MICROSTRUCTURAL AND MECHANICAL PROPERTY CHARACTERIZATION OF SUPERPLASTICALLY FORMED INCONEL alloy 718SPF

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Abstract

Superplastic forming (SPF) of aluminum- and titanium-based alloys has become a significant manufacturing method for aerospace engine and fuselage components. Largely overlooked by design engineers is the applicability of fine-grained INCONEL® alloy 718SPF* to this process. This paper seeks to show the compatibility of this alloy to current SPF practice and equipment. Extensive processing parameters are presented based on laboratory data as well as post SPF tensile properties taken from material processed on commercial SPF equipment.

INCONEL alloy 718SPF can be superplastically formed at 954°C (1750°F) using flow stresses generally less than 72 MPa (10.4 psi) at an initial strain rate of 1.3×10^{-3} s^{-1} and < 28 MPa (4 psi) at 1.3×10^{-4} s^{-1}. The elongation to failure increases markedly with decreasing strain rate, exceeding 350% at an initial strain rate of 1.3×10^{-3} s^{-1}, 450% at 1.3×10^{-4} s^{-1} and 750% at 3.3×10^{-5} s^{-1}. Laboratory data are used to calculate "m" values (a measure of strain rate sensitivity) which increase from 0.28 at an initial strain rate of 1.3×10^{-3} s^{-1}, to 0.45 at 1.3×10^{-4} s^{-1} and to 0.83 at 3.3×10^{-5} s^{-1}.

The original tensile properties and grain size are compared to the post SPF-processed material for several values of total strain. For material SPF-processed through engineering strains of less than approximately 200%, original properties persist. Achievement under these processing conditions of nominal aged tensile properties is similarly demonstrated.

Metallography is used to measure the percentage area of cavitation as a function of total strain and at failure for several strain rates. Under similar conditions, the average roundness coefficient (a measure of cavity growth by diffusion) is also computed for various strain rates. At an initial strain rate of 10^{-2} s^{-1}, the area of cavitation at failure is < 0.01% but increases with decreasing strain rate becoming 2.8% at 370% engineering strain and a strain rate of 1.3×10^{-3} s^{-1}. The average roundness coefficient increases from 0.47 to 0.63 for the conditions described above.

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Introduction

There is a market need for complex shaped parts for commercial and military aircraft applications requiring high nickel alloys to withstand a combination of high temperature, hot gas corrosion and high strength. Conventional methods of fabricating these components requires extensive welding and fabrication methods resulting in higher than desired costs and excessive parts inventories. Superplastic forming, now highly sophisticated and used extensively for producing titanium and aluminum alloy aircraft parts, would be an ideal solution for producing nickel alloy components as well. However, for this to occur, a minimum level of technology must exist for an alloy which both meets the technical requirements of the end-use and is amenable to the SPF practices and equipment now in commercial use. This paper seeks to show the applicability of INCONEL alloy 718SPF to this manufacturing method by describing the SPF characteristics of this alloy and the subsequent properties and microstructure of the finished part. The merits of INCONEL alloy 718 for commercial and military aircraft airframe and engine components have been long established and are widely known.

Materials and Procedures

Two heats of INCONEL alloy 718SPF were selected for this study. The composition of each heat is presented in Table 1. Tensile properties and grain size are given in Table 2. These heats were produced by vacuum melting followed by electroslag remelting. The material was then hot worked using conventional practice. However, the cold working procedure was altered to assure the production of an ultrafine grain size.

Heat HT3463EK was evaluated for superplastic forming characteristics by Y. Ma and T. G. Langdon at the University of Southern California, Los Angeles, CA (1). Heat HT4262EK was superplastically formed on conventional SPF equipment by P. Comley of Murdock, Inc., Compton, CA at 954°C (1,750°F) using an argon gas pressure of 2.1 MPa (300 psi) and a time of approximately 4h. The SPF part was evaluated for tensile properties life and microstructure (grain size and area of cavitation) at various locations in the component.

Superplastic Forming Characteristics of INCONEL alloy 718SPF

954°C (1,750°F) was chosen as the aim temperature for characterization of the SPF parameters of INCONEL alloy 718SPF.(2) The grain size stability of INCONEL alloy 718SPF during the time for typical SPF of a conventional component should be excellent at 954°C (1,750°F) as exemplified by the grain size data shown in Figure 1.

Table 1. Composition of INCONEL alloy 718SPF Heats Studied (Wt %)

Heat Number	C	Mn	S	Fe	Ni	Cr	Al	Ti	Mo	Nb
HT3463EK	0.02	0.08	0.001	18.04	53.52	18.51	0.47	1.04	3.04	5.01
HT4262EK	0.03	0.08	0.001	17.97	53.47	18.47	0.52	1.04	2.88	5.11

Table 2. Mechanical Properties of Mill Annealed INCONEL alloy 718SPF

	Room Temperature Tensile Properties			
	Heat HT3463EK 0.51 mm (0.02 in) gauge		Heat HT4262EK 1.22 mm (0.048 in) gauge	
Mill Annealed*				
0.2% Y.S., MPa (ksi)	852 (124)		815 (118)	
U.T.S., MPa (ksi)	1,121 (163)		1,114 (162)	
Elongation, %	29.0		33.0	
Hardness, Rc	25		32	
Grain Size ASTM #	13		12	
Aged**				
0.2% Y.S., MPa (ksi)	1,461 (212)		1,323 (192)	
U.T.S., MPa (ksi)	1,586 (230)		1,519 (220)	
Elongation, %	14.0		19.0	
Hardness, Rc	44		46	
Aged**	649°C (1200°F) Tensile Properties			
0.2% Y.S., MPa (ksi)	1,116 (162)		1,105 (160)	
U.T.S., (MPa (ksi)	1,201 (174)		1,244 (180)	
Elongation, %	22.0		21.0	
Aged**	649°C(1200°F)Stress Rupture Properties			
	Life h	Elong. %	Life h	Elong.%
Stress, 793 MPa (115 ksi)	12.2	9.8	-	-
Stress, 724 MPa (105 ksi)	-	-	57.7	12.5

*Continuous Process Anneal: 927°C (1700°F)/4.57 M (15 ft) per min.

**Aging Condition: 954°C (1750°F)/1h/AC plus 719°C (1325°F)/8h/FC at 56°C (100°F)/h to 621°C (1150°F) plus 621°C (1150°F)/8h/AC.

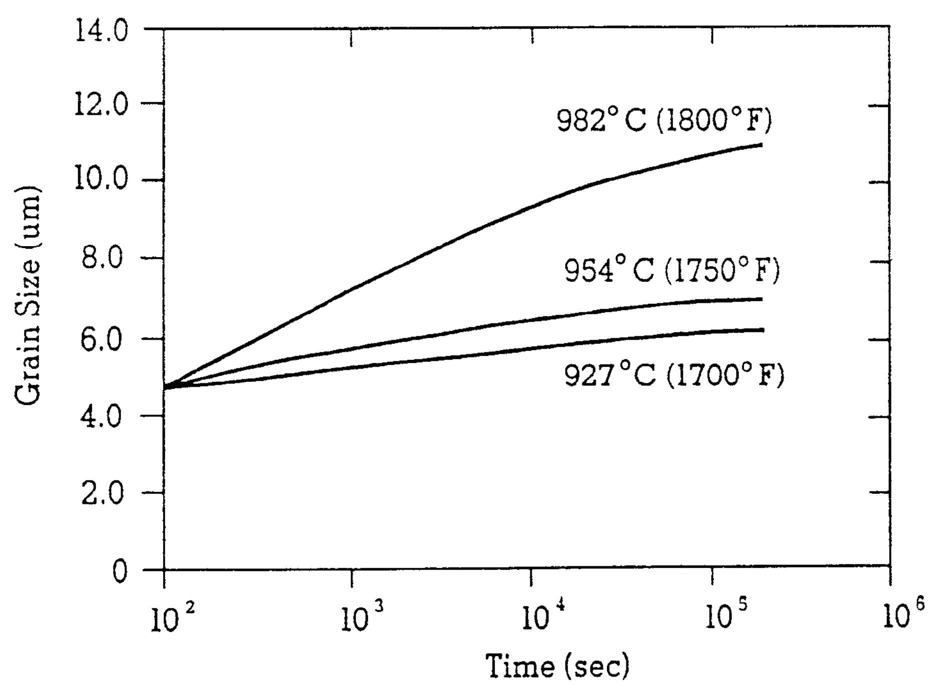

Figure 1. Plot of grain growth versus time at 927°C (1700°F), 954°C (1750°F) and 982°C (1800°F) for INCONEL alloy 718SPF.

To conduct the SPF process parameter evaluation, ten specimens were machined from 1.22 mm (0.048 in) sheet of INCONEL alloy 718SPF and tested at 954°C (1,750°F) to failure at varying strain rates from 1.33 x 10^{-2} s^{-1} to 1.33 x 10^{-5} s^{-1}. The test results are presented in tabular form in Table 3 and graphically in Figure 2. A plot of engineering strain (total elongation) versus the initial strain rate is presented in Figure 3. Engineering strain increased from 150% at an initial strain rate of 1.3 x 10^{-2} s^{-1} to 760% at 3.3 x 10^{-5} s^{-1}. For the typical SPF strain rates of 10^{-3} to 10^{-4} s^{-1}, the available engineering strains are approximately 280% at the faster strain rate to 480% at the slower strain rate.

Table 3. The SPF Characteristics of Strain and Strain Rate at Maximum Stress and Elongation at Failure for 10 Initial Strain Rates for INCONEL alloy 718SPF at 954°C (1750°F)

Specimen	Initial Strain Rate, s^{-1}	Elongation to Failure, %	Max. Stress, MPa (ksi)
1	1.33 x 10^{-2}	150	154.4 (22.4)
2	6.67 x 10^{-3}	194	119.3 (17.3)
3	3.33 x 10^{-3}	222	100.7 (14.6)
4	1.33 x 10^{-3}	269	71.7 (10.4)
5	6.67 x 10^{-4}	312	57.0 (8.27)
6	3.33 x 10^{-4}	406	43.4 (6.29)
7	1.33 x 10^{-4}	444	26.3 (3.81)
8	6.67 x 10^{-5}	538	16.5 (2.40)
9	3.33 x 10^{-5}	763	14.3 (2.08)
10	1.33 x 10^{-5}	212	4.9 (0.71)

Specimen	Strain at Max Stress, %	Strain Rate at Max Stress, s^{-1}
1	19.2	1.12 x 10^{-2}
2	19.2	5.60 x 10^{-3}
3	19.6	2.78 x 10^{-3}
4	85.1	7.19 x 10^{-4}
5	58.6	4.21 x 10^{-4}
6	109.0	1.59 x 10^{-4}
7	88.4	7.06 x 10^{-5}
8	146.0	2.71 x 10^{-5}
9	120.0	1.51 x 10^{-5}
10	137.0	5.60 x 10^{-6}

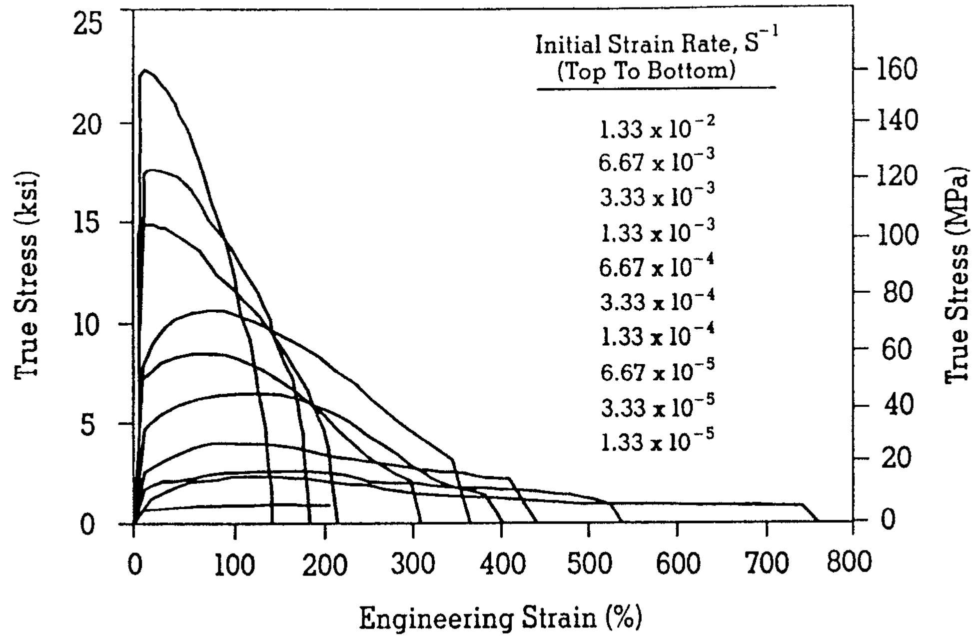

Figure 2. Plot of true stress versus engineering strain for 10 strain rates at 954°C (1750°F), for INCONEL alloy 718SPF, Heat HT3463EK.

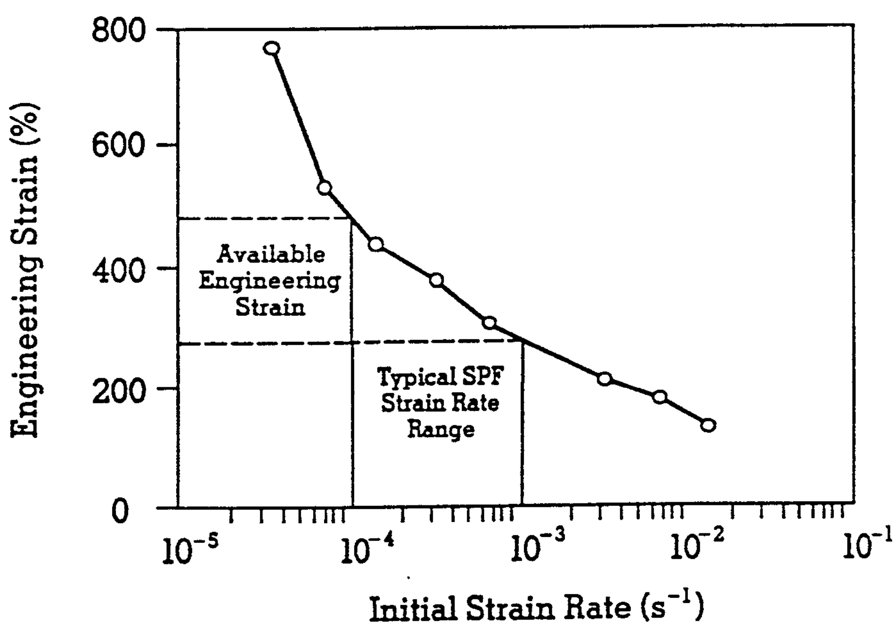

Figure 3. Engineering strain versus strain rate at 954°C (1750°F) for INCONEL alloy 718SPF, Heat HT3463EK. For typical SPF strain rates, the available engineering strain is highlighted.

A plot of the true strain rate at maximum stress versus the true stress at maximum stress is presented in Figure 4. This plot defines the maximum stresses that must be generated during SPF in order to deform INCONEL alloy 718SPF at the conventional strain rates of 10-3 to 10-4 s-1. The necessary stress range is from nearly 27.6 to 82.7 MPa (4 to 12 ksi). Also shown in

Figure 4 is the changing value of n at different strain rates as determined by Equation 1:

$$\dot{\epsilon} = \kappa\sigma^n \quad (1)$$

where $\dot{\epsilon}$ = true strain rate, σ = true stress, κ = constant

The value of n is the slope of log $\dot{\epsilon}$ vs. log σ and is typically between 1 and 2.5 in the region of most practical SPF interest.(4)

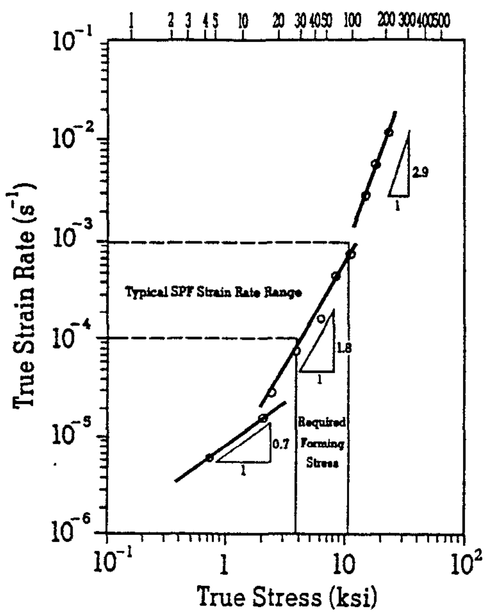

Figure 4. Plot of true rate vs. true stress (both at maximum stress) for INCONEL alloy 718SPF, Heat HT3463EK. For typical SPF strain rates, the required forming stress range is highlighted.

The measure of strain rate sensitivity, m, is calculated from the data of Table 3 and plotted in Figure 5. The m value of INCONEL alloy 718SPF does not reach 0.4 until the initial strain rate is reduced to 10^{-4} s^{-1} suggesting that INCONEL alloy 718SPF is more precisely defined as a near-SPF alloy for the typical SPF conditions employed in industry today.

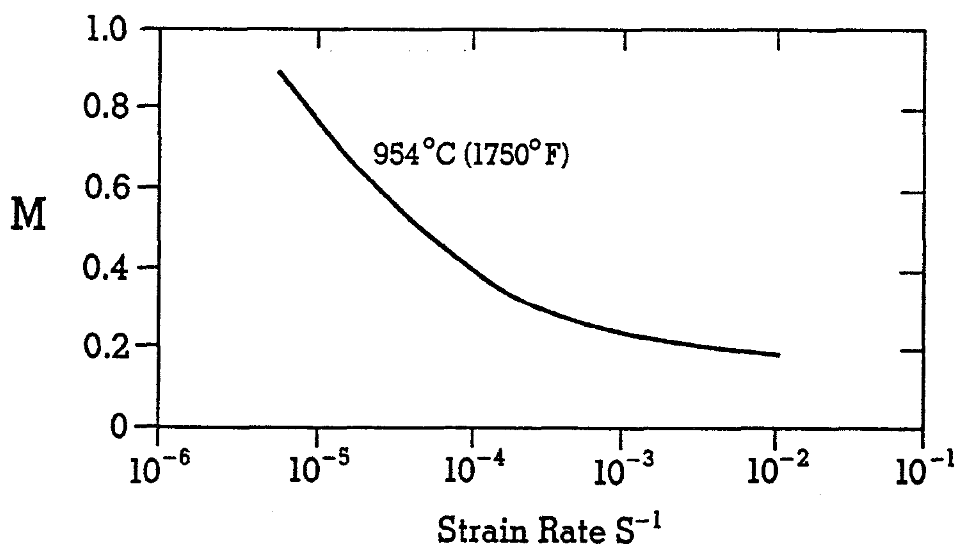

Figure 5. Plot of m values, a measure of strain rate sensitivity versus strain rate at 954°C (1750°F) for INCONEL alloy 718SPF.

Tensile Properties of Superplastically Formed INCONEL alloy 718SPF

The heats of INCONEL alloy 718SPF used in this study were evaluated prior to initiating the SPF study for their tensile and stress rupture properties. See Table 2. Both heats meet the room temperature and 649°C (1,200°F) strength and ductility requirements of ASM 5596G as mill annealed and as aged.

Table 4 compares the mill annealed properties of INCONEL alloy 718SPF with that of superplastically formed material with reductions in gauge of 13%, 19% and 33%. It is noted that under these conditions the alloy exceeds the annealed property maximum requirements of AMS 5596G due to the ultrafine grain size of the material. While grain size remains constant, increased deformation during SPF results in reduced hardness, tensile strength and elongation.

Table 4. Effect of SPF* on Room Temperature Tensile Properties of INCONEL alloy 718SPF 1.22 mm (0.048 in.) Gauge Sheet

		Room Temperature Tensile Properties as Function of Percent Reduction in Gauge		
	Mill Annealed**	13%	19%	33%
0.2% Y.S ., MPa (ksi)	815 (118)	750 (109)	773 (112)	700 (102)
U.T.S., MPa (ksi)	1,114 (162)	1,108 (161)	1,102 (160)	1,003 (146)
Elongation, %	33.0	22.0	22.0	14.0
Hardness, Rc	32	29	27	Rb 99
Grain Size ASTM No.	12	12	12	12

*SPF Conditions: 954°C (1750°F)/2.06 MPa (0.3 ksi)
**Continuous Process Anneal: 927°C (1700°F)/4.57M (15 ft)/ min.

Table 5 shows the criticality of time (0, 0.33 and 1.0h) at 954°C (1,700°F) on restoring aged room temperature tensile ductility (the minimum elongation of AMS 5596G is 12%). Tensile properties and hardness are satisfactory as are tensile properties at 649°C (1,200°F) for the times evaluated. Because of the fine grain size of the post SPF material, it is not possible to achieve stress rupture properties of ASM 5596G without incorporating a grain growth annealing step prior to the aging heat treatment.

Table 5. Effect of Time at An Annealing Temperature of 954°C (1750°F) Prior to Aging* after SPF to 33% Reduction in Gauge

	Room Temperature Tensile Properties			
	0.0 h	0.33 h	1.0 h	AMS 5596G**
0.2% Y.S., MPa (ksi)	989 (143)	1,140 (165)	1,193 (173)	1,034 (150)
U.T.S., MPa (ksi)	1,171 (170)	1,325 (192)	1,372 (199)	1,241 (180)
Elongation, %	6.0	9.0	16.0	12.0
Hardness, Rc	41	44	44	36
	649°C (1200°F) Tensile Properties			
	0.0 h	0.33 h	1.0 h	AMS 5596G**
0.2 Y.S., MPa (ksi)	855 (124)	1,055 (153)	1,001 (145)	827 (120)
U.T.S., MPa (ksi)	1,007 (146)	1,120 (162)	1,155 (168)	1,000 (145)
Elongation, %	26.0	16.0	20.0	5.0

*Aging Conditions: 719°C (1325°F)/8h/FC at 56°C (100°F)/h to 621°C (1,150°F) + 621°C (1,150°F)/8h /AC
**Minimum Properties

Cavitation

The propensity of INCONEL alloy 718SPF to form pores during superplastically forming (cavitation) was measured (using an image analysis software package) by metallographic examination of the tensile specimens tested to fracture at varying initial strain rates at 954°C (1,750°F) as exemplified in Table 6. This alloy is subject to cavitation during SPF with the degree of cavitation increasing with decreasing initial strain rate. At an initial strain rate of 10^{-2} s^{-1}, the area of cavitation, as measured near the fracture tip, is less than 0.01% for a tensile elongation of 150%. However, the degree of cavitation increases at a strain rate of 10^{-3} s^{-1} to 2.0% (369% elongation); becoming 10.3% at a strain rate of 10^{-5} s^{-1} (538% elongation). Table 6 shows that as the strain rate is decreased, the average cavity size and roundness coefficient increases. The average roundness coefficient is an indication of the degree of diffusion associated with cavity growth. A roundness coefficient of one indicates a perfect circular shape while a smaller value of the roundness coefficient relates more to cavity elongation. The increase in roundness coefficient at the strain rate of 10^{-3} s^{-1} or less suggests that cavity growth by diffusion is becoming increasingly significant for decreasing strain rates (longer times at temperature).

Table 6. The Effect of Strain Rate at 954°C (1750°F) on The Size and Area of Cavitation of INCONEL alloy 718SPF The Average Roundness Coefficient of The Cavities Is Also Presented

Strain Rate, s^{-1}	1.3×10^{-2}	1.3×10^{-3}	6.7×10^{-5}
Total Elongation[1],%	150.0	369.0	538.0
Cavitation Area[2],%	<0.01	2.60	10.60
Avg. Cavity Area, um^2	5.20	145.0	580.0
Avg. Roundness Coefficient[3]	0.47	0.63	0.63

[1]Specimen tested to fracture.

[2]Based on a measured area of 0.83 mm^2 near the fracture tip.

[3]Defined as $(4\pi$ area)/perimeter$)^2$ where a value of 1.0 represents a perfect circle and values less than 1.0 represent deviation from a circle.

Because SPF components are normally produced at strain rates of 10^{-3} s^{-1} to 10^{-4} s^{-1} with actual total elongations of less than 200%, four INCONEL alloy 718SPF specimens were evaluated at 954°C (1,750°F) for strains of 86% and 194% at an initial strain rate of 10^{-3} s^{-1} and for strains of 73% and 132% at an initial strain rate of 10^{-4} s^{-1}. The area of cavitation was measured metallographically using an area of 0.83 mm^2 (0.0012 in^2) from the gauge length. The results are presented in Table 7 and are combined with the results of Table 6 in Figure 6. The data show that increasing elongation and decreasing strain rate, increase the area of cavitation. However, at total elongations of less than 200% at either a strain rate of 10^{-3} or 10^{-4} s^{-1}, the area of cavitation is less than 0.5% and can be held below 0.1% for elongations of less than 100% at a strain rate of 10^{-3} s^{-1}. Typical cavity size, as shown in Table 7, is again larger for the slower strain rate and greater total elongation. Cavitation tends to nucleate and grow around inclusions present in the alloy. Analysis of the number of cavities of a given size as a function of total strain shows a significant increase in the number of cavities within the smallest size range examined (0 to 2 μm^2) as the elongation increases, supporting the concept that cavities are continuously being nucleated throughout the test. Thus, the extent and distribution of inclusions becomes an important issue in superplastic forming of INCONEL alloy 718SPF.

Table 7. **The Effect of Strain Rate and Total Strain at 954°C (1750°F) on the Size and Area of Cavitation of INCONEL alloy 718SPF**

Initial Strain Rate, s^{-1}	1.3×10^{-3}	1.3×10^{-4}	1.3×10^{-3}	1.3×10^{-4}
Total Strain, %	86.0	73.0	194.0	132.0
Cavitation Area, %	0.04	0.18	0.45	0.34
Avg. Cavity Size, um^2	2.40	8.90	10.50	11.20

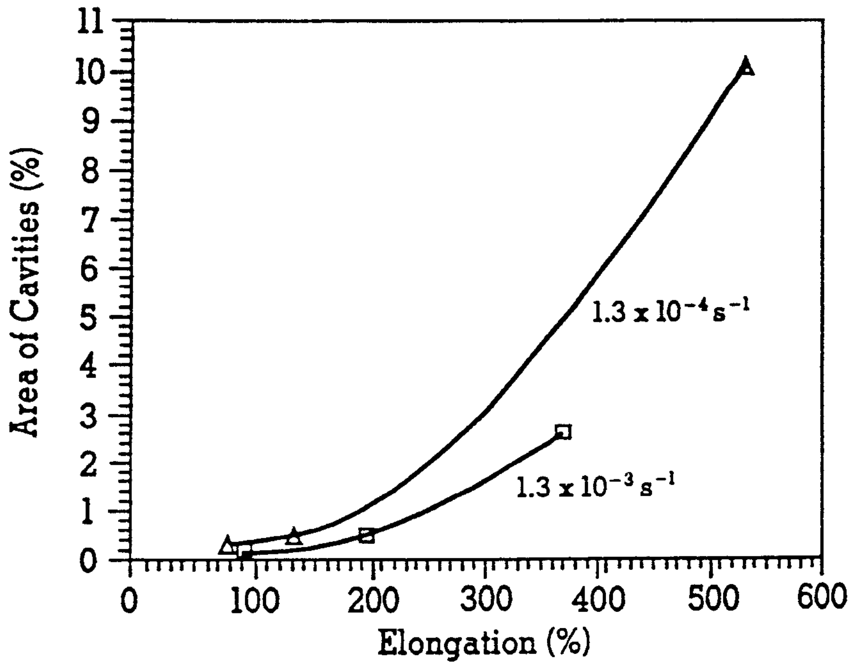

Figure 6. Plot of Percent Area of Cavitation Versus Total Elongation for Two Typical Strain Rates at 954°C (1750°F for INCONEL alloy 718SPF.

Summary

The aim of this paper is to show the applicability of INCONEL alloy 718SPF to current superplastic forming practice and equipment; to describe the processing parameters and to define the properties and microstructure of superplastically formed material. Based on this effort, a number of conclusions can be drawn:

1. INCONEL alloy 718SPF can be produced with an ASTM grain size of #10 or smaller and, subsequently, superplastically formed at 954°C (1750°F) using argon gas pressures of 2.1 MPa (300 psi).

2. For INCONEL alloy 718SPF, the elongation to failure increases markedly with decreasing strain rate, exceeding 350% at an initial strain rate of $1.3 \times 10^{-3} s^{-1}$, 450% at $1.3 \times 10^{-4} s^{-1}$ and 750% at $3.3 \times 10^{-5} s^{-1}$.

3. For INCONEL alloy 718SPF, the maximum true stress decreases with decreasing strain rate becoming less than 71.7 MPa (10.4 psi) at an initial strain rate of $1.3 \times 10^{-3} s^{-1}$ and less than 27.6 MPa (4 psi) at $1.3 \times 10^{-4} s^{-1}$.

4. INCONEL alloy 718SPF retains its original tensile properties after superplastic forming, at least, through engineering strains approximating 200%.

5. AMS aged tensile properties are achieved through standard aging heat treatments.

6. The development of cavities at tensile failure is insignificant at a strain rate of 10^{-2} s^{-1} (less than 0.01% by area) but becomes increasingly important as the strain rate decreases.

References

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