FULL SCALE GATORIZING^{TM} OF FINE GRAIN INCONEL 718

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Abstract

Previous subscale work showed that commercially available fine-grained Inconel 718 billet could be successfully Gatorized at parameters that would be compatible with current forging facilities. Additional work including full scale forging trials was recommended and has subsequently been completed. Two mults from the heat used to conduct the subscale forging trials were procured and used for full scale forging trials at Pratt & Whitney's Gatorizing facility in Columbus, GA. Two forging processes were used to assess the forging characteristics of the fine grain material. Both trials were conducted as two step processes and with an intermediate "delta dumping" to promote grain refinement and superplasticity in the final forging. Based on forging stress measurements, the more successful process was the one that maximized grain refinement prior to final forging. Complete die travel was achieved together with nearly complete die fill. As forged the material exhibited an extremely uniform and homogeneous grain size and post forging heat treatment trials were then conducted to establish the microstructural response. In addition, mechanical property testing (tensile, stress rupture and fatigue) was conducted and the material exhibited properties comparable to premium quality rotor grade conventional hot die or hammer forgings.

Superalloys 718, 625, 706 and Various Derivatives
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^{TM}Gatorizing – Trademark of United Technologies

Introduction

Gatorizing™ is an isothermal forging process utilizing slow strain rates to promote superplastic deformation of very fine-grained material at low flow stresses. By its very nature, near-net-shape forgings can be made with lower input weights and reduced machining costs. This process is extensively used in the forging of powder metal (PM) superalloys because of the very uniform and fine grain size achieved in the extruded billet as well as the high cost associated with the PM product. However it is not typically used in the forging of cast and wrought processed alloys because they do not offer the very fine-grained structure needed for the Gatorizing process.

There had been much work to obtain fine-grained billet during conversion from ingot. Studies with alloys such as 718, 901, or A286 succeeded in producing fine-grained billet by using precipitating phases to restrict grain growth [1-3], and among these processes, the "delta processed" 718 was capable of yielding average grain size of ASTM 11 in the billet [3]. The delta processed billet was used in the forgeability studies in conventional closed die forging [4-6], and more recently, in the study of Gatorizing through subscale forgings [7].

The subscale Gatorizing work above showed that commercially available Inconel 718 billet could be successfully Gatorized within limits of current forging facilities. The purpose of the present work is to extend the subscale work to full size forging, evaluate and establish Gatorizing parameters required in the full size forging, and evaluate part properties in comparison to premium quality rotor grade conventional forgings.

Experimental Procedure

The UDIMET Alloy 718 used in the Gatorizing process development was produced by sequences of vacuum induction melting (VIM), electro-slag remelting (ESR) and vacuum arc remelting (VAR). The chemical composition is given in Table I and met the AMS 5662 requirements.

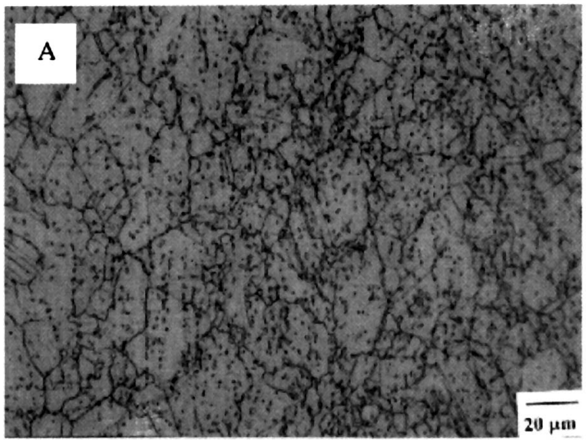
Table I: Chemical Composition of UDIMET Alloy 718

Heat		C	Mn	S	Fe	Cr	Al	Ti	Mo	Cb+Ta	Ni
7059-1	wt%	0.033	0.08	0.0005	Bal.	17.7	0.59	0.97	2.86	5.36	52.8
AMS5662	min	-	-	-	-	17	0.2	0.65	2.80	4.80	50
AMS5662	max	0.08	0.35	0.015	Bal.	21	0.8	1.15	3.30	5.55	55

The ingot was converted using processing sequences to develop an ultra fine-grained billet microstructure. The conversion by "delta processing" was described elsewhere[3]. Example of the billet microstructure is shown in Figure 1. The billet diameter was 19 cm, and the grain sizes were ASTM 12 at the edge and ASTM 9 at the center of the billet.

In the full-size Gatorizing experiment, tooling used to produce a contoured disk from conventional PM billet was selected for the forging trials. The die was about 60 cm in dia. and 8 cm in thickness at the rim. A two-step Gatorizing (isothermal forging) process consisting of an initial flat pancake operation to convert the microstructure to a finer grain size for improved superplasticity in the second forging step was defined. The second step was a contoured-forging operation to demonstrate near-net-shape capability. Two step forging processes are routinely used in producing PM superalloy forgings.

The flow stresses of the billet material were determined using isothermal tensile tests in earlier work[7]. Figure 2 shows the peak flow stresses for several strain rates and test temperatures. In the finish, contour forging step, conditions were selected to keep the maximum stress below 250 MPa from die stress considerations. Higher stress in the pancake operation was however



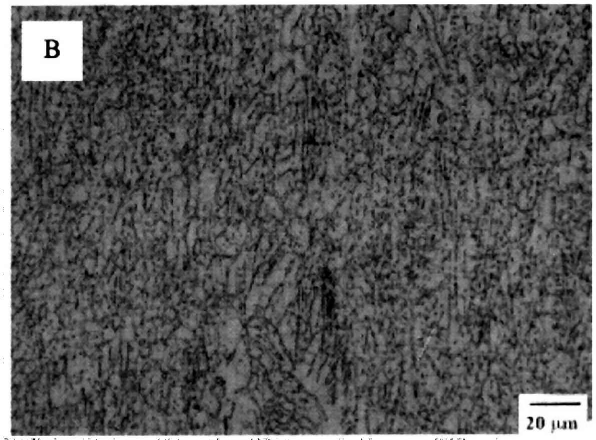


Figure 1 – As-received microstructure of fine-grained billet: (A) Billet center location, and (B) Billet edge location.

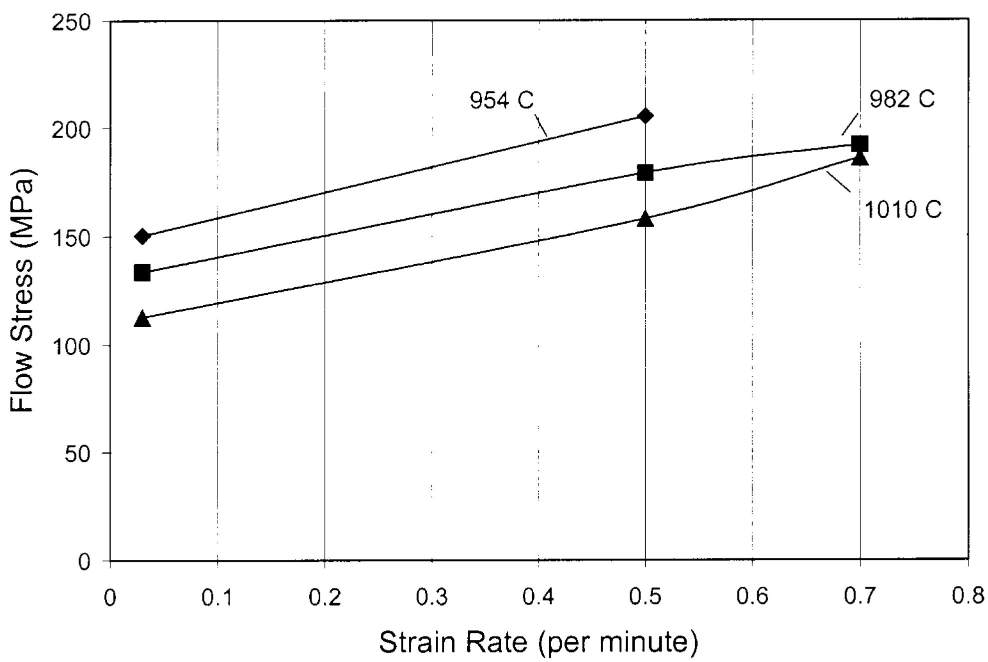


Figure 2 – Flow stresses of the fine-grained billet at several strain rates and temperatures.

acceptable due to absence of any contour in the die. Two pancake forging conditions were employed: (a) 954°C(1750°F), 0.3 per min. strain rate (higher peak stress, FG718-001), and (b) 982°C(1800°F), 0.05 per min. strain rate (lower peak stress, FG718-002)

The flow stress tests of the billet material also showed that the peak stress was followed by reduction in the flow stress due to dynamic recystallization of the forging mult. The reduced flow stress of the pancake was then exploited in the final 2nd step contour forging. The final forging was carried out at lower temperature (954°C for FG718-001 and 968°C for FG718-002) to prevent any growth of the refined grain size in the pancake forgings. A low strain rate of 0.05 per min. was used to promote superplasticity.

Two forgings were made using conditions described above. Both as-forged and heat treated microstructures were evaluated. The heat treatment consisted of solution at 954°C/2 hr followed by oil quench and aging at 718°C/8 hrs. and furnace cool to 621°C/8 hrs. One forging (FG718-001) was subjected to mechanical property characterization. Tensile tests were done at room temperature (RT), 538°C and 649°C. Creep tests were done at 649°C/758 MPa and the combination stress-rupture tests at 649°C/758 MPa and 704°C/413 MPa. The low cycle fatigue (LCF) tests were done using notched specimens with K_t=2.55 at RT, 288°C and 607°C.

Results

Pancake Forging and Microstructure: The pancake forging produced was of approximate size 46 cm dia. and 5.8 cm thick For the two forging conditions the flow stresses calculated from press tonnage are shown in Figure 3 as a function of ram position. For pancake FG718-001, the lower temperature/higher strain rate produced a peak stress of about 250 MPa, which decreased to 100-125 MPa due to dynamic recryatallization. For pancake FG718-002, the higher temperature/lower strain rate helped to reduce the peak stress to about 150 MPa, which further decreased to 70 MPa also due to dynamic recrystallization. The above two conditions provided pancake materials with microstructures shown in Figure 4. The FG718-001 exhibited an average grain size of ASTM 12-13 with about 5% ASTM 11. The FG718-002 exhibited an average grain size of ASTM 11-12 with isolated (<5%) ASTM 8.

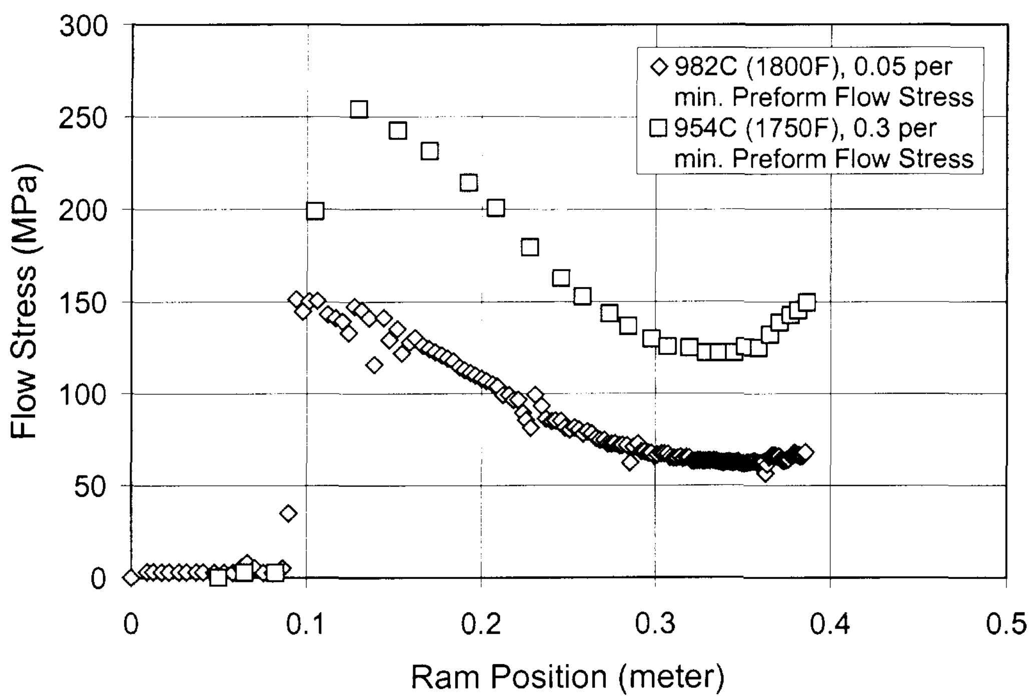


Figure 3 – Flow stresses with ram position in the initial pancake forging (shown for two forging conditions).

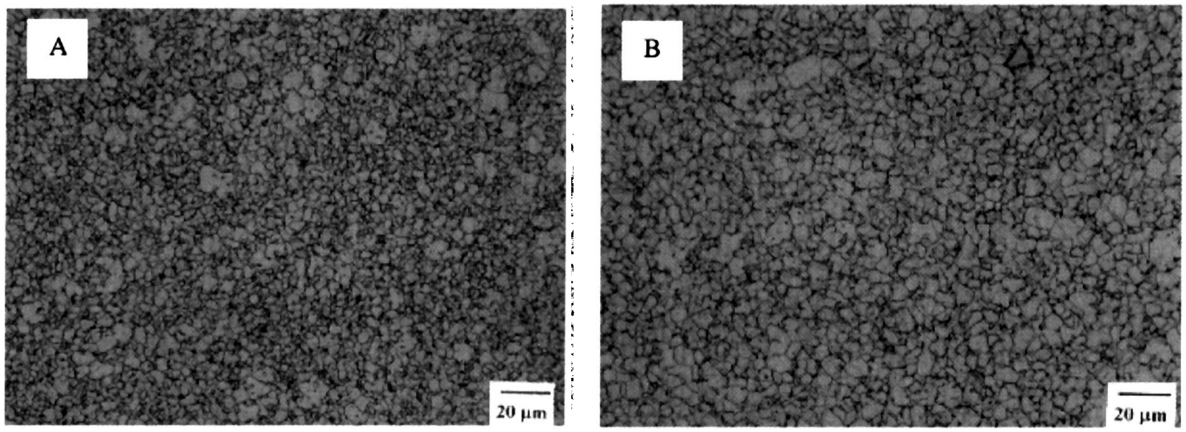


Figure 4: The microstructure following initial pancake forging shown for two forging conditions: (A) 954°C, 0.3 per min. strain rate, (B) 982°C, 0.05 per min. strain rate.

2nd Step Forging and Microstructure: In the 2nd step forging, a temperature range 954-969°C was selected to prevent grain growth of preform grains and therefore, keep the flow stresses at a reduced level. The pancakes however responded differently to the above temperature exposure prior to the 2nd step contoured forging. After exposure, the bore-slug from pancake FG718-001 exhibited grain size finer than ASTM 10 uniformly, while that of the pancake FG718-002 tended to develop regions of ASTM 6-8 due to a propensity for irregular grain growth. Further thermal exposure experiments demonstrated that this tendency towards irregular grain growth is eliminated if additional δ phase is precipitated through 'δ dumping' at 915°C/24 hr. Consequently, it was possible in either pancake, to start the 2nd step forging with a uniform grain size of finer than ASTM 10 (isolated grains were no coarser than ASTM 7-8). The flow stresses were therefore kept at about 60-80 MPa in either forging in the 2nd step. Example of press tonnage and calculated flow stress are shown in Figure 5.

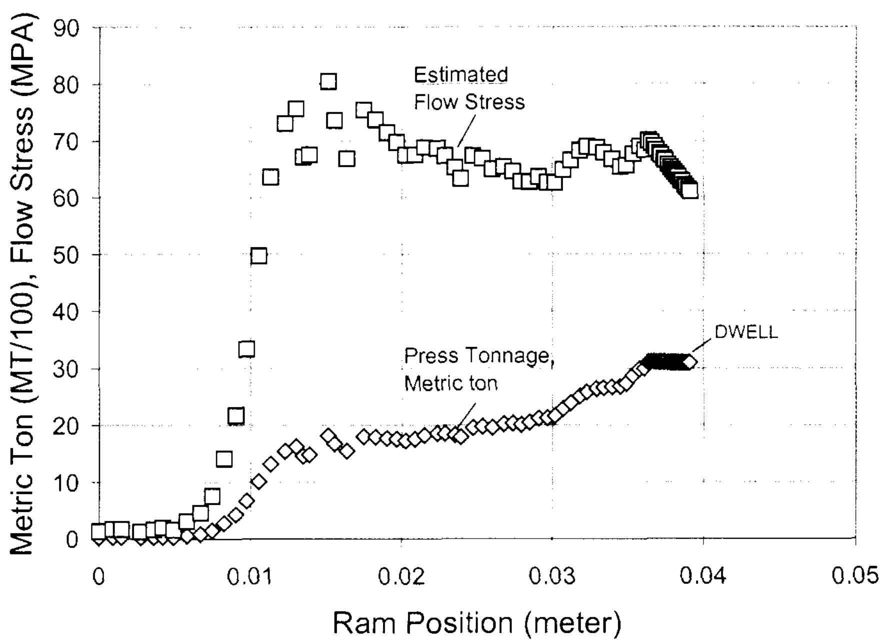


Figure 5 - Example of press tonnage and calculated flow stress in the 2nd step contoured forging.

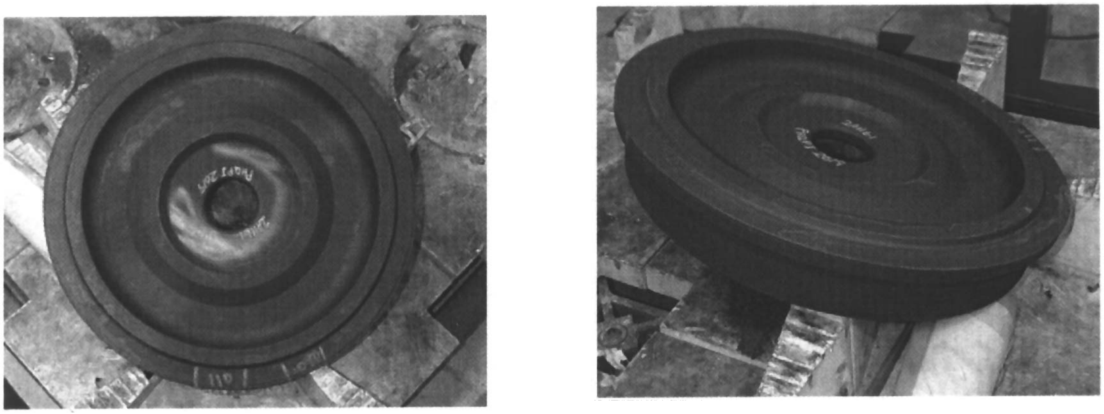


Figure 6 - Illustration of contoured forging (approximate size: 60 cm in diameter).

The contoured forging produced in the 2nd step is illustrated in Figure 6. The as-forged microstructure was very uniform with a grain size of ASTM 12 observed across a radial section of the disk. Example of the as-forged microstructure is shown in Figure 7. The standard Inconel 718 heat treatment (solution at 954°C) produced a uniform ASTM 11-12 grain structure. Example of the heat-treated microstructure is shown in Figure 8.

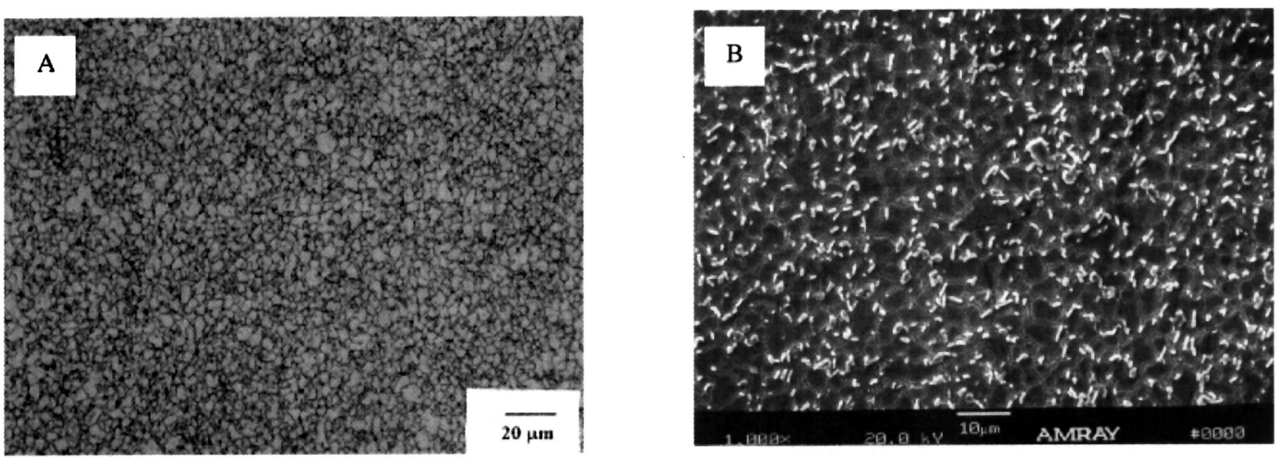


Figure 7 - Example of as-forged microstructure: (A) Optical image, and (B) SEM (Scanning Electron Microscope) image showing delta distribution.

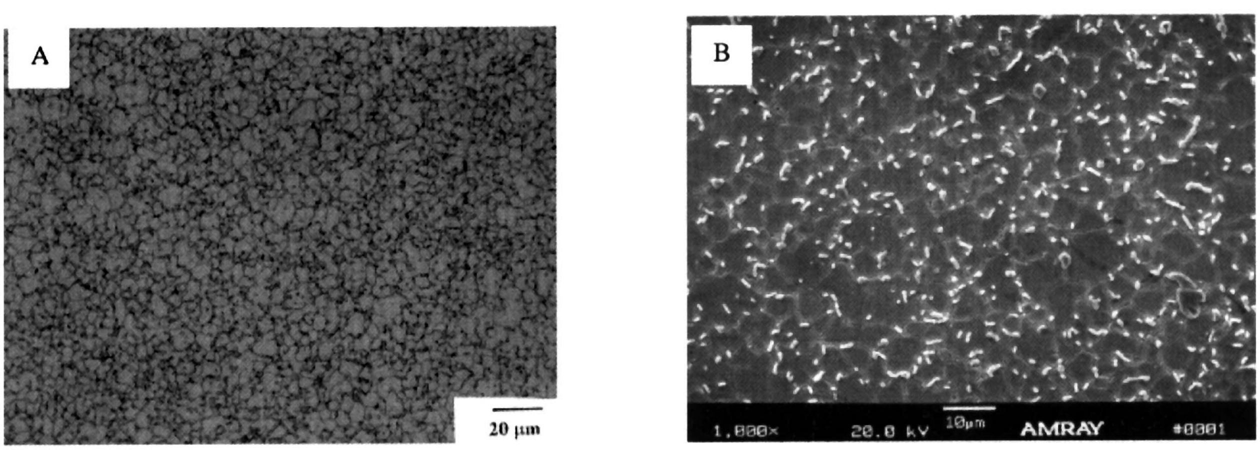


Figure 8 - Example of heat-treated microstructure: (A) Optical image, and (B) SEM (Scanning Electron Microscope) image showing delta distribution.

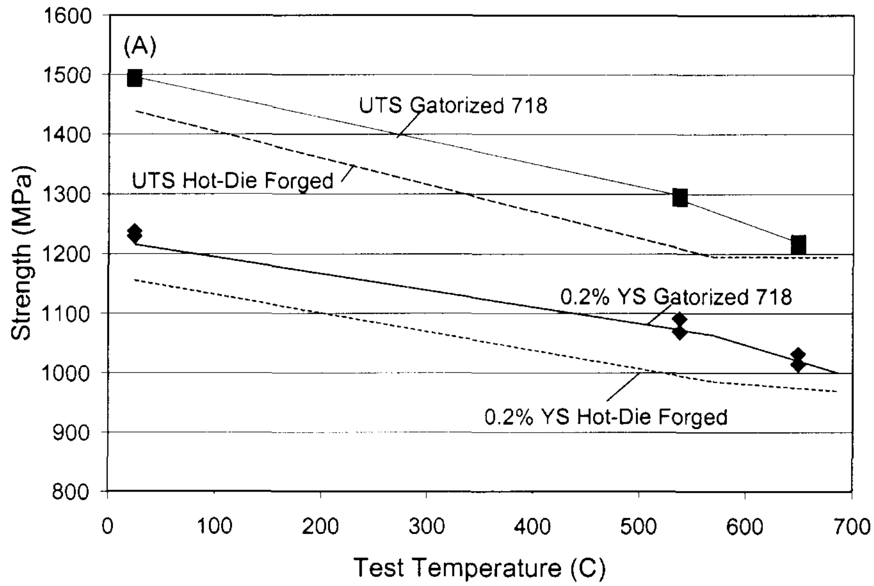


Figure 9 – The 0.2% yield strength and ultimate tensile strength of Gatorized 718 relative to hot-die forged material.

Mechanical Properties: The 0.2% yield strength and the ultimate tensile strength of the Gatorized 718 are shown in Figure 9 compared to typical hot die forged material for similar grain size and part configuration. The ductility (% elongation and % reduction in area) comparison is shown in Figure 10. Both strength and ductility properties of Gatorized 718 were similar to those of hot die the forged part, and the slightly higher strength of Gatorized 718 may be attributed to a small difference in the grain size.

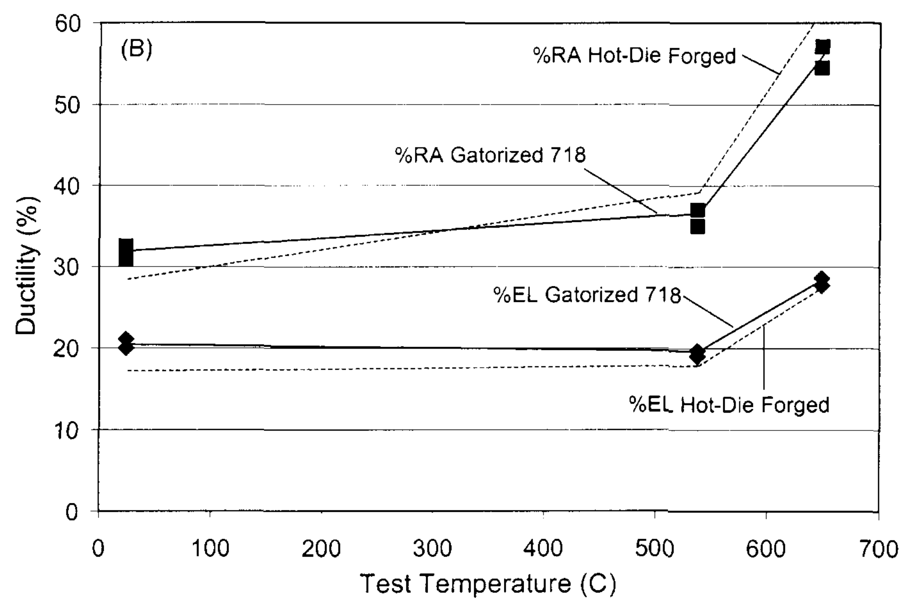


Figure 10– The % elongation and reduction of area of Gatorized 718 relative to hot-die forged material.

In the combination (smooth/notch) stress-rupture tests, the Gatorized 718 was notch-ductile with failure in the smooth section. Tests at both 649°C/758 MPa and 704°C/413 MPa showed slight reduction in stress-rupture life compared to the typical hot-die forged material as shown in Figure 11. However, Gatorized stress-rupture life generally exceeded minimum lives of the scatter in the hot-die forged material. Further characterization is needed before this difference can be attributed to forging process differences.

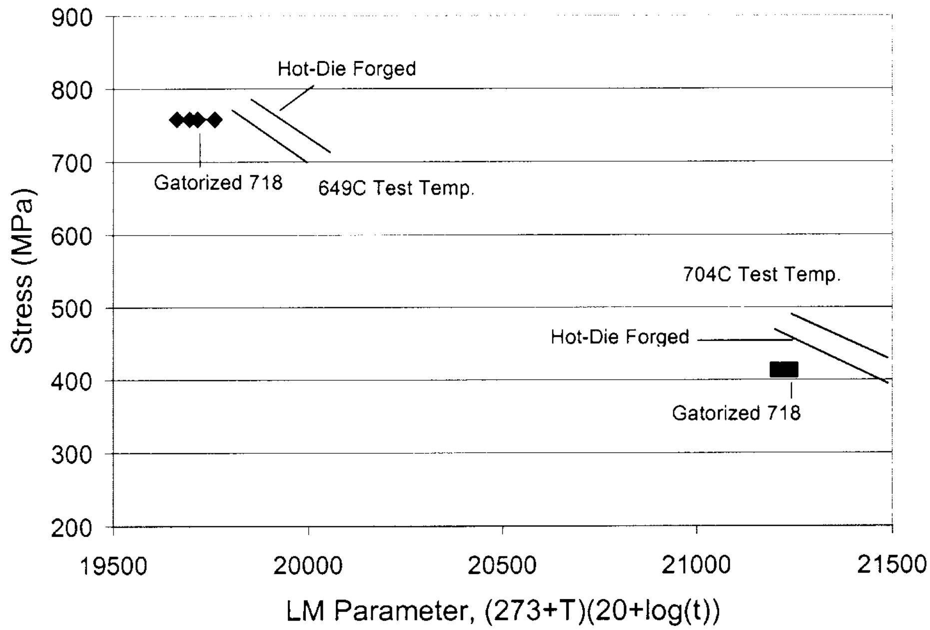


Figure 11 – Combination stress-rupture lives of Gatorized 718 relative to hot-die forged material.

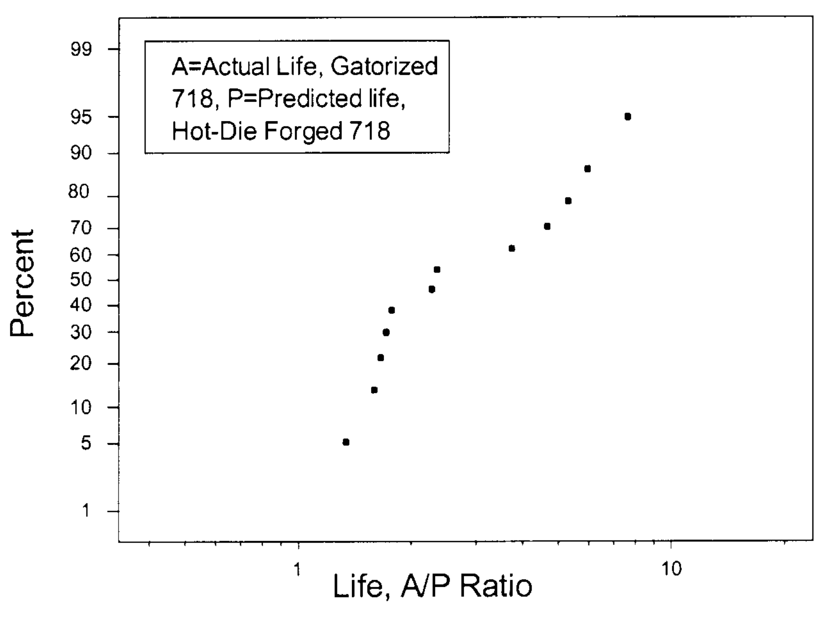


Figure 12 – The notched (K_t=2.55) low cycle fatigue life of Gatorized 718 relative to hot-die forged material.

The notched LCF properties are presented in Figure 12 relative to hot die forged material. The data represents all test conditions used in this study and was normalized with respect to hot die data of same test conditions. The Gatorized material showed lives comparable to or better than the hot die forged material.

Conclusions

1. Gatorizing to near-net-shape full size disk was achieved using delta-processed fine-grained Alloy 718 billet (with grain sizes ASTM 9-12 from center to edge). A two-step forging process at sub-solvus temperature (954-968C) was shown suitable for a rotor disk of 60 cm in dia. and 8 cm. in thickness. The first step consisted of a pancake forging to convert the microstructure to a fine grain size (ASTM 12/13) for improved superplasticity in the second step. The second step was contoured forge operation that demonstrated near-net-shape capability.

2. Gatorizing provides excellent grain size control resulting in an uniform ASTM 12/13 grain size with isolated grains no coarser than ASTM 11 in the as-forged condition.

3. The mechanical properties of Gatorized Alloy 718 were generally equivalent to premium, rotor grade hot-die forged parts of similar grain size. Strength and low cycle fatigue properties were superior, and a slight reduction in creep properties observed for the parts evaluated in this study.

Acknowledgement

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