Superplastic Forming and Diffusion Bonding of Inconel 718

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This paper presents the results of a program designed to delineate the capabilities of Inconel 718 for superplastic forming (SPF) and diffusion bonding (DB) as low-cost, weight-saving processes for fabricating rocket engine parts. Elevated temperature total elongation and step-strain rate tests indicate that specially processed, fine-grained Inconel 718 behaves sufficiently superplastically to indicate the potential for the SPF of parts of considerable complexity. This is further confirmed with the SPF of a model part and a section of an actual rocket engine part. It is shown that Inconel 718 can be diffusion bonded using a nickel interface layer to form high shear strength bonds.

Introduction

INCONEL 718 is a nickel-based superalloy used extensively in rocket engine components, including those in the Space Shuttle main engine (SSME), because of an advantageous combination of properties. Costs of fabricating complex manifolding and similar components from Inconel 718 would be reduced significantly if these parts could be produced by superplastic forming and diffusion bonding procedures. The advantages of these processes lie in the much increased design flexibility and reduction in the number of details required to construct a part that reduces cost, and, in many cases, reduces weight. Also, parts formed by SPF are not subject to springback and do not contain residual stresses, which simplifies subsequent welding. Diffusion bonding (DB) can be and has been combined with SPF to further extend design flexibility and reduce cost and weight.

The requirements for developing superplasticity are well known, although the detailed mechanism is still somewhat controversial. (A detailed discussion of superplasticity has been published by Edington et al.[1]) A fine grain size, generally less than about 10 μm, is normally required in combination with a temperature for deformation of approximately one-half the homologous temperature and, further, the grain structure must be reasonably stable at the deformation temperature so that the grain size remains fine enough to produce superplastic deformation.

There is little reported information on the development of superplasticity in Ni-based alloys. However, sone activities have been directed toward the development and evaluation of superplasticity in such materials as IN-100 and IN-744.[2-4] There is nothing in the literature that has demonstrated the superplastic potential of Inconel 718, and prior evaluations, results of which are included in Figs. 1 and 2, showed that conventionally produced Inconel 718 exhibits a grain size too large to permit SPF, at least at rates suitable to be considered for commercial applications. However, available evidence[5] suggested that a very fine grain size with sufficient stability to permit SPF could be achieved in Inconel 718.

This program was initiated to determine the SPF potential of fine-grained Inconel 718 and, if feasible, to demonstrate SPF and DB of Inconel 718 as low-cost, weight-saving fabrication techniques for rocket engine components.

Experimental

Material

The Inconel 718 evaluated in this program was fine grained. The first material obtained was a sheet 0.050 in. thick on which the initial and most comprehensive studies of the superplastic behavior of Inconel 718 were conducted. Subsequently, thicker sheets of fine-grained Inconel 718 were obtained and tested to demonstrate that material suitable for SPF of full-size parts could be obtained. All materials investigated in this program had certified chemical analysis in accordance with the specification composition given in Table 1. The various sheet sizes used are listed along with their grain sizes in Table 2.

Tensile Tests to Establish Superplastic Behavior

Elevated temperature tensile tests were conducted on the material in the as-received condition to determine the strain rate sensitivity of the flow stress and the total elongation capabilities of the material under constant strain rate conditions. The tests were conducted at temperatures of 1700-1900°F. The strain rate sensitivity of the flow stress was measured by conducting a step-strain rate test on a sample including strain rates from less than 10^{-6} to 10^{-2} s^{-1}. The test procedure followed and the data reduction methods utilized have been described by Ghosh and Hamilton.[6] From the flow stress/strain rate data, the strain rate sensitivity exponent m was determined as a function of the strain rate. $m = d\ln\sigma / d\ln\dot{\epsilon}$ where σ is stress and $\dot{\epsilon}$ strain rate. m is a measure of the ability of a metal to be deformed without necking and rupture and must be greater than 0.3 for a metal to behave superplastically.

Tensile specimens of the material also were subjected to total elongation tests at various temperatures and strain rates. The total elongation tests were conducted utilizing a recent modification of the Instron machine so that the crosshead velocity could be adjusted automatically as the gage length of

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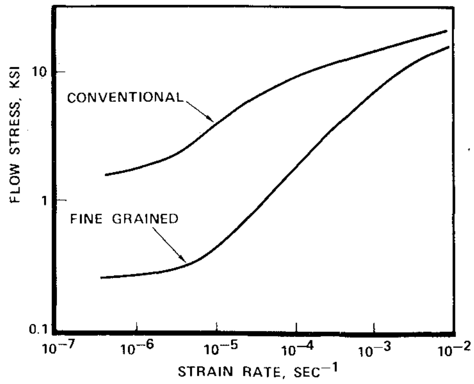

Fig. 1 Flow stress vs strain rate for conventional and fine-grained 0.05-in.-thick Inconel 718.

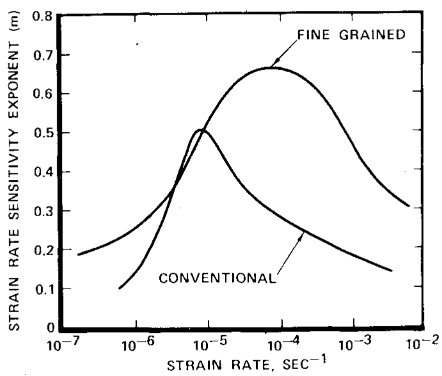

Fig. 2 Strain rate sensitivity exponent vs strain rate for conventional and fine-grained 0.05-in.-thick Inconel 718.

Table 1 Specification composition limits for Inconel 718

Element	Composition, wt.%
Carbon	0.08 max
Manganese	0.35 max
Silicon	0.35 max
Phosphorus	0.015 max
Sulfur	0.015 max
Chromium	17.0-21.0
Cobalt	1.0 max
Molybdenum	2.80-3.30
Columbium (+tantalum)	4.75-5.50
Titanium	0.65-1.15
Aluminum	0.20-0.80
Iron	Remainder
Copper	0.30 max
Nickel (+cobalt)	50.00-55.0
Boron	0.006 max

the test specimen increased so that the strain rate within the gage section could be maintained approximately constant. The technique is described by Ghosh and Hamilton[6] along with verification of the suitability of this technique for maintaining strain rate control.

Superplastic Forming Tests

A model part and a section of a full-scale SSME part were superplastically formed by gas pressure forming into a die. To superplastically form a component, it is necessary to establish a pressure/time profile that ultimately determines the strain rate at which the part is formed. For simple shapes this is done analytically with established computer programs. For the more complex geometries, curve blending techniques are used whereby portions of different pressure/time profiles are selected to approximate different stages of the forming cycle. This procedure was used and, based on data from the tensile tests, the pressure/time profiles required to superplastically form the parts were established.

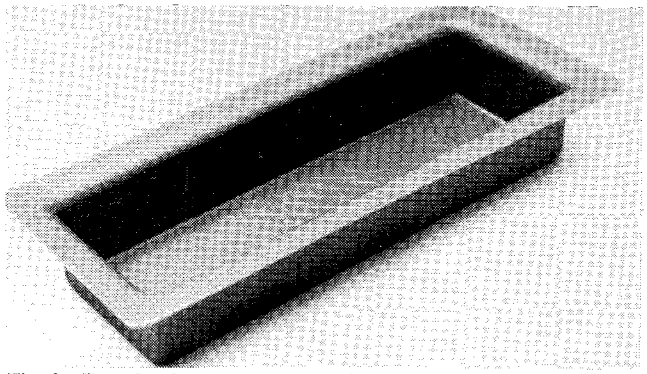

Fig. 3 Part that has been superplastically formed from fine-grained, 0.050-in.-thick Inconel 718.

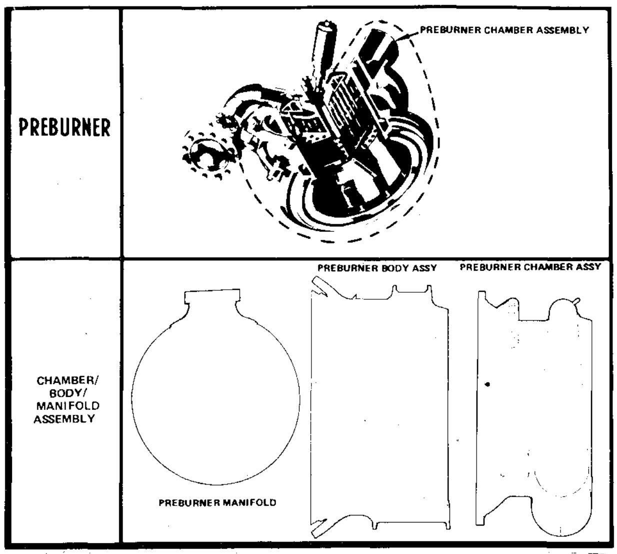

Fig. 4 Schematic of SSME preburner manifold.

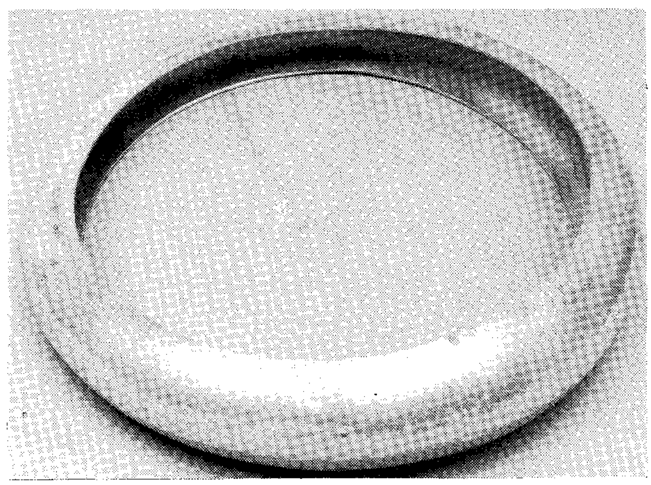

Fig. 5 Electron beam welded superplastically formed Inconel 718 manifold half-sections.

Diffusion Bonding

Diffusion bonding tests were conducted on both uncoated and nickel-coated Inconel 718 specimens.

Table 2 Grain sizes of Inconel 718 materials

	Grain size, μm		
Material sheet thickness, in.	Longitudinal, L (rolling direction)	Long transverse, LT (width direction)	Short transverse, ST (thickness direction)
0.050	~6	~6	~6
0.090	9.8	5.4	5.5
0.105	10.4	7.8	8.3
0.100 Heat 29J2	7.8	7.5	7.7
0.100 Heat 0372	7.9	7.6	7.6

Table 3 Superplasticity tensile test data for fine-grained Inconel 718 sheet (longitudinal)

Sheet thickness, in.	Temperature, °F	Strain rate, s^{-1}	Elongation %
0.090	1700	2×10^{-4}	156
	1800	2×10^{-4}	150
	1900	2×10^{-4}	85
0.090	1700	10^{-3}	110
	1800	10^{-3}	210
	1900	10^{-3}	90
0.105	1700	2×10^{-4}	87
	1800	2×10^{-4}	140
	1900	2×10^{-4}	—
0.105	1700	10^{-3}	124
	1800	10^{-3}	210
	1900	10^{-3}	98

For tests on uncoated specimens, surface preparation involved acid cleaning, polishing with 600 grit SiC paper, cleaning and degreasing with acetone, and placing the pieces in a vacuum chamber without delay. For nickel-coated specimens, preparation involved cleaning and degreasing, followed by anodic etching and nickel plating.

Bonding work was conducted on 1 × 1 in. coupon specimens of the 0.050-in.-thick Inconel 718 sheet. Elevated temperature $\sigma/\dot{\epsilon}$ data developed on this material in the SPF tensile tests were used to calculate the required pressure and time for diffusion bonding. The bonding experiments were conducted on an Instron machine run under load control in order to impose constant pressure during bonding. This machine is equipped with a Centorr vacuum furnace that can maintain up to 5×10^{-6} Torr vacuum and is capable of rapid heating to the bonding temperatures. At the end of each test, the load was removed and the specimen was allowed to cool to near room temperature in the vacuum before opening the chamber.

Results

Superplastic Forming

The grain size stability of the fine-grained, 0.050-in.-thick Inconel 718 sheet was assessed in a preliminary evaluation of 1-h exposures of the material at various temperatures between 1700-1900°F. There was no grain growth at 1700°F but very rapid grain growth at 1900°F resulting in a large grain size not considered suitable for superplastic deformation. Thus, the SPF tensile test studies on the 0.050-in.-thick Inconel 718 sheet were limited to temperatures below 1900°F.

The results of the total elongation and step-strain rate tests on the fine-grained, 0.050-in.-thick Inconel 718 showed elongations as high as 294% and m values of 0.63 were achieved. The total elongations observed for the 0.050-in.-thick Inconel 718 in the SPF tensile tests are well beyond the conventional forming processes and are sufficient to permit significant SPF operations with this material. The fine-grained, 0.050-in.-thick Inconel 718 exhibited much lower flow stresses than for conventional material containing a coarser grain size. Comparison of the flow stresses and corresponding m values as functions of strain rate are shown in Figs. 1 and 2.

Table 4 Inconel 718 SSME parts considered candidates for SPF

Preburners:
- Fuel manifold, fuel preburner
- Fuel manifold, oxidizer preburner

Main injector:
- Oxidizer dome torus
- Inlet shell

Nozzle:
- Coolant control valve body
- Aft inlet manifold

Main combustion chamber:
- Aft inlet manifold shell
- Forward outlet manifold shells

Low-pressure fuel turbopump:
- Manifold

High-pressure fuel turbopump:
- Housing assembly
- Volute, housing

Hot gas manifold and heat exchanger:
- Shell, structural fuel
- Shell, structural oxidizer

High-pressure oxidizer turbopump:
- Housing, main pump assembly

The encouraging results from the tensile tests led to the gas pressure SPF into a die of the 0.050-in. Inconel 718 sheet to form the 6 × 2 × 1 in. (internal cavity dimensions) pan shown in Fig. 3. The tight forming around the edges and particularly in the corners is impressive.

With the positive results with the 0.050-in.-thick Inconel 718, the fine-grained, 0.090- and 0.105-in.-thick sheet materials characterized in Tables 1 and 2 were obtained. The results of SPF total elongation tests on these materials are given in Table 3. The elongations are somewhat lower for the 0.090- and 0.105-in.-thick materials than for the 0.050-in.-thick sheet, but are sufficiently high to indicate that many parts could be superplastically formed from these materials.

With the availability of fine-grained Inconel 718 of sufficient thickness and width, the SPF of a section of an actual part was initiated. A large number of SSME parts are made of Inconel 718 for a total weight of Inconel 718 in the engine of 2230 lb. Thus, the SSME parts were reviewed and some 78 were identified as being potential candidates for the application of SPF. Table 4 lists major components of the SSME and in each case, one or two parts considered candidates for SPF. The part selected for SPF was the fuel manifold of the SSME oxidizer preburner shown in Fig. 4. This part is currently produced by machining a forged ring. The approximately 0.090-in.-thick, 12-in.-diam toroidal section was fabricated by SPF half-sections that were joined to form the toroidal section. The manifold half-sections were formed from 0.1 × 18 × 18 in. sheets, the grain sizes of which are given in Table 2. The half-sections were prepared by gas pressure forming the sheets into a die. Twelve half-sections were successfully superplastically formed with no failures. The as-formed manifold half-sections were trimmed by electrical discharge machining and electron beam welded together to form a toroidal section, as shown in Fig. 5. Visual

Table 5 Effect of SPF on tensile strength of Inconel 718

Specimen[a]	Superplastic effective strain	Ultimate strength, ksi	Yield strength, ksi
As-received	---	223	194
Plain strain	0.246	192	160
Balanced biaxial	0.245	195	167

[a] All specimens heat treated as follows: 1800°F/h + 1325°F/8 h, furnace cooled 100°F/1 h to 1150°F/10 h.

Table 6 Shear test results for diffusion bonds in Inconel 718

Bond temperature, °F	Bond strength, ksi
1800	98.4
1800	87.7
1800	98.9
1800	26.0
1800	93.8
1800	51.8
1750	8.0[a]
1750	145.9
1750	68.2

NOTES: Tests conducted at room temperature at crosshead speed of 0.02 in./min. All specimens heat treated as follows: 1800°F/1 h + 1325°F/8 h, furnace cooled 100°F/h to 1150°F/10 h.
[a] Badly oxidized bond plane.

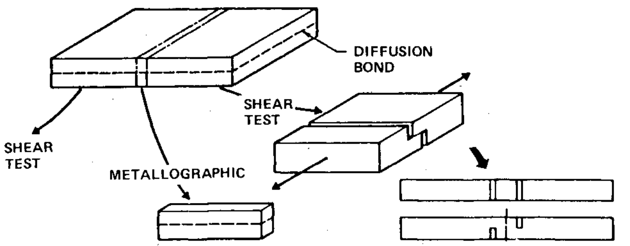

Fig. 6 Schematic of diffusion bonding setup and shear test specimens.

examination of the weld revealed full root penetration, uniform and acceptable weld geometry, very little root spatter, and no obvious defects.

To simulate strains measured in the manifold and provide flat specimens for tensile tests, rectangular pans, such as shown in Fig. 3, were superplastically formed using equivalent SPF procedures. Specimens were machined from the sidewalls of these pans where plane strain conditions exist and from the bottom of the pans where biaxial conditions exist. All specimens, including unstrained standards, were solution treated and age hardened to full strength with results of room-temperature tensile tests shown in Table 5. From these results it is clear that the SPF process does reduce both yield and ultimate tensile strength. However, the tensile strengths after SPF are above the accepted Inconel 718 design minimums of 180 ksi ultimate tensile strength and 150 ksi tensile yield strength.

Diffusion Bonding

An effort was initiated to investigate the diffusion bonding (DB) of Inconel 718. Since it was known from prior work[7,8] that temperature, pressure, time, and bonding atmosphere influence the DB process, the main objective was to develop an appropriate set of bond parameters, and conduct experiments to verify these parameters. The parameter development primarily considers the creep of surface asperities of the adjoining pieces at elevated temperature under the action of normal pressure. The role of diffusion becomes important in later stages causing microvoid coalescence, grain boundary migration, recrystallization, and grain growth. In addition to the above parameters, surface conditions prior to bonding can have a profound influence on the quality of the diffusion bond. Surface cleanliness is, of course, essential.

As a first approach, it was decided to attempt bonding of properly cleaned Inconel 718 surfaces utilizing the pressure/time/temperature combinations calculated on the basis of previous theoretical work. However, even with high applied pressure, the bond across the interface was incomplete. Thus, a second approach was investigated which focused on using a nickel film at the bond interface. Such a film can undergo softening and, thus, help to achieve intimate contact at a much lower pressure.

With the Ni coating, excellent bonds resulted at acceptable bonding temperatures and pressures. Bond strength tests were used to further define optimum bonding parameters. To assess bond strength, shear test specimens of the type shown in Fig. 6 were machined from bonded coupons.This is a room-temperature test wherein the machined slots cause failure in the bond plane if the bond is weak.

Table 6 lists results of these shear tests conducted on bonded specimens after the aging treatment. It is observed from this table that bond shear strengths are generally good for the best DB conditions. These strengths compare quite well with the properties of the base material (shear strength, 75 ksi). In some cases the bond strength was greater than the parent metal strength and shearing was not restricted to the bond plane.

Conclusions

1) Complex Inconel 718 parts can be fabricated by superplastic forming.
2) Inconel 718 parts made by SPF can be dimensionally accurate and repeatable.
3) Mechanical properties of Inconel 718 after SPF are comparable to those of conventionally processed material.
4) SPF Inconel 718 can be electron beam welded to produce visually good weld joints.
5) Inconel 718 can be diffusion bonded using nickel as a transition material to produce bonds with shear strengths comparable to those of the base metal.

Acknowledgments

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