EVALUATION OF THE MICROSTRUCTURE AND MECHANICAL

PROPERTIES OF DELTA PROCESSED ALLOY 718

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Abstract

The mechanical behavior of Inconel 718 processed using the Delta Process (DP) conversion technique was studied. The DP conversion sequence uses a intentional delta phase precipitation cycle and subsequent thermomechanical processing to produce uniform fine grain billet and bar stock. The process was developed to improve the mechanical properties through the elimination of occasional coarse grains which are common in conventionally processed materials. The net effect resulted in a decreased standard deviation in the mechanical properties and an increase in the minimum properties.

The microstructure, tensile, low cycle fatigue, and cyclic crack growth behaviors of DP718 impeller, disk forgings and bar stock were investigated. Forged DP718 properties were compared to conventionally processed Inconel 718 and another high strength material. The DP718 bar stock properties were compared to conventionally processed Inconel 718.

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Introduction

The design criteria of rotating gas turbine components require high strength and low-cycle fatigue resistance. In addition, to maximize the calculated low cycle fatigue life, the characteristic standard deviation in material properties needs to be minimized. A contributing factor to property deviation in high strength, fine grain materials like Inconel 718 (IN718) is the presence of occasional large grains. These large grains, during specimen LCF testing, are premature crack initiation sites resulting in lower fatigue life and contribute to data scatter (1). It was determined that the elimination of the occasional large grains in fine grain (ASTM 8 and finer) IN718 was required to meet the design requirements of compressor disks, impellers, and shafting applications of advanced turbine engines.

In conjunction with material producers, Allied-Signal has successfully developed an ingot to billet/bar conversion practice that eliminates the occasional coarse grains common in conventional fine grain IN718. The conversion sequence uses an intentional delta phase precipitation cycle and subsequent thermomechanical processing to produce uniform fine-grain billet and bar stock known as Delta Processed (DP) 718. This paper reports the microstructure and resultant mechanical properties of DP718. Comparisons are made to conventionally processed IN718 and another alternative high strength fine grain material. It is shown that DP718 provides significant property improvements in both forged and bar product forms. In addition, the consistency of the material structure, combined with process controls, allows for relaxation of stringent quality inspection plans providing a net cost savings.

Gas turbine components for which DP718 has been applied, or under evaluation, include axial compressor disks, centrifugal impellers, tie-shafts, and low pressure turbine disks. Generally these components operate at temperatures lower than 800°F and require high tensile strengths, superior fatigue resistance and moderate crack growth resistance. These components are primarily life limited by cyclic fatigue. Creep is generally not a life limiting factor with the exception of the tie-shaft application. The tie-shaft must must maintain a tensile assembly load that acts to hold the rotating group together. All the components are machined from forgings except for the tie-shaft which is machined from rolled bar stock.

Material Processing

Description of the Delta Process

The Delta Process was derived from the original "Mini-grain" process developed by Brown, et al. (2). The process exploited the unique dual phase metallurgy of IN718 to facilitate recrystallization while controlling the grain growth. The orthorombic δ phase was precipitated during a thermal treatment between the γ'' and δ solvus temperatures resulting in a uniform dispersion of Widmastatten δ phase throughout the matrix. Subsequent thermomechanical processing below the δ solvus spheroidized the δ phase and dynamically recrystallized the material. The presence of the δ phase, however, prevented grain growth resulting in a uniform fine grain microstructure. Figure 1 shows a graphical presentation of the delta process.

Care was taken to balance the δ precipitation cycle with the final reduction operations. If the precipitation was performed too early, excessive δ phase was precipitated during subsequent reduction operations and yield strength properties were reduced. Conversely, if the cycle was performed too late, the δ phase was not adequately spheroidized and full recrystallization of the material was not achieved.

Billet Processing. The billet product of two triple melted ingots (Heat 5632 and 7142), of chemistry shown in Table 1, were produced by Teledyne-Allvac for the forging program. The billet material for this program was press forged to an intermediate diameter using conventional fine grain processing. After the precipitation cycle, conversion to the final diameter was performed below the δ phase solvus using a rotary forge (3).

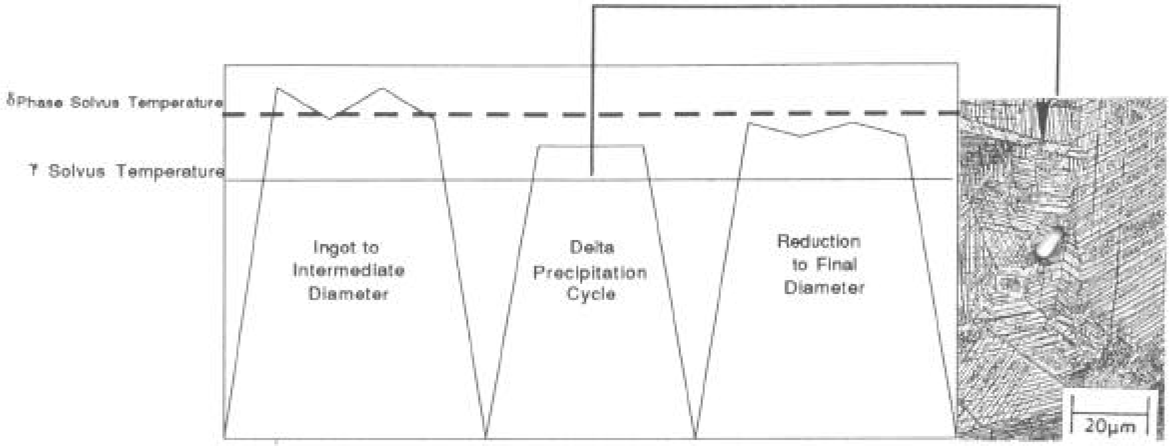


Figure 1 - Graphical representation of the Delta Process.

The 8 and 6 inch diameter billet microstructures were extremely uniform and fine grain from the surface to the center. The grain size of the billet was ASTM 8 and finer with occasional grains as large than ASTM 6. Most of the Widmastatten δ phase was spheroidized during the subsolvus reductions, as shown in Figure 2. However, some areas of partially spheroidized δ phase were present in the center of the 8 inch billet from heat 5632. Therefore, the conversion process was modified on the subsequent 8 inch diameter billet to perform the δ cycle earlier in the process followed by press forging which resulted in better center penetration before rotary forging to the final diameter.

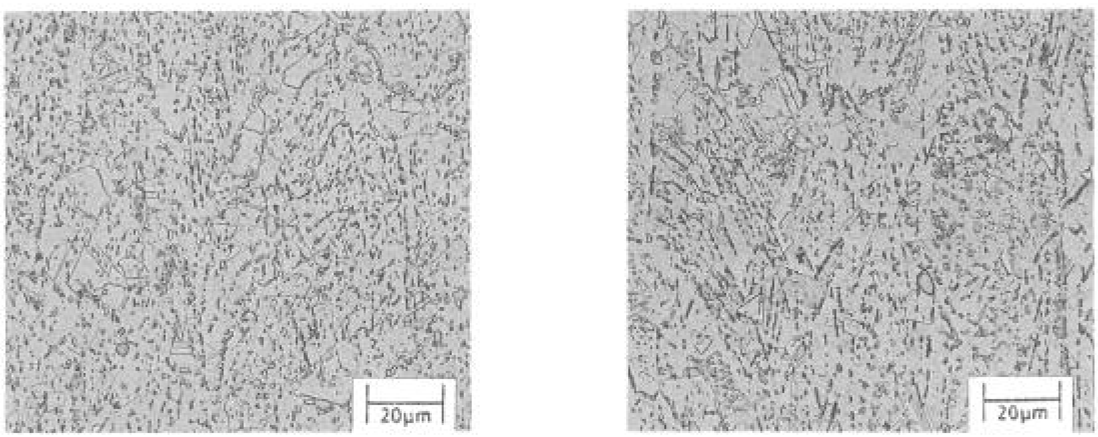


Figure 2 - Representative microstructure of the 8 inch billet. Areas near the center of the billet exhibited partially spheroidized δ phase.

Bar Stock Processing. Two double melted heats (7188 and BA09) were used in the bar stock program. The bar material was process similar to the billet with the exception that the δ precipitation cycle was conducted later in the reduction sequence at a size commensurate to the final bar diameter. In addition, the final reduction operations for the bar stock were performed on a rolling mill (4).

The bar stock at 3 inch and 1.5 inch diameter exhibited a fully recrystallized, fine grain microstructure. The grain size was ASTM 11 from the surface to center in both the 3 and 1.5 inch diameter bar and the δ phase had been fully spheroidized as shown in Figure 3. The consistency of the DP718 bar prompted a large reduction in the production metallographic inspection. This resulted in a net cost savings of 24% for the DP718 compared to conventional IN718. In addition, the inventory turnover was increased by eliminating the time required to complete the receiving inspection.

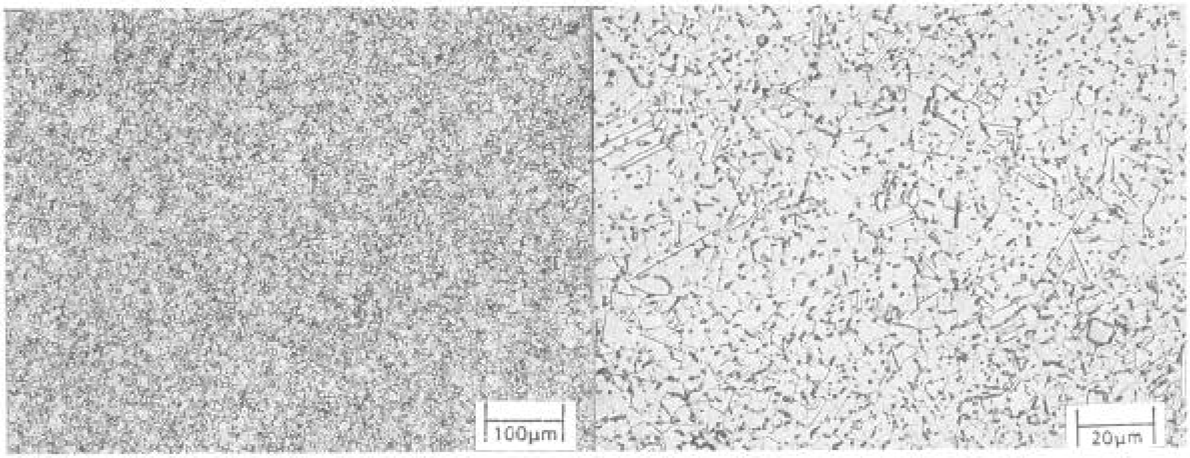


Figure 3 - Representative microstructure of 1.5 and 3.0 inch diameter DP718 bar stock.

Table 1- Chemical composition of DP718 billet and bar stock.

Heat	Ni	Cr	Co	Mo	Nb+Ta	Ti	Al	Fe
5632	52.65	17.65	.49	2.90	5.41	.99	.52	Bal.
7142	52.70	17.98	.29	2.91	5.30	.98	.45	Bal.
7188	52.80	17.87	.24	2.92	5.35	.95	.39	Bal.
BA09	53.00	17.92	.21	2.88	5.20	.96	.56	Bal.

Forging Process. A total of 9 impeller and 14 disk forgings were evaluated in the program. The forgings were produced by Wyman-Gordon using conventional hammer forging practices. The forging temperatures were maintained below the δ phase solvus to prevent grain growth. Subsequent solution treatment temperatures were carefully chosen to ensure adequate partial solution of δ phase for γ'' formation without causing grain growth.

The forgings were solution treated and aged as follows:

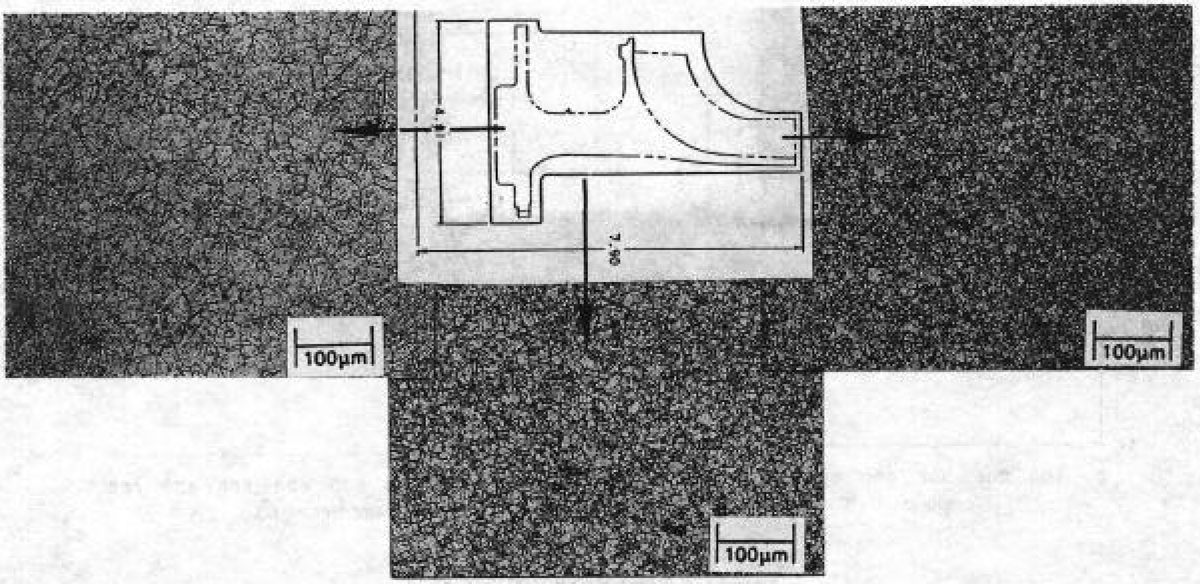
Solution Treatment	1775°F+/-15°F for 1 hour; water quench
Precipitation Age	1325°F+/-25°F for 8 hours; furnace cool 100°F/hr to 1150°F+/-25°F and hold for 8 hours; air cool

Microstructures of Forgings. The DP718 forgings were consistently fine grain regardless of the forging size or geometry. The macrostructure and microstructure was evaluated on a full radial cross section from each forging. The macrostructure of the forgings was consistently uniform across the full cross section. The microstructure of the solution treated and aged forgings was, fully recrystallized, and fine grain as shown in Figure 4. The grain size of all the forgings met the requirement of ASTM 8 or finer with occasional grains as large as ASTM 6.

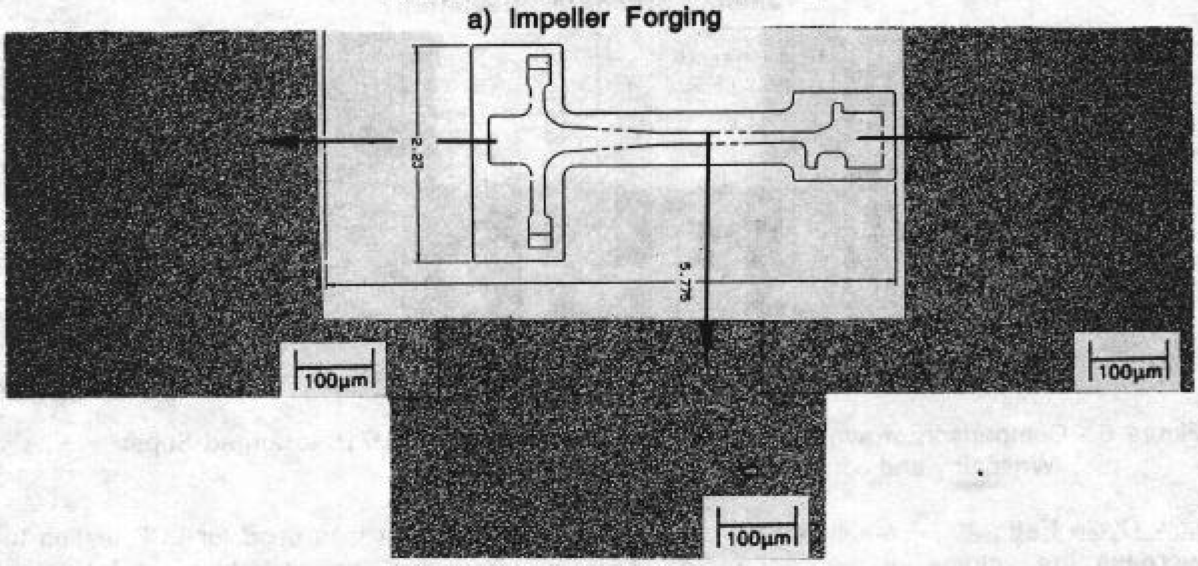
Mechanical Property Results

Properties of Forgings.

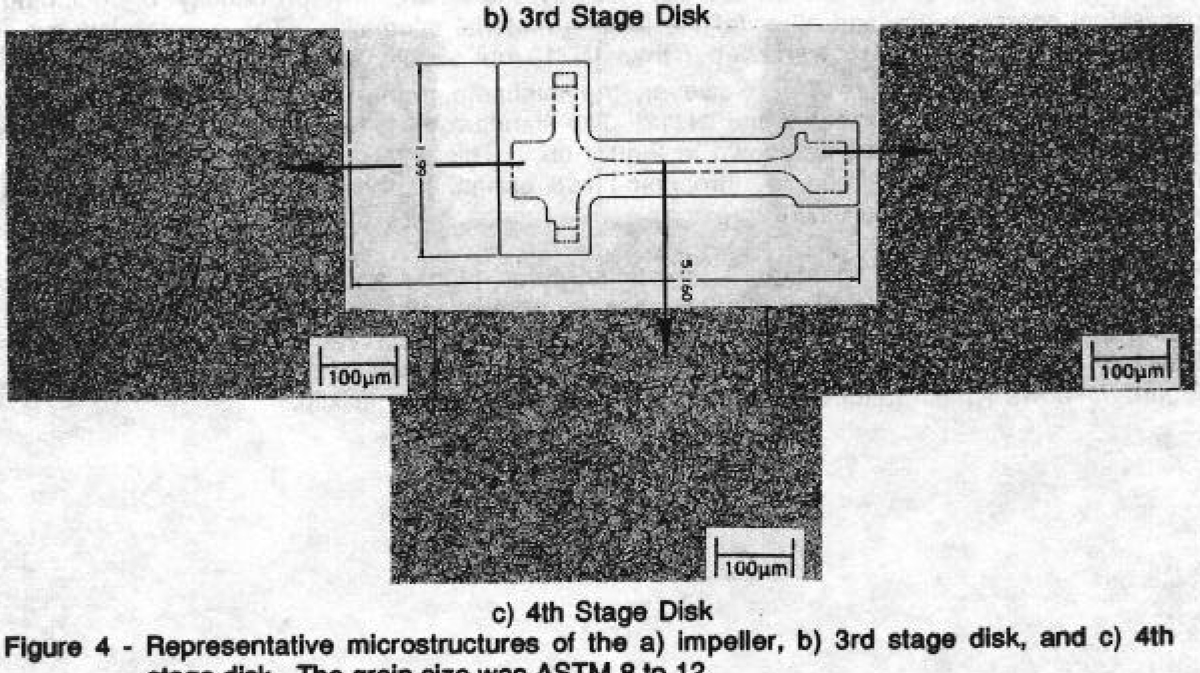
Tensile Properties. The average tensile properties of the DP718 forgings were compared to the average properties of IN718 and another high strength disk material, Super Waspaloy. Super Waspaloy is a fine grain, high strength version of Waspaloy produced by thermomechanical processing below the γ' solvus. As shown in Figure 5, the yield strength of the DP718 forgings was comparable to IN718 and Super Waspaloy. The DP718 ultimate tensile strength was higher than IN718 but lower than Super Waspaloy. The ductility of DP718 was comparable to both IN718 and Super Waspaloy as shown by the percent reduction in area. The standard deviation of the DP718 tensile properties was less than both IN718 and Super Waspaloy.



a) Impeller Forging



b) 3rd Stage Disk



c) 4th Stage Disk

Figure 4 - Representative microstructures of the a) impeller, b) 3rd stage disk, and c) 4th stage disk. The grain size was ASTM 8 to 12.

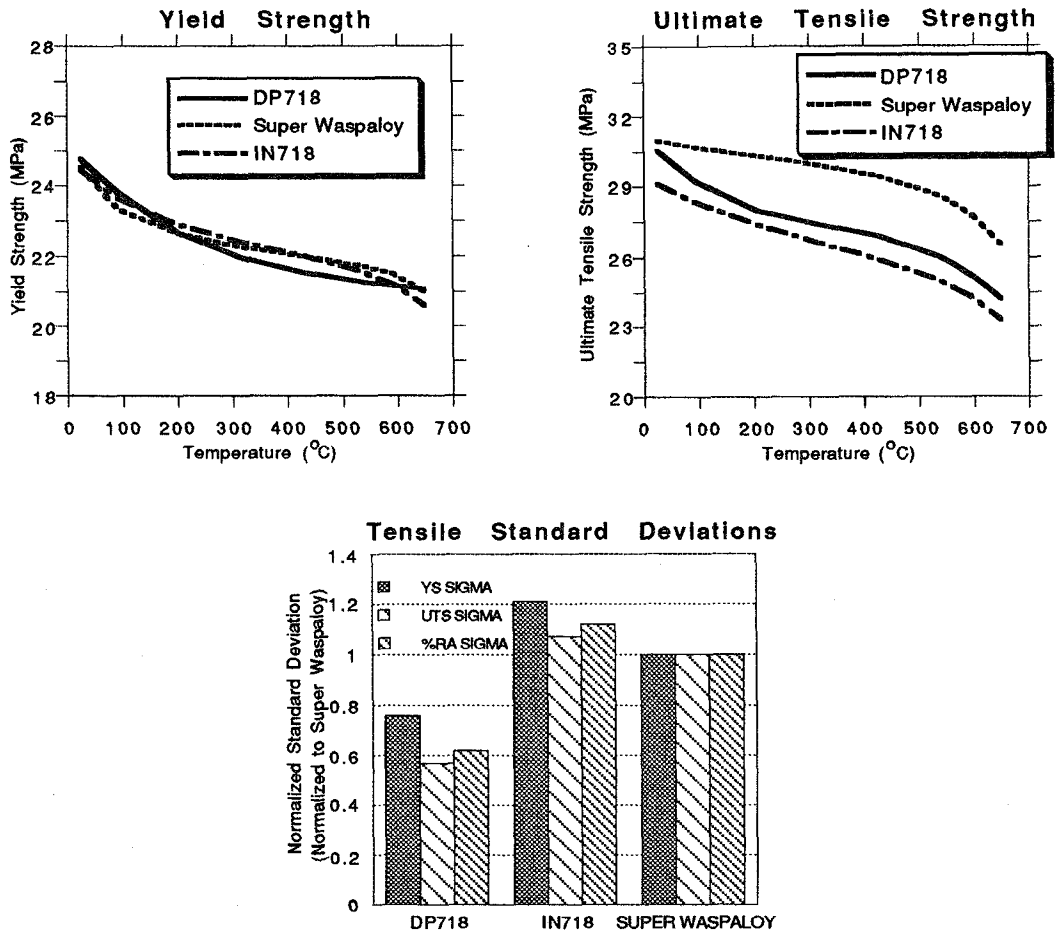
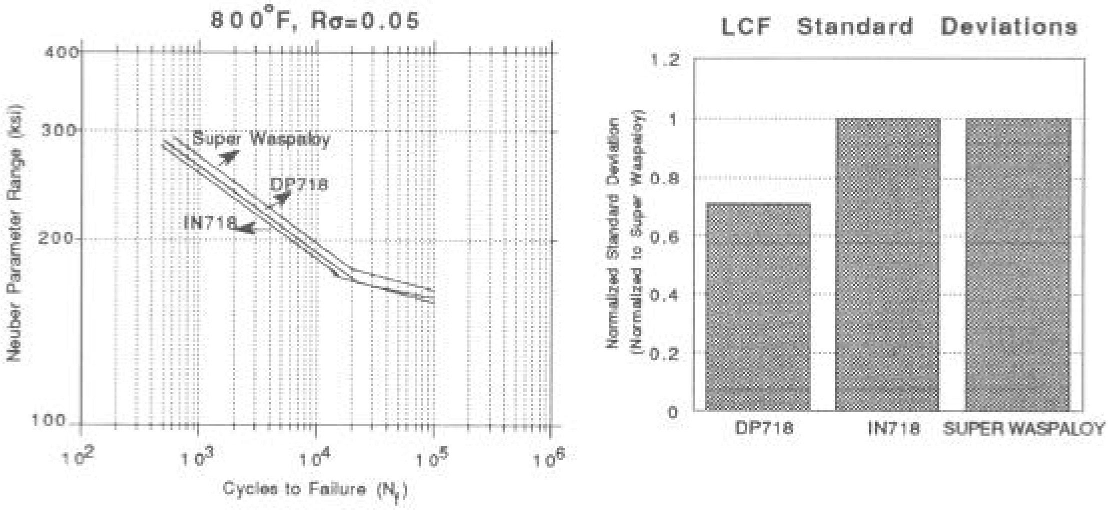


Figure 5 - Comparison of average tensile properties of forged DP718 to forged Super Waspaloy and conventional IN718.

<u>Low Cycle Fatigue</u>. A specimen with a 0.4 inch gage diameter was used for LCF testing to increase the volume of material tested, thereby increasing the probability of including occasional coarse grains and other fatigue limiting material anomalies. The average low cycle fatigue properties of DP718 were better than IN718 but slightly lower than Super Waspaloy 800°F, as shown in Figure 6a. However, the minimum properties of the DP718 forgings were better than Super Waspaloy and IN718. The standard deviation of DP718 was lower than Super Waspaloy and IN718 as shown in Figure 6b. This was due to the elimination of the microstructural variations, coarse unrecrystallized grains, in the DP718 that were present in the Super Waspaloy and IN718 forgings.

Fatigue fracture initiated in stage I, crystallographic planar slip or from primary carbide particles rich in Nb. Carbide initiation sites were predominantly observed in specimens tested at $R\varepsilon=0.05$, whereas, crystallographic initiation was observed in specimens tested at $R\varepsilon=-1.0$. This was attributed to the mean stress differences between the two test conditions. Figure 7 shows typical fatigue initiation from a carbide and planar slip.



a) b)

Figure 6 - Comparison of average LCF properties of forged DP718 to forged Super Waspaloy and IN718. Minimum DP718 properties were higher than Super Waspaloy and IN718,however, due to a lower standard deviation in the data.

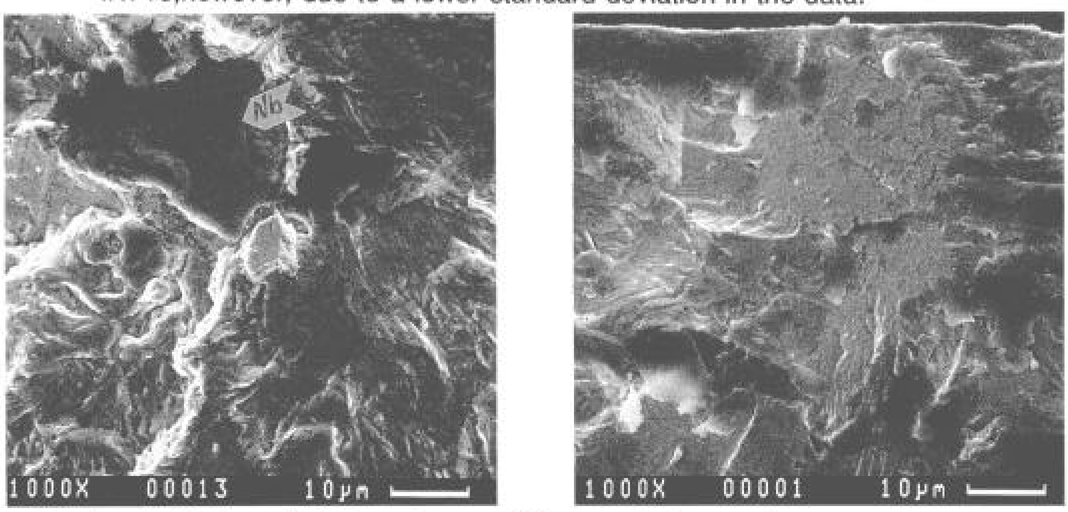


Figure 7 - Typical fatigue initiation from carbides and planar slip.

Cyclic Crack Growth Properties. The cyclic crack growth behavior of DP718 at 800°F was similar to Super Waspaloy as shown in Figure 8.

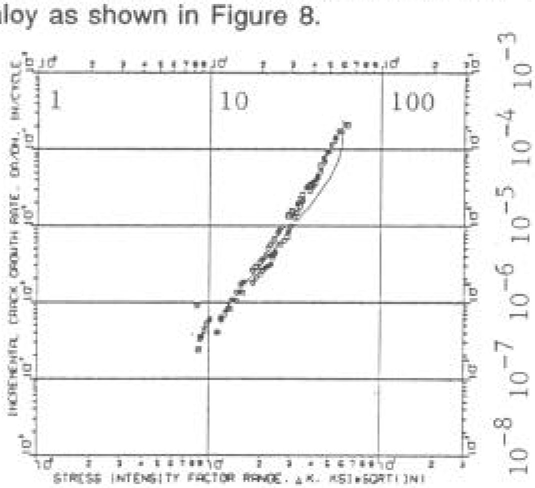


Figure 8 - Comparison of cyclic crack growth properties of forged DP718 (□) to forged Super Waspaloy (solid line), 800°F.

Bar Stock Properties.

Adjustments to the δ precipitation cycle and solution heat treatment contributed to the consistency of tensile properties between the two bar sizes. The end result was statistically similar data between the 1.5 and 3 inch diameter bar stock.

Tensile. The tensile properties of the DP718 bar stock exhibited improvement when compared to conventional IN718 properties. The average yield strength properties of DP718 bar were similar to IN718, as shown in Figure 9. However, the standard deviation in the yield strength data was greatly reduced; thereby, increasing the minimum yield properties by 1.5 MPa. The DP718 ultimate tensile strength was improved over IN718. The ductility of DP718 was comparable to IN718 as shown by the comparison of the reduction in area, Figure 9.

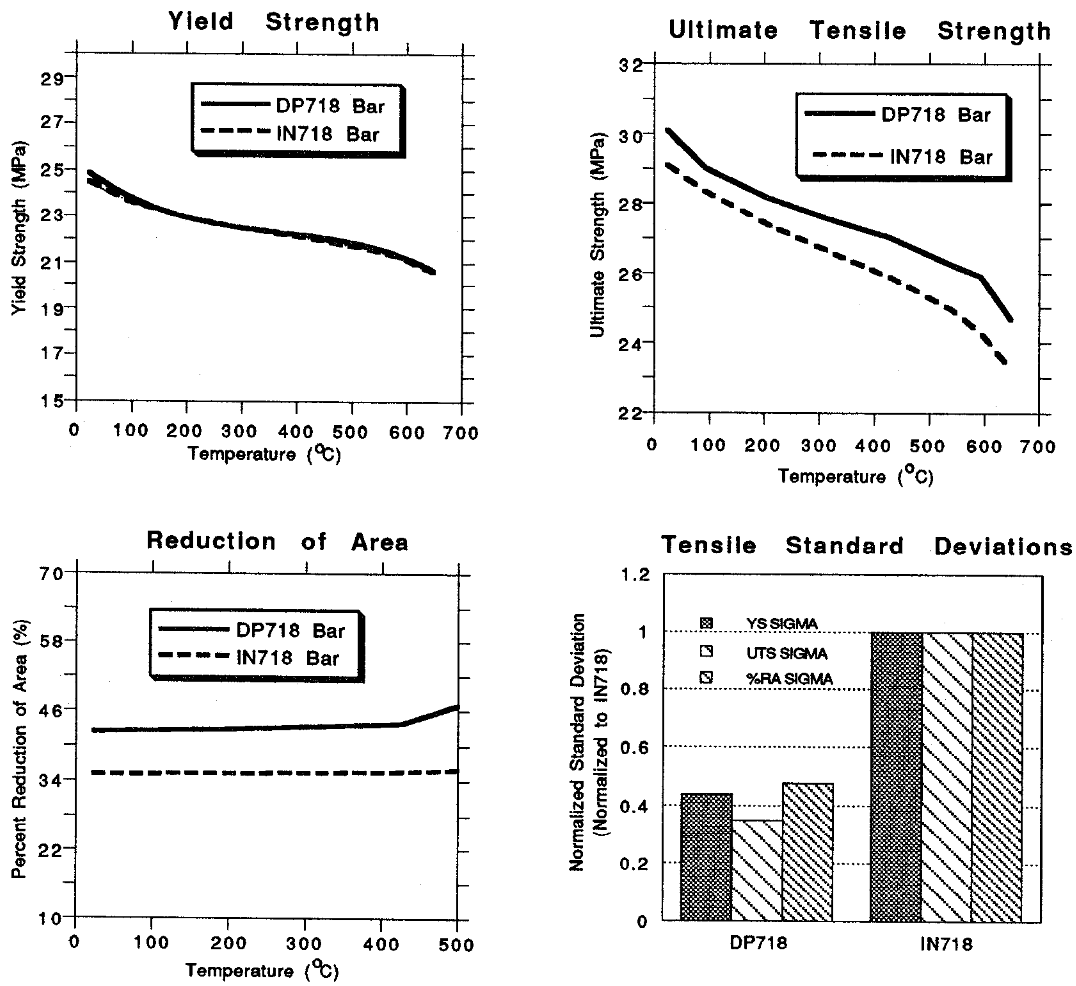
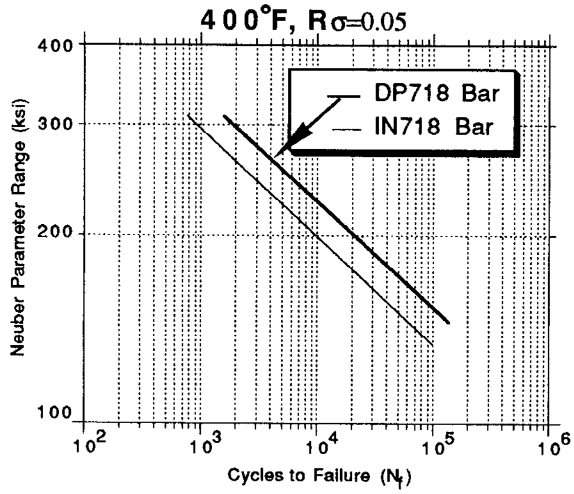
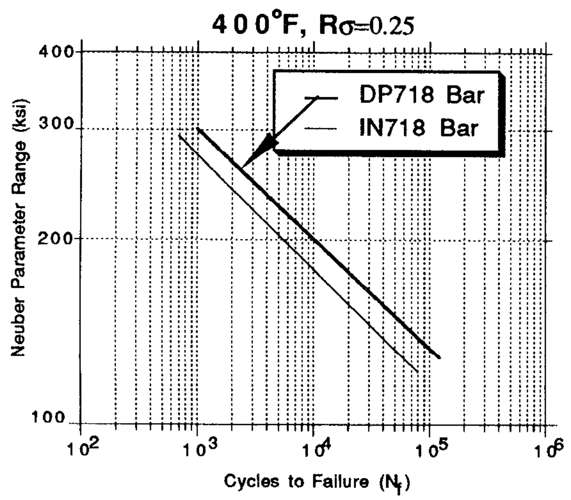


Figure 9 - Comparison of average tensile properties of DP718 bar stock to IN718 bar stock.

Low Cycle Fatigue. The average low cycle fatigue properties of the DP718 bar were improved a nominal 15% over IN718. The DP718 exhibited the most significant improvements at low strain ranges were occasional coarse grains limit the fatigue resistance of conventional material. Figure 10 shows the improvement of average LCF properties of DP718 bar to IN718 at 400°F at two stress ratios. As with the forged DP718, the DP718 bar stock LCF data had a smaller standard deviation than the IN718.





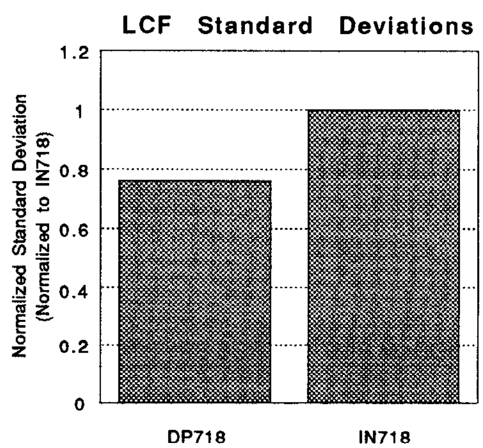


Figure 10 - Comparison of average LCF properties of DP718 bar stock to IN718 bar stock.

Summary

The Delta Process exploited the interactions between the metallurgical phases of Inconel 718 and theromechanical processing. This resulted in reproducible fine grain billet that was forged with less expensive forging techniques to produce high strength forgings. The key to the forging process was to maintain temperatures below the δ solvus to prevent grain growth. The subsequent solution temperature should adequately solution enough δ phase for good γ'' precipitation without grain growth.

The mechanical properties of DP718 forgings were shown to be better than conventionally processed IN718 and Super Waspaloy below 800°F. As a result, DP718 forgings have been the bill of material for production TFE1042 engines. The DP718 tensile properties were comparable to Super Waspaloy and IN718. The low cycle fatigue properties of the DP718 forgings were superior to the conventionally processed materials. The standard deviation of the DP718 mechanical properties was lower than the standard deviations of both Super Waspaloy and IN718.

The Delta Process was also shown to be adaptable to producing various bar stock sizes resulting in improved properties at a lower cost. The DP718 bar stock exhibited uniform fine grain microstructures at two different bar diameters. This has allowed frequency of inspection to be relaxed for DP718 bar stock resulting in lower inspection costs and increased inventory turnover. The improved properties of DP718 have increased the design margin for production tie-shafts and have provided the property enhancement necessary for advanced shaft designs. The 1.5 inch diameter DP718 bar stock is currently the production material for all turbofan and turboprop tie-shafts.

References

1. D. Ruckle, T. Banik, and C. Ruiz, "Process Control Necessary for Improved Fatigue Capability of INCO 178, (GED Internal Memo 1989).

2. E.E. Brown, R.C. Boettner, and D.L. Ruckle, "Minigrain^{TM} Processing of Nickel-base Alloys" (Paper presented at the 2nd International Symposium on Superalloys, Seven Springs, Pennsylvania, 1972).

3. T. Banik, "Ultra Fine Grain INCO 718 Evaluation" (GED Internal Report, 1989).

4. C. Ruiz, "Characterization of Delta Processed Alloy 718 for Use in High Temperature Shaft Applications" (GED Internal Report, 1992).