Fabricating INCONEL® alloy 625LCF®

INCONEL® alloy 625LCF® (UNS N06626) is a fatigue-resistant bellows-quality version of INCONEL alloy 625. The chemical composition and microstructure of alloy 625LCF are closely controlled. Alloy 625LCF is specially melted and processed to provide exceptional resistance to thermal and mechanical fatigue. Alloy 625LCF offers the same reliable corrosion resistance for which alloy 625 is well known throughout the marine, aerospace, processing, and automotive industries. Alloy 625LCF products offer a high level of performance for critical applications that require maximum resistance to corrosion along with optimum mechanical properties. Potential applications are aircraft ducting, containment and exhaust components, automotive flexible exhaust couplings, and bellows for marine service, and chemical and petrochemical expansion joints.

SAE specification AMS 5879 has been issued to address the superior fatigue strength and special properties only available with INCONEL alloy 625LCF. Those requiring material with these properties must reference this specification to ensure that they receive the desired product. While alloy 625LCF meets all properties specified for the conventional grade of alloy 625 (e.g., ASTM B 443 and SAE AMS 5599), conventionally produced alloy 625 will not meet the requirements of AMS 5879. INCONEL alloy 625LCF must be specifically referenced.

The limiting chemical composition of INCONEL alloy 625LCF is given in Table 1. The alloy is vacuum induction melted (VIM) for composition control. Carbon, silicon, and nitrogen are limited to low levels. This composition in conjunction with stringent thermal and mechanical processing produces a microstructure that results in greatly enhanced fatigue resistance.

The fatigue resistance of alloy 625LCF is compared with that of conventional alloy 625 in Figure 1. It is seen that the fatigue life of alloy 625LCF can be 100 times that of conventional alloy 625. This can result in greatly improved service life over that possible with conventional alloy 625 products.

INCONEL alloy 625LCF offers improved mechanical properties over conventional alloy 625. Mechanical properties for alloy 625LCF sheet at temperatures up to 1300°F (700°C) are plotted in Figure 2.

The superior strength of alloy 625LCF is evident in the allowable design stresses specified by ASME for Section VIII, Division 1 construction. The allowable stresses defined in ASME Code Case 2276 are approximately 4 ksi greater than the equivalent values for alloy 625.

Alloy 625LCF exhibits optimum properties for bellows applications. The alloy is processed to maintain a fine grain size of ASTM No.5 or finer depending upon gauge thickness.

INCONEL alloy 625LCF is available as cold-rolled / annealed sheet and strip in thicknesses from 0.005 to 0.250 in. (0.13 to 6.4 mm) and widths to 48 in. (1220 mm). It can be supplied as flattened sheets cut to the purchaser's specified length or as continuous coils up to 20,000 lb. (9,000 kg). Alloy 625LCF sheet and strip are typically supplied to the thickness tolerances of ASTM B 443. However, special tolerances are available when required. Contact Special Metals – Commercial Services to discuss special needs.

Table 1 - Limiting Chemical Composition of INCONEL alloy 625LCF

Nickel	58.0 min.
Chromium	20.0-23.0
Molybdenum	8.0-10.0
Niobium + Tantalum	3.15-4.15
Iron	5.0 max.
Carbon	0.03 max.
Silicon	0.15 max.
Nitrogen	0.02 max.
Manganese	0.50 max.
Sulfur	0.015 max.
Aluminum	0.40 max.
Titanium	0.40 max.
Phosphorus	0.015 max.
Cobalt	1.0 max.

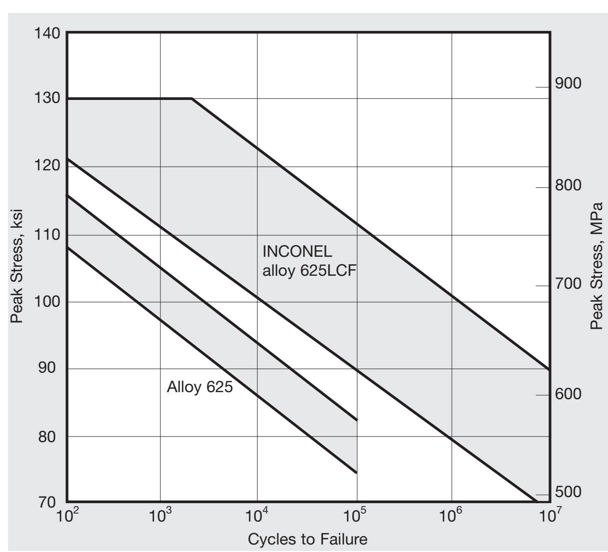


Figure 1. Ranges of low-cycle fatigue strength[a] obtainable with INCONEL alloy 625LCF and alloy 625 at temperatures of 900-1200°F (480-650°C).

[a]Pull/pull tests with 5 ksi (34 MPa) base stress.

Cold Forming Characteristics

INCONEL alloy 625LCF work hardens rapidly during cold working. While this characteristic increases strength and improves fatigue resistance, it can inhibit formability. Figure 3 plots the typical range of the work hardening rate (expressed in terms of R_C hardness) as a function of percent cold work. In Figure 4, typical room-temperature tensile properties are shown as a function of percent cold work.

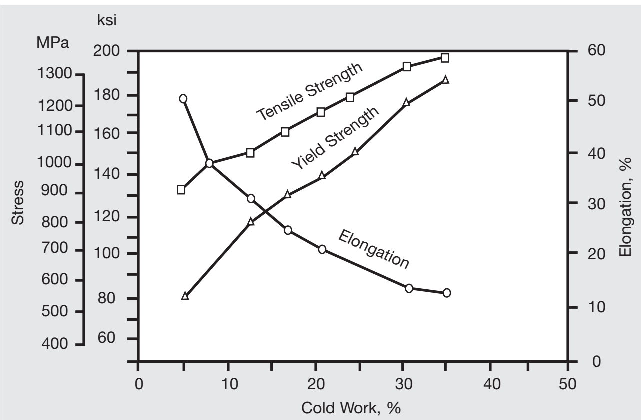


Figure 4. Effect of percent cold work on the tensile properties of INCONEL alloy 625LCF.

Annealing Characteristics

A benefit to the design engineer, working to achieve desired performance characteristics, is that INCONEL alloy 625LCF can be annealed, within limits, to specific ranges of grain size and tensile properties. Properties after the anneal depend on the amount of cold work prior to anneal and the time, temperature and atmosphere of the anneal.

For thin strip, best ductility is obtained by annealing in either a hydrogen or a vacuum atmosphere. In addition, while the rate of air-cooling is generally not critical for INCONEL alloy 625LCF, very slow cooling (e.g. furnace cooling) is not recommended.

Table 2 shows the ASTM grain size for 30% cold worked sheet after annealing at the indicated temperatures for times between 1 and 30 minutes.

Table 3 lists the effect of cold work on ASTM grain size and room-temperature tensile properties for sheet annealed for five minutes at 1750°F (955°C).

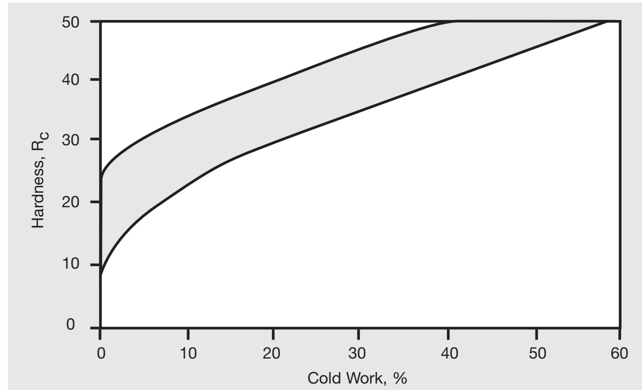


Figure 3. Work hardening range vs. percent cold work for INCONEL alloy 625LCF.

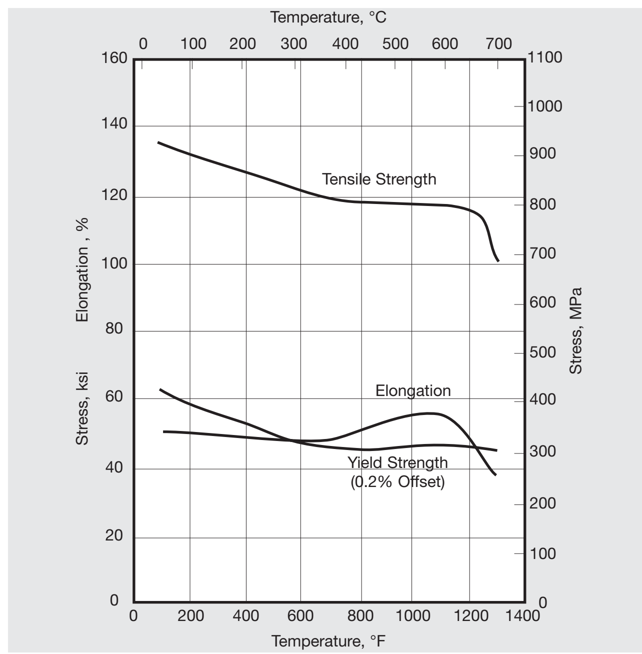


Figure 2. High-temperature tensile properties of annealed sheet.

Table 2 - ASTM Grain Size for 30% Cold Worked INCONEL alloy 625LCF Sheet after Annealing at the Indicated Temperatures and Times

Temperature	Time, minutes			
	1	5	10	30
1750°F (955°C)	10	9.5	9.5	9.5
1850°F (1010°C)	10	10	9.5	9
1900°F (1040°C)	9	8.5	8	7
1950°F (1065°C)	8	7.5	7	7

Table 3 - Effect of Cold Work on Grain Size and Room-Temperature Tensile Properties of INCONEL alloy 625LCF Sheet, Annealed at 1750°F (955°C) for Five Minutes

Percent Reduction	ASTM Grain Size	Yield Strength (0.2% Offset)		Tensile Strength		Elongation, %	Reduction of Area, %
		ksi	MPa	ksi	MPa		
5	9	82	563	138	952	46	99
10	9	67	462	133	916	48	96
15	9	69	478	135	931	48	97
20	9	76	524	141	972	46	97
30	10	76	524	141	972	42	98
40	10	77	529	141	972	42	98
50	10	79	545	148	1017	40	98

Developing Spring-Type Properties in Cold-Worked Sheet and Strip

Where spring-type properties are desired, it is possible to direct-age both annealed and cold-worked sheet and strip to obtain higher tensile properties with only moderate reduction in ductility. These moderate gains in tensile properties are achieved by aging annealed material between 1100°F (595°C) and 1200°F (650°C) for 1 to 24 hours.

Table 4 provides a typical example of the properties that can be achieved by cold working plus aging.

Table 4 - Effect on Hardness and Room-Temperature Tensile Properties of Cold Working and Aging INCONEL alloy 625LCF at 1150°F (620°C) and 1200°F (650°C) for Varying Times

Cold Work, %	Aging Time, h	Yield Strength (0.2% Offset)		Tensile Strength		Elongation, %	Hardness, R_C
		ksi	MPa	ksi	MPa		
As annealed, prior to cold work		73	503	135	933	49.2	98
		Aged at 1150°F (620°C)					
2.5	4	85	584	140	963	43.1	27
	8	90	619	142	982	42.3	27
	16	99	684	149	1029	39.5	28
	24	107	738	155	1069	37.2	32
5.0	4	100	688	145	999	39.1	31
	8	102	703	147	1014	37.8	31
	16	107	738	154	1062	36.7	32
	24	117	808	160	1100	34.2	34
		Aged at 1200°F (650°C)					
2.5	4	88	608	140	963	38.1	25
	8	91	630	144	992	42.0	27
	16	104	718	154	1062	37.6	30
	24	113	781	161	1112	35.0	34
5.0	4	106	730	146	1009	36.8	28
	8	104	719	150	1031	35.2	31
	16	119	820	159	1094	28.5	32
	24	111	768	156	1075	34.6	32

Properties that Determine Formability

Three material properties determine the strain distribution during forming, and thereby formability. These are the strain hardening exponent (‘n’ value), the plastic strain ratio (‘R’ value) and the strain rate sensitivity (‘m’ value). The ability to distribute strain uniformly depends on the ‘n’ and the ‘m’ values. While these properties can vary with temperature, tensile properties, microstructure and gauge, the values for ‘n’, ‘R’ and ‘m’ are defined mathematically as follows:

1. $$n = \frac{\partial \ln \sigma}{\partial \ln \varepsilon}$$

   where σ = true stress

   ε = true strain

2. $$\bar{R} = (R_0 + R_{45} + R_{90})/4$$

note: subscripts refer to the angle between the tensile specimen axis and the rolling direction.

3. $$m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}$$

   where $\dot{\varepsilon}$ = true strain rate

Values of these properties for INCONEL alloy 625LCF have been determined by the Colorado School of Mines[1]. The strain hardening exponent ‘n’ was based on a standard power law analysis of the Holloman equation,

4. $$\sigma = K\varepsilon^n$$

   where K=coefficient

over the strain range from 10% to 30% engineering strain. The values for ‘n’ as a function of strain rate at 73°F (23°C) are given in Figure 5 for three degrees of orientation with respect to the rolling direction. The strain hardening exponent is decreasing with increasing strain rate reflecting the fact that the yield strength is increasing faster than the ultimate tensile strength as the strain rate is increased. High values of ‘n’ tend to distribute increasing strain to regions of lower strain and flow stress, thereby predicting good formability in a stretching operation.

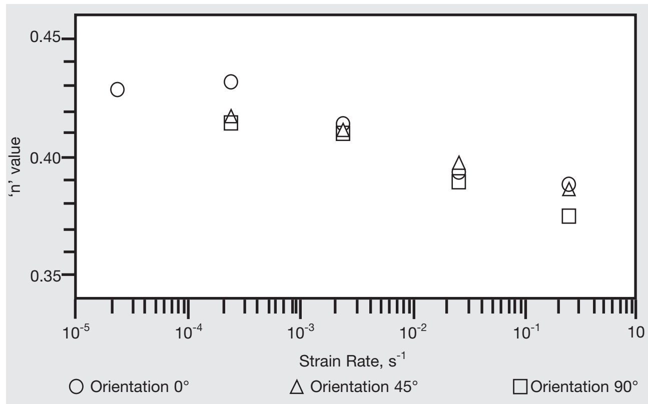


Figure 5. Strain hardening exponent (‘n’) as a function of strain rate for INCONEL alloy 625LCF at 73°F (23°C).

The plastic strain ratio ‘R’ relates to drawability and is defined as the ratio of true width strain to true thickness strain in the uniform elongation region of a tensile test. The ‘R’ value is an indication of the ability of a material to resist thinning. A high ‘R’ value indicates an alloy with good drawing properties. The ‘R’ value is determined on the assumption of volume constancy and for INCONEL alloy 625LCF is not dependent on strain rate. The typical value of the plastic strain ratio for INCONEL alloy 625LCF is 0.965 and the value of the planar anisotropy, ΔR, is 0.22, where ΔR is defined as:

5. $$\Delta R = (R_0 + R_{90} - 2R_{45})/2$$

Lack of planar anisotropy is defined by a value of ΔR=0.0. The value of ΔR determines the extent of earing in a deep drawing operation.

The resistance of INCONEL alloy 625LCF to necking during stretching operations can be measured by the strain rate sensitivity value, ‘m.’ The ‘m’ values for INCONEL alloy 625LCF are 0.0073 at 10% engineering strain and 0.0025 at 30% engineering strain. The positive strain rate sensitivity of INCONEL alloy 625LCF indicates that the flow stress increases with the rate of deformation. This condition is beneficial in distributing strain more uniformly in that, at a given strain rate, the material resists further deformation in regions that are being strained more rapidly than in adjacent regions by increasing the flow stress in those regions.

[1]P. Roamer, C.J. Van Tyne, D.K. Matlock, “Formability of Nickel-Base Superalloy Sheet,” Research Report - Special Alloys and Stainless Steels, Advanced Steel Processing and Products Research Center, Colorado School of Mines, Golden, Colorado, September, 1996.

Forming Limit Diagram

Figure 6 shows the forming limit diagram for INCONEL alloy 625LCF. This is useful for predicting the limits of deformation available to a designer fabricating a component by drawing, stretching, punching or stamping. In practice, die friction can alter the shape of this diagram. The lower left quadrant represents safe drawing limits for INCONEL alloy 625LCF and the lower right depicts safe biaxial stretching limits. The upper quadrants represent regions of near failure and failure for these operations.

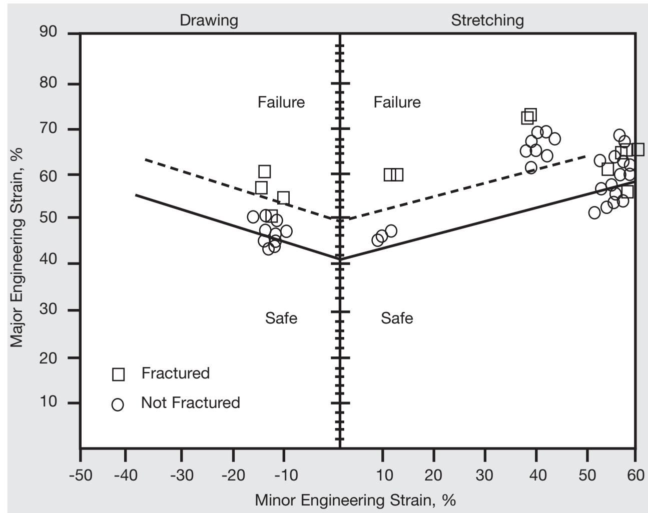


Figure 6. Forming limit diagram for INCONEL alloy 625LCF.

Calculating “Springback”

Special attention to springback after forming may be necessary due to the high yield strength of INCONEL alloy 625LCF. Using a multi-purpose design formula developed by B.M. Botros at A&T State University in Greensboro, NC, the springback characteristics for INCONEL alloy 625LCF, as a function of angle of bend and bend radius, can be approximated.[2] The formula used for determining springback is given in equation 6. The functions used in the equation are found in Figure 7. Use of the equation can help in defining the degree of springback for any given set of sheet, strip or tube bending conditions. With INCONEL alloy 625LCF, there is a definite tendency for the degree of springback to increase as the radius of bend increases and a lesser tendency to increase as the angle of bend decreases. The degree of springback also increases as the yield strength increases and the sheet or strip thickness decreases. The degree of springback also increases as a function of bend angle for 0.062 in (1.6 mm) and 0.125 in (3.2 mm) sheet having a 60 ksi (415 MPa) yield strength. See Figure 8.

6. $\delta = (\theta_2 - \theta_1)/\theta_1 = 301[rs(1 - \nu^2)/Et][(180/\theta_1) - 1]$

Where:

δ = Springback, %

θ_1 = Bend angle, degrees

θ_2 = Angle of bend after springback, degrees

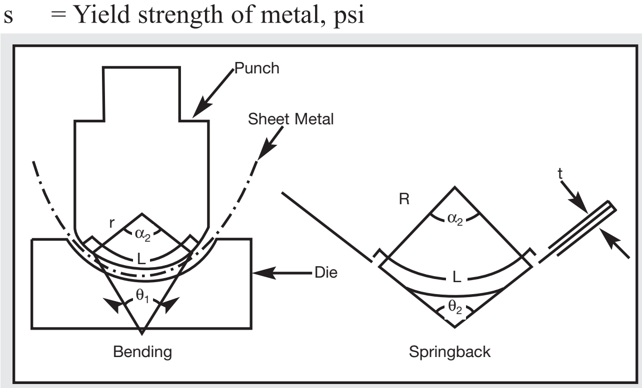
ν = Poisson’s ratio for INCONEL alloy 625LCF, 0.28 at room temperature

E = Modulus of elasticity of INCONEL alloy 625LCF, 30.1×10^3 ksi at room temperature.

t = Thickness of material, inches

r = Radius of bend (die radius), inches

s = Yield strength of metal, psi



[2]“Formula helps to predict amount of metal springback,” *Product Engineering, March 11, 1968*.

Figure 7. Schematic defining bend angle, bending radius and thickness used in equation 6.

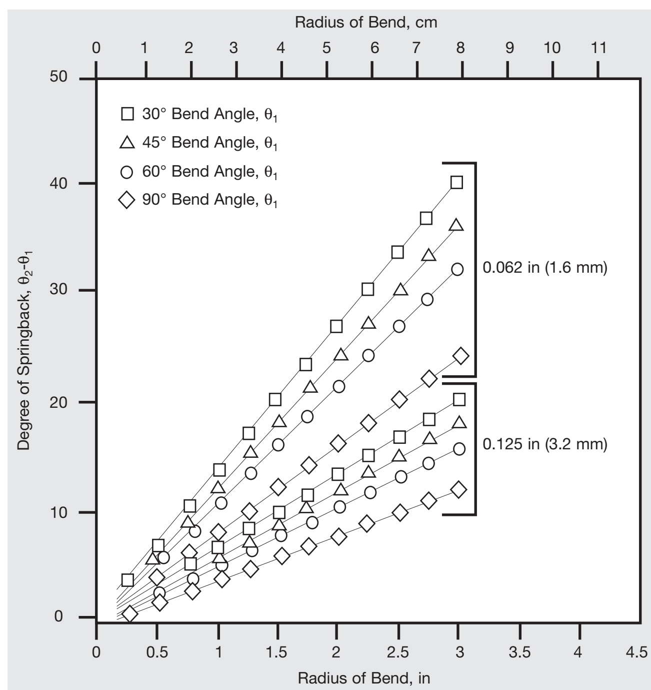


Figure 8. Degree of springback for INCONEL alloy 625LCF. Nominal gauge is 0.062 in (1.6 mm) and 0.125 in (3.2 mm) at 60 ksi (414 MPa) yield strength.

Dimensional Stability

A knowledge of dimensional stability is critical for tight tolerance control in INCONEL alloy 625LCF components exposed to temperatures in excess of 1000°F (540°C). Figure 9 shows the alloy's shrinkage as a function of time and temperature. These shrinkage characteristics are due to phase precipitation.

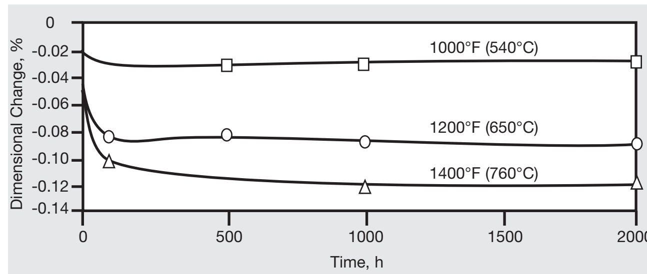


Figure 9. Dimensional stability of INCONEL alloy 625LCF at 1000°F (540°C), 1200°F (650°C) and 1400°F (750°C) for times up to 2000 hours.

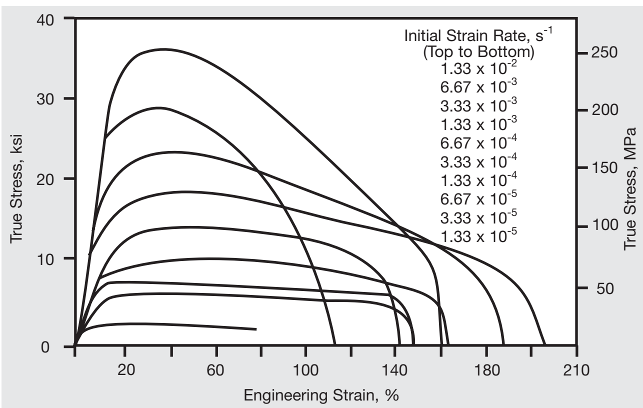


Figure 10. Effect of strain rate on the flow stress of INCONEL alloy 625LCF at 1750°F (955°C)

Creep Forming

INCONEL alloy 625LCF can be creep formed at temperatures below 1900°F (1040°C) and still retain a fine grain microstructure as well as bellows-specification tensile properties. Figure 10 shows the effect of strain rate at 1750°F (955°C) on the flow stress of INCONEL alloy 625LCF. The flow stress characteristics and moderate ductility of the alloy suggest "near" superplastic forming characteristics.

Available Products and Specifications

INCONEL alloy 625LCF is designated as UNS number N06626. It also meets the requirements of N06625.
The alloy is available in the standard mill forms of sheet and strip.
Alloy 625LCF sheet and strip are supplied to the requirements of SAE/AMS 5879. Allowable design stresses and rules for ASME Section VIII, Division 1 construction for service up to 800°F (427°C) are defined in ASME Code Case 2276.
Alloy 625LCF products also meet the requirements for INCONEL alloy 625 - Grade 1 as specified by ASTM B 443/ASME SB 443.

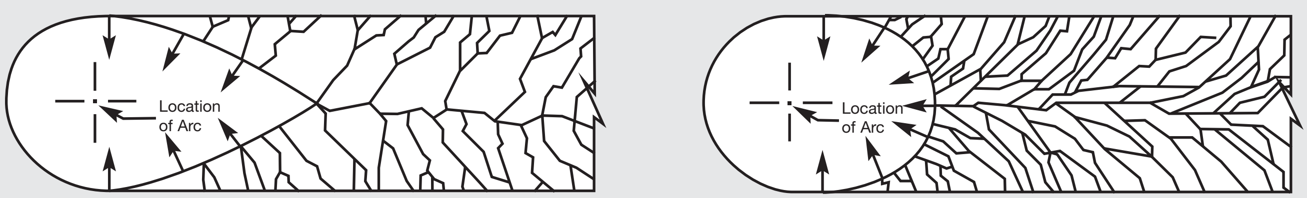
Joining

INCONEL alloy 625LCF exhibits outstanding weldability by a wide variety of common fusion processes. Thin bellows material is generally joined without filler metal (autogenous) using the Gas Tungsten Arc Welding (GTAW) or Plasma Arc Welding (PAW) processes. High speed welding, using the GTAW process, requires magnetic arc deflection to maintain the arc in proper relation to the torch. While thin gauges can be welded at high speeds, the weld grain structure will be coarse and not exhibit the highest ductility. For optimum ductility, travel speed must be slow enough to produce an elliptical weld puddle rather than the tear-drop shape which results from high speed welding (see Figure 11). The solidification direction in elliptical puddles is constantly changing relative to grains, producing a competitive solidification and a resultant finer structure. This, in turn, will produce the highest as-welded ductility.

Furnace brazing in argon, hydrogen, or vacuum environments should be carried out at temperatures low enough (1900°F (1040°C) or less) and for time periods short enough (5 minutes or less) to avoid significant grain growth. However, the solidus of the braze filler should be high enough to allow adequate base metal stress relaxation to avoid liquid metal embrittlement. Shielding gas quality and cleanliness are important for consistent braze flow without resorting to nickel plating. Erosion of the thin gauges during brazing can be minimized by using filler metals low in boron and high in silicon, such as BNi-8 (AWS A5.8) which can be used at 1850-1900°F (1010-1040°C).

Applications requiring high environmental resistance from the braze filler should consider more noble braze alloys of gold and/or palladium. In general, braze joint strength increases as the braze gap decreases, provided that the filler will flow consistently in narrower gaps.

INCONEL alloy 625LCF can also be readily joined by resistance welding processes, such as spot, projection, seam and flash welding. These processes are generally limited to lap joints in thin sheet. Strip flash welding can produce butt joints. INCONEL alloy 625LCF has a relatively high electrical resistance (776 ohm/circ mil•ft) and requires a high electrode or upset pressure due to its tensile properties. However, most of this pressure can be derived from spring, air or fluid pressures. The time and amount of current flow must be accurately controlled to minimize expulsions, surface burning and inconsistent strengths.



a. Undesirable weld speed resulting in tear-drop shaped weld puddle.

b. Desirable weld speed resulting in elliptical weld puddle.

Figure 11. Schematic representation illustrating modification of macroscopic growth pattern caused by competitive growth favoring grains with <100> direction nearly parallel to the maximum temperature gradient in the weld puddle.

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