been used for refractory anchor supports in an ammonia plant.

Waste to Energy and Biomass Incinerators

INCONEL alloy 693 is a candidate for service in high-temperature waste and biomass incinerators at temperatures above 700°C (1292°F), where fuel ash corrosion, chloridation and sulfidation can cause rapid failure of traditional materials. Alloy 693 may be used to protect superheater walls in low NOx plants. The material can be used either solid or as a weld overlay.

Thermal Processing

With its excellent resistance to corrosive attack and deterioration at elevated temperatures, alloy 693 is a candidate for construction of thermal processing equipment and in chemical processes where high levels of chlorine or sulfur are present. Catalyst manufacturing processes, where high levels of sulfur are present, may require alloy 693.

Burner Nozzles

Alloy 693 may be used as an upgrade for alloy 601 and alloy 602CA in heating burner nozzles, which can suffer metal dusting due to new low sulfur regulations for heating oil.

High-Temperature Fuel Cell Reformers

Alloy 693 is a candidate for service in high temperature fuel cell developments where synthesis gas is produced (e.g., fuel cells to power automobiles). Typical product forms are strip and tube. Some designs of high temperature fuel cells have gas compositions with the potential to induce metal dusting. Alloy 693 should be of special interest for this service.