Ultra Fine Grain Processed UDIMET® Alloy 718 for Isothermal Forging

C. A. Petri, T. Deragon, and F. A. Schweizer, Special Metals Corporation, New Hartford, NY
and J.J. Schirra , Pratt - Whitney Aircraft , East Hartford, CT

Abstract

Laboratory trials indicate ultra fine grain UDIMET® Alloy 718 exhibits mechanical processing characteristics compatible with isothermal forge processing requirements over the temperature range 954 °C to 1010 °C. The combination of the ultra fine grain billet and a dual strain rate process provides the optimal flow stress. The two step process minimizes the effects of strain rate sensitivity and takes advantage of the recrystallization that occurs during the initial forging reduction. Production scale forging trials are planned to verify the subscale trends and to characterize the mechanical properties of the material in large cross-sections.

Superalloys 718, 625, 706 and Various Derivatives
Edited by E.A. Loria
The Minerals, Metals & Materials Society, 1997

Introduction

Gatorizing TM is a low strain rate, isothermal forging process that utilizes the lower flow stresses associated with very fine-grained materials. Gatorizing offers the advantage of near-net-shape forging which results in lower input weight and lower machining costs per part. This process has been extensively used in the forging of powder metal superalloys. Cast-wrought processing generally does not provide the very fine grain structure needed for the Gatorizing process.

Much work has been done to control the grain size in nickel-iron base superalloys during ingot conversion. Muzyka[1] suggested using the available phases such as delta in Alloy 718 or eta in Alloy 901 or Alloy A286 to pin the grain boundaries restricting grain growth. E. E. Brown et al[2] utilized this concept and developed a method to produce extremely fine grain structures (ASTM 10 or finer) in Alloy 901 and Alloy 718, termed MINIGRAIN processing. This process utilizes a heat treatment to precipitate the phase and subsequent forging below the delta or eta solvus, which acts as a barrier to grain growth. High forging reductions are used to develop a uniform dispersion of the phase.

For ingot-to-billet conversion, a modification of the MINIGRAIN process has been used to produce reforge stock with grain sizes ASTM 10 or finer. The process, designated delta-processed or ultra fine grain, incorporates a sub delta solvus heat treatment to precipitate delta needles in the gamma matrix. Subsequent cogging at subsolvus conditions with spheroidal delta phase present restricts grain coarsening. The forgeablity of delta-processed Alloy 718 billet has been evaluated for conventional closed die forging by several investigators.[3-6]

The purpose of this work was to determine if ultra fine grain UDIMET Alloy 718 was amenable to the Gatorizing process. Strain-rate-controlled tensile testing and subscale compression trials were performed on ultra fine grain material to determine the flow stresses and forged structures.

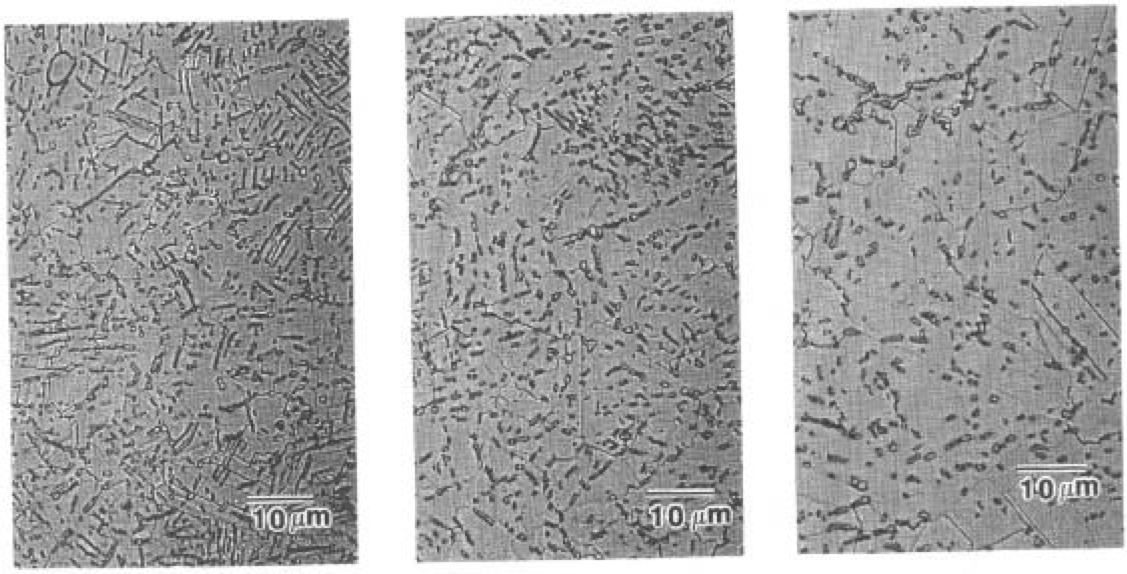
Experimental Procedure

Material Processing The UDIMET Alloy 718 material utilized for the experiment was produced by VIM +ESR +VAR melting sequence. The composition of the starting material was consistent with AMS 5662 requirements, as indicated in Table I.

Table I The chemical composition of Alloy 718

Heat (wt%)	C	Mn	S	Fe	Ni	Cr	Al	Ti	Mo	Cb+Ta
915757	.03	.07	.0002	18	54	18	0.5	1.0	3.0	5.3
AMS 5662 min	----	----	----	----	50	17	0.2	0.65	2.80	4.80
max	.08	0.35	.015	REM	55	21	0.8	1.15	3.30	5.55

Conversion from ingot to billet incorporated an intermediate heat treatment operation to promote the precipitation of delta phase. Subsequent conversion operations were performed below the delta solvus to develop an ultra fine grain microstructure. The resulting grain size of the finished 19 cm diameter billet was ASTM 12 at the edge of the billet, coarsening to ASTM 9 at the center of the billet. The billet microstructure consists of a uniform matrix with spheroidal delta at the grain boundaries, as indicated in Figure 1.



Billet Outer Diameter (UFG6)
ASTM 12.2 +/- 0.4

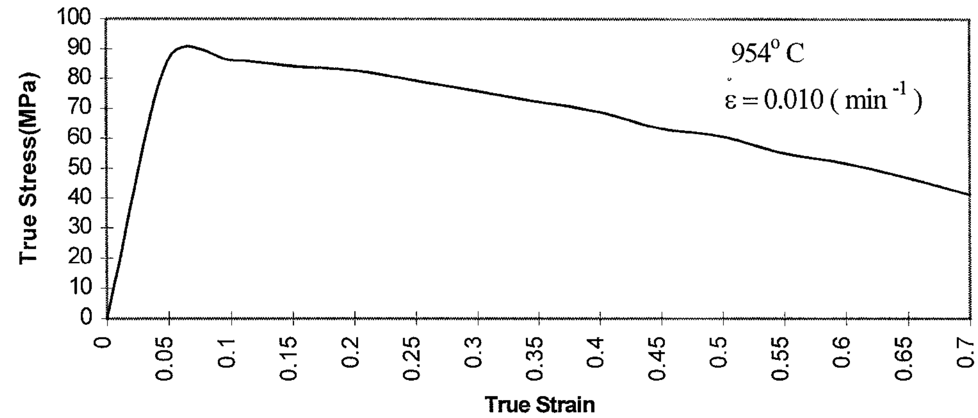
Billet Mid - Radius (UFG7)
ASTM 10.3 +/- 0.3

Billet Center (UFG8)
ASTM 9 +/- 0.7

Figure 1 - The microstructure of ultra fine grain Alloy 718 billet. Spheroidal delta phase present at the grain boundaries. (Kallings Etchant)

Controlled -Strain-Rate Tensile Testing Controlled-strain-rate tensile tests were performed to determine the optimum working conditions for triple melt, ultra fine grain Alloy 718 reforging billet. An MTS 810 Electro Hydraulic Tensile Testing Machine was used to conduct the testing. A standard laboratory cylindrical furnace and proportional analog controllers were used for temperature control. Stroke rate control was obtained using a Linear Voltage Displacement Transducer (LVDT) in the column. The data was collected by a Data Pro data acquisition unit.

The tensile specimens were heated to the test temperature and held for thirty minutes prior to applying the load. The samples were tested at 954 °C, 982 °C, 996 °C , 1010 °C, and 1038 °C. The strain rate was evaluated over the range of 4.98×10^{-3} min^{-1} to 1.698 min^{-1} for each test temperature. Selected tests were performed with a stepped-strain-rate test procedure to evaluate the strain rate sensitivity. The test temperature was held constant during the stepped-strain-rate test. The strain rate was varied from a lower strain rate to a higher strain rate and then reduced to the lower strain rate before the completion of the test. [7] The peak flow stresses of Alloy 718 were determined from the true-stress versus true-strain curves produced by the computer data collection system. Representative stress strain curves from the two test practices are presented in Figure 2. The tensile samples were sectioned longitudinally, metallographically prepared, and examined.



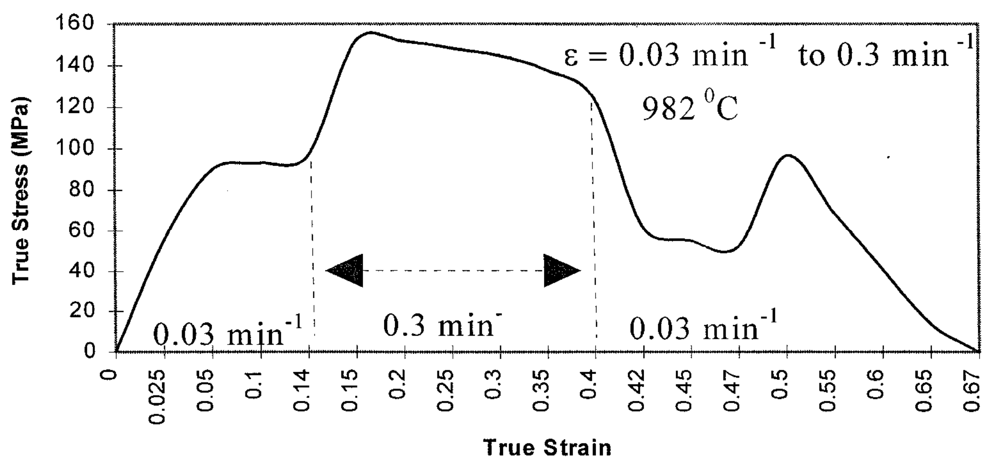


Figure 2 - Representative true-stress versus true-strain curves from the two test practices for ultra fine grain Alloy 718 billet .

Compression Trials Test blanks (2.54 cm dia. X 7.62 cm long) were machined from the outer diameter, mid-radius, and center billet positions. Isothermal forging trials were conducted on a 226,800 kg subscale forging press at the PWA West Palm Beach facility. The samples were forged to a final thickness of 1.27 cm (83% reduction in thickness) at 4 °C (25°F) intervals between 954 °C and 1010 °C and at strain rates of 0.05 to 0.1 min^{-1}.

After initial trials, several tests were performed at 996°C using a two step upset practice, first forging at a strain rate of 0.05 min^{-1} to 50% reduction followed by forging at 0.1 min^{-1} for the balance of the reduction. Segments of each forged pancake were metallographically evaluated in the as-forged condition. Segments were then processed through simulated solution heat treatment cycles of 954°C, 982°C, and 1004°C for 1 hour followed by an air cool and metallographic evaluation.

Results / Discussion

Controlled-Strain-Rate Tensile Testing The tensile peak flow stress results are given in Table II. A significant drop in peak flow stress was observed at all temperatures when lowering the strain rate from 0.5 min^{-1} to 0.01 min^{-1}. This suggests that the Gatorizing strain rate needs to be lower then 0.5 min^{-1} and close to 0.01 min^{-1}. To further determine the optimum strain rate, stepped-strain-rate tests were conducted; these results are given in Table III and representative curves are plotted in Figure 2. This test provides a means to establish the strain rate sensitivity exponent M at various processing conditions in accordance with: [7]

$$M = \frac{\log(\sigma_2 / \sigma_1)}{\log(\dot{\varepsilon}_2 / \dot{\varepsilon}_1)}$$

These results support and better define the flow stress results, suggesting that the Gatorizing strain rate should be lower then 0.3 min^{-1}. It is interesting to note that the strain rate sensitivity for the ultra fine grain material approached 0.3 for the test conditions used, as indicated in Figure 3. Metals generally have a strain rate sensitivity value (M) less than 0.1 at room temperature and from 0.1 to 0.2 in the hot working region.[7] The low value of M indicates that this material does not exhibit sufficient strain rate sensitivity necessary for superplastic deformation (M > 0.3) under these conditions. [7]

Table II - Controlled-Strain-Rate Tensile Flow Stress Results for Ultra Fine Grain Alloy 718 Billet

Peak Flow Stress (MPa)				
ε $(min)^{-1}$	954°C	982°C	1010°C	1038°C
0.498	186	172	152	121
0.01002	86	76	59	48
0.00498	79	62	55	41

Table III - Stepped-Controlled-Strain-Rate Tensile Results for Ultra Fine Grain Alloy 718 Billet

Peak Flow Stress (MPa) For The Changing-Strain-Rate Tensiles					
Changing-Strain-Rate ε $(min)^{-1}$	954°C	982°C	996°C	1010°C	1038°C
1.398 to 1.698	----	200 to 207	----	172 to 179	----
0.702 to 1.002	----	145 to 152	----	159 to 165	----
0.3 to 0.498	----	----	152 to 169	----	----
0.03 to 0.3	110 to 179	97 to 152	----	76 to 124	69 to 110

%Elong. From The Changing-Strain-Rate Tensile Samples					
Changing-Strain-Rate ε $(min)^{-1}$	954°C	982°C	996°C	1010°C	1038°C
1.398 to 1.698	----	91	----	103	----
0.702 to 1.002	----	93	----	87	----
0.3 to 0.498	----	----	86	----	----
0.03 to 0.3	99	102	----	102	109

Table IV - Summary of Strain Rate Sensitivity for the Controlled-Strain-Rate Tensile Tests for Ultra Fine Grain Alloy 718 Billet

	Strain Rate Sensitivity M				
Changing-Strain-Rate (min^{-1})	954 °C	982 °C	996 °C	1010 °C	1038 °C
0.702 to 1.002		0.13		0.12	
0.300 to 0.498			0.21		
0.030 to 0.300	0.21	0.20		0.21	0.20
0.005 to 0.010		0.29			

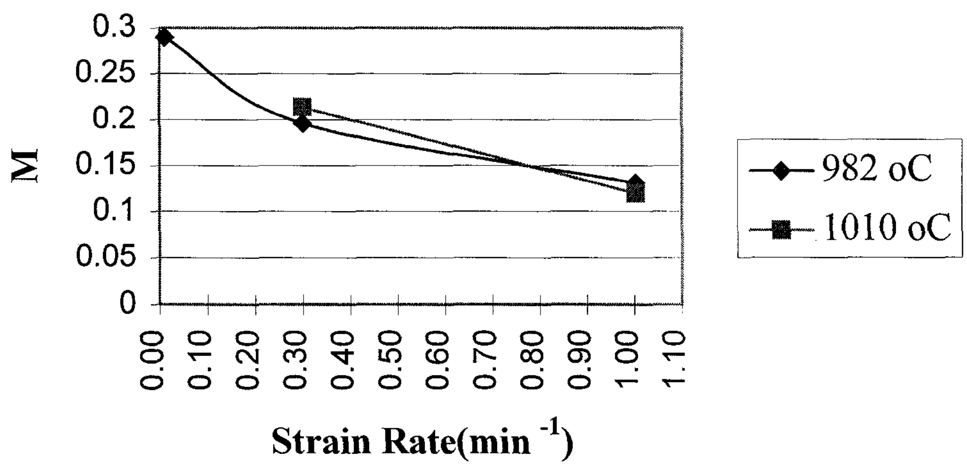
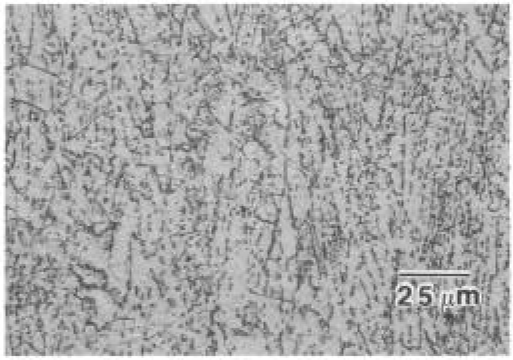
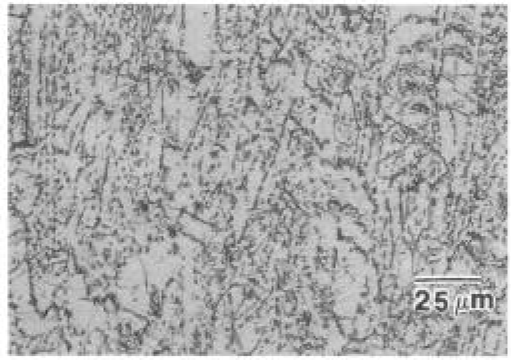


Figure 3 - Calculated strain rate sensitivity for the 982°C and 1010°C controlled strain rate tests for ultra fine grain Alloy 718 billet.

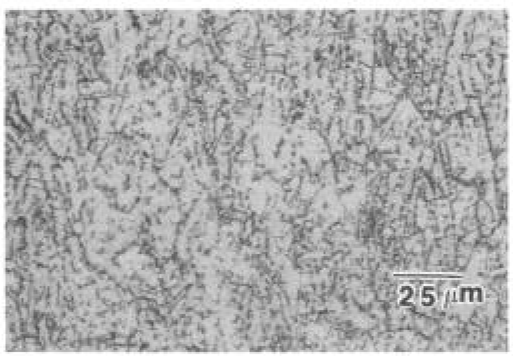
The microstructures evaluated after the controlled-strain-rate tensile testing exhibit a uniform grain size with a secondary spheroidal delta phase, as presented in Figure 4 and Table V. The grain size was evaluated in the tensile specimens slightly above the threaded region. A small amount of grain growth is evident in the ultra fine grain Alloy 718 with an increase in test temperature at the lower strain rates of 0.005 to 0.01. The grain coarsening evident at the higher strain rate of 0.5 min^{-1} for a given temperature may have been caused by the coarser starting grain size of the tensile specimens. Some of the tensile specimens were obtained near the center section of the billet having an ASTM 9 grain size. In general, the billet grain size was retained for temperatures below the delta solvus (996 °C). At temperature above the delta solvus, grain coarsening occurred.



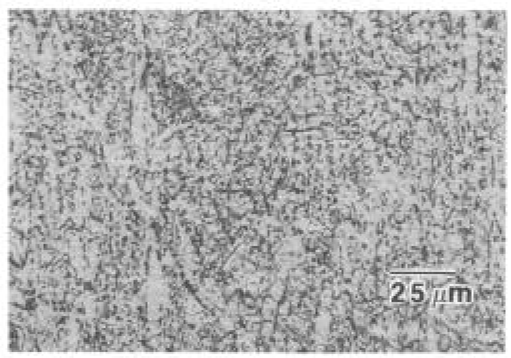
954°C



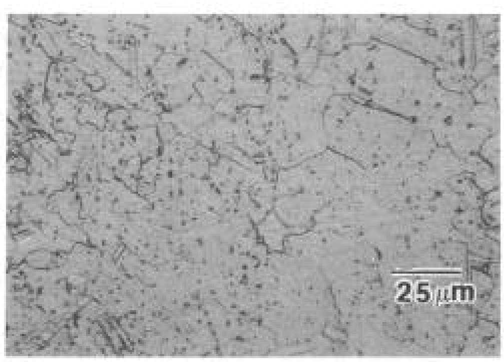
982°C



996°C



1010°C



1038°C

Figure 4 - Ultra fine grain UDIMET Alloy 718 with a secondary delta phase at the grain boundaries in the tensile samples tested at the indicated temperature. (Kallings Etchant)

Table V - Controlled-Strain-Rate Tensile Grain Size Results for Ultra Fine Grain Alloy 718

ASTM Grain Size From The Tensile Samples				
ε (min)$^{-1}$	954°C	982°C	1010°C	1038°C
0.498	7 to 9	8 to 9	6 to 8	8.5
0.01002	10	10	9.5	8.5, 30 % ALA 6
0.00498	10 , 10% ALA 7	10 , 3% ALA 7	9, 20 % ALA 6	8.5, 20 % ALA 5

ASTM Grain Size From The Tensile Samples For The Changing-Strain-Rate Tensile Tests					
Changing ε (min)$^{-1}$	954°C	982°C	996°C	1010°C	1038°C
1.398 to 1.698	----	9	----	9	----
0.702 to 1.002	----	10	----	8.5	----
0.3 to 0.498	----	----	8.5	----	----
0.03 to 0.3	8 to 9	7 to 8	----	8 to 9	8

Hot Compression Testing Flow stress data for the various compression trials are summarized in Table VI. In general, flow stress decreased with increased forging temperature. Furthermore, the results exhibit a decrease in flow stress with increased reduction in thickness which is probably due to dynamic recrystallization occurring during the testing. Comparison of these flow stresses to those previously observed on standard fine grain material (ASTM 9)[8] shows a significant (28%) reduction in flow stress at 1010°C. The correlation of flow stress and grain growth in ultra fine grain Alloy 718 is representative of the correlations seen in other studies conducted on delta-processed 718.[6]

Table VI - Summary of the Hot Compression Flow Stresses for Ultra Fine Grain Alloy 718

Compression Sample			Forging		Flow Stress (MPa)	
Compression ID	Billet Location	Grain Size	Temperature	Strain Rate	Maximum	Running
UFG1	Outer Diameter	ASTM 12.2	954 °C	0.1 min^{-1}	172	124
UFG6	Outer Diameter	ASTM 12.2	982 °C	0.1 min^{-1}	138	110
UFG2	Outer Diameter	ASTM 12	1010 °C	0.1 min^{-1}	124	110
UFG3*	Outer Diameter	ASTM 12	996 °C	.05 min^{-1}	117	110
				0.1 min^{-1}	103	97
UFG 8*	Center	ASTM 9	996 °C	.05 min^{-1}	131	117
				0.1 min^{-1}	103	97

* Dual strain rate forging trials. Forged at 0.05 min^{-1} to 50% reduction followed by forging at 0.1 min^{-1}.

These trends were validated in the dual strain rate forging trials where the slower strain rates resulted in reduced flow stresses for both billet center and outer diameter. When the strain rate was increased from 0.05 to 0.1 min^{-1} at 50% reduction in the thickness, little increase in flow stress was observed, as indicated in Figure 5. Dynamic recrystallization during the initial reduction at the slower strain rate appears to refine the grain size and reduce the flow stress, allowing the process to be continued at a higher strain rate.

Table VII presents the grain sizes from the compression samples as a function of forging temperature, strain rate, and heat treatment. As-forged grain size was refined with decreasing forging temperature ranging from ASTM 12 at a forging temperature of 1010°C to ASTM 13-14 at a forging temperature of 954°C. For all temperatures there was evidence of grain coarsening in the as-heat-treated compression samples. The degree of coarsening was a function of temperature and the as-forged grain size. Typical microstructures are presented in Figure 6.

Over a 50°C solution heat treat window (954°C - 1004 °C), subsolvus Gatorized material can produce a grain size finer than ASTM 7, which is consistent with the requirements for welded high compressor rotors.

To further investigate compatibility with production Gatorizing facilities, full scale forging, heat treatment, and mechanical property characterization will be performed.

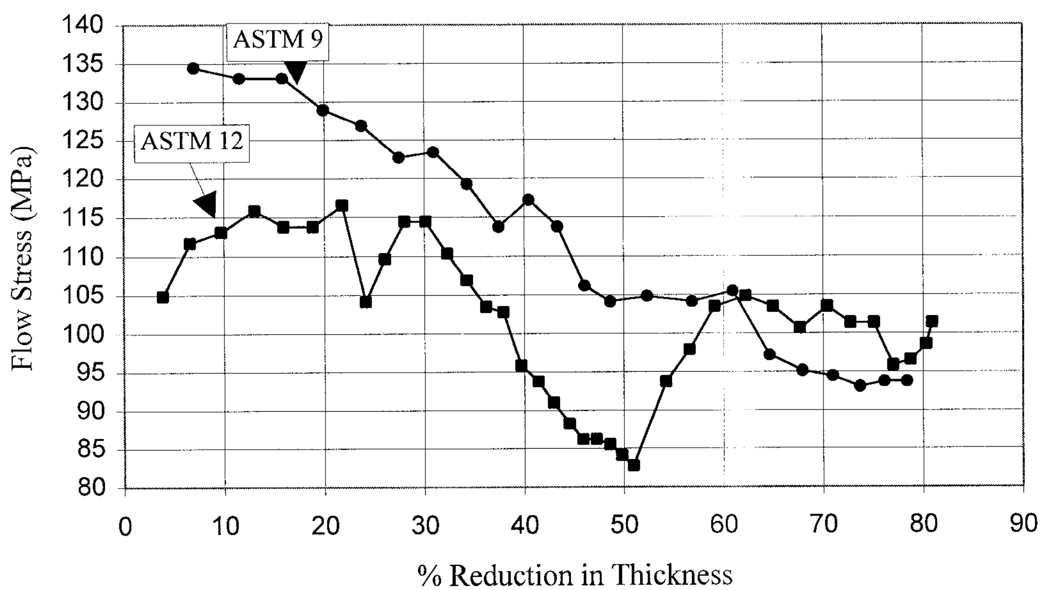
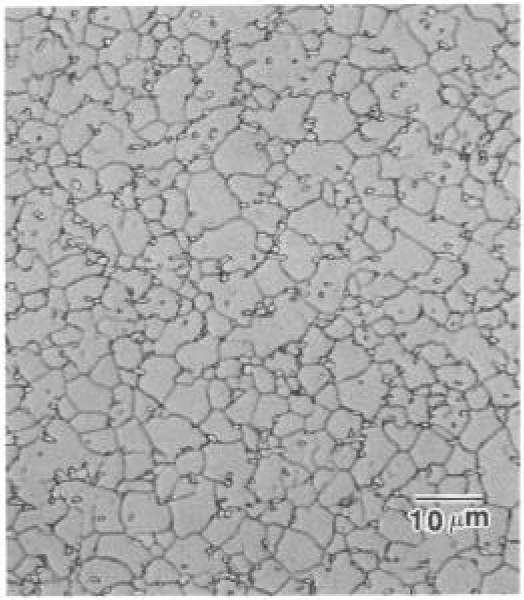


Figure 5 - Flow stress vs. reduction in thickness for ultra fine grain Alloy 718 material. All forgings conducted at a test temperature of 996 °C. A two step process strain rate of 0.05 min^{-1} to 50% reduction followed by 0.1 min^{-1}.

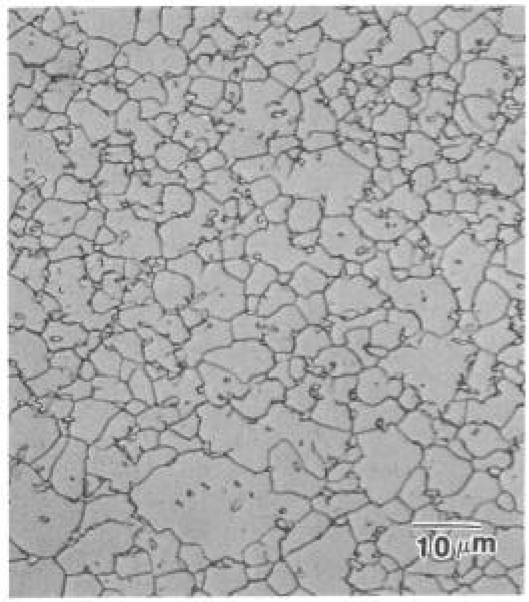
Table VII - Summary of Isothermally Forged and Heat-Treated Grain Sizes for Ultra Fine Grain Alloy 718.

Compression Sample			Forging	Forged and Heat-Treated ASTM Grain Size			
Compression ID	Billet Location	Grain Size	Temperature	As Forged	954 °C	982 °C	1004 °C
UFG1	Outer Diameter	ASTM 12.2	954 °C	13.6	12.8	10.3	8.7
UFG6	Outer Diameter	ASTM 12.2	982 °C	12.8	12.6	8.8	8.6
UFG2	Outer Diameter	ASTM 12	1010 °C	12	10.5	9.1	7.9
UFG3*	Outer Diameter	ASTM 12	996 °C	12.2	11.7	7.8	7.9
UFG 8*	Center	ASTM 9	996 °C	12.2	12.1	8.7	8.2

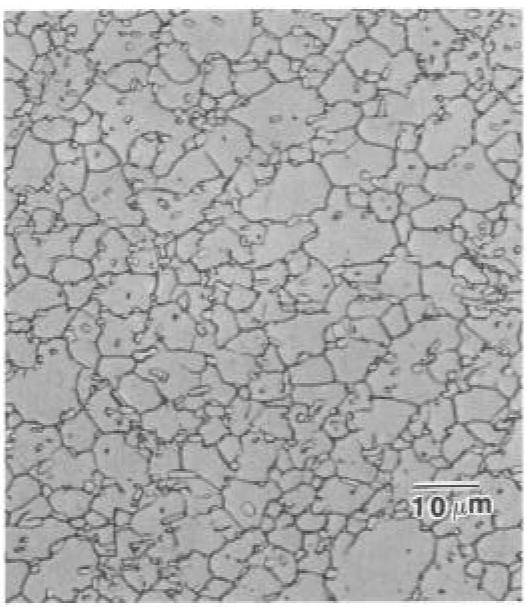
* Dual strain rate forging trials. Forged at 0.05 min^{-1} to 50% reduction followed by forging at 0.1 min^{-1}.



As-Forged (UFG3) Outer Diameter



As-Forged (UFG8) Center



As-Forged (UFG3) + 954°C / 1 Hr / AC

Figure 6 - Microstructure of the compression samples in the as-forged condition and after a 954 °C / 1 Hr / AC heat treatment. (Kallings Etchant)

Conclusions

1. Delta-processed Alloy 718 billet grain size (ASTM 11-12) is fine enough to sufficiently reduce flow stresses to below 100 MPa at temperatures below the delta solvus (954°C-996°C).

2. This reduction in flow stress should be sufficient to allow Alloy 718 to be Gatorized at subsolvus temperatures.

3. At subsolvus temperatures (954°C-996°C), the gatorizing process results in recrystallization to a uniform fine grain size.

4. Dual strain rate Gatorizing, using a low initial strain rate followed by a higher strain rate, can be used to refine a coarse starting structure and lower the flow stress for the second step.

References

1. D. R. Muzyka, "Met. Eng. Q.",11,12 (1971).

2. E.E. Brown, R.C. Boetlner, and D.L. Ruckle, Superalloy - Processing, Battelle Columbus Laboratories, Columbus, Ohio MCIC - 72 - 10 , 1972..

3. A.W. Dix, J. M. Hyzak, and R.P. Singh, "Applications of Ultra Fine Grain Alloy 718 Forging Billet.", Superalloys 1992, (Warrendale, PA: The Metallurgical Society, 1992), pp. 23 - 32.

4. C. Ruiz, A. Obabueki, and K. Gillespie, "Evaluation of the Microstructure and Mechanical properties of Delta Processed Alloy 718." , Superalloys 1992, (Warrendale, PA: The Metallurgical Society, 1992), pp. 33 - 42.

5. T. Banik, S.O. Mancuso, and G. E. Maurer, " An Evaluation of the Forgeability of Delta Processed Udimet Alloy 718DP", Superalloy 718, 625, 706 and Various Derivatives; (Edited by E.A. Loria; 1994) Conference Proceedings.

6. T. Banik, P.W.Keefe, G.E. Maurer, and L.Petzold, "Ultra Fine Grain / Ultra Low Carbon 718", Superalloy 718, 625 and Various Derivatives; (Edited by E.A. Loria; 1991) Conference Proceedings.

7. Dieter, Mechanical Metallurgy; (McGraw - Hill, 1986), pp 297 - 301.

8. J.Schirra, personal communication.