ROTARY FORGE PROCESSING OF DIRECT AGED INCONEL 718 FOR AIRCRAFT ENGINE SHAFTS

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Abstract

The increase in aircraft engine thrust has required that main engine shaft material exhibit improved tensile strength and cyclic capability. The application of a "Direct Age" heat treatment to a controlled GFM fine grain billet process is discussed. "Direct Aged" tensile and low cycle fatigue properties are presented and compared to fine grain solution and aged material. Improvements in tensile properties were noted at temperatures up to 1200F with the largest improvement occurring at the bar surface. No difference in microstructure or properties was noted along the bar when bars were limited to less than 30′ in length. Longitudinal properties were found to be slightly higher than those measured in the tangential direction. It is concluded that application of the "Direct Age" heat treatment to a controlled GFM ingot conversion practice can be used to improve Inconel 718 aircraft engine shaft properties.

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Introduction

Inconel 718 is extensively used in aircraft engine components because of the wide variation in properties that can be readily developed through specific thermomechanical processing (1,2). By selecting the appropriate metal working temperature and heat treatment, three variations of Inconel 718 can be developed. These are often referred to as "Standard 718" which is processed to produce an ASTM 4-6 grain size, "High Strength 718" which is processed to an ASTM 8 grain size, and "Direct Aged 718" which is processed to an ASTM 10 grain size and is directly aged without a solution anneal (3).

The structure/properties of forgings developed by selecting a thermomechanical processing sequence will be dependent upon the cleanliness and microstructure of the billet/bar from which it is forged. Thus the emphasis in recent years has been to improve ingot cleanliness through ceramic filtering (4) and melt practice (5) and to modify the ingot conversion practice to obtain fine grain billet. By controlling both the melting and conversion practice, it is possible to produce billet/bar of sufficient cleanliness and uniformity of microstructure that it can be utilized without subsequent forging (6). This approach, often referred to as "slice from billet", is not generally used in nickel base alloys because of the relatively low utilization ratio of initial to final weight of shaped components, but the control of billet/bar is directly applicable to aircraft engine shaft components.

A main aircraft engine shaft is essentially billet, the diameter of which depends upon the application, and thus the shaft properties are determined by the melting and ingot conversion practices. Standard shaft material can be readily attained through normal processing followed by a solution and age. By control of the ingot conversion practice, a finer grain, improved property level can be produced. Further property improvements can be attained by utilizing a direct age process. The purpose of this work is to evaluate the properties of direct aged Inconel 718 shaft material made by the controlled GFM conversion practice.

Material Processing

Material for both Direct Age and fine grain, Solution and Aged Inconel 718 barstock originates as a vacuum induction melted plus vacuum arc remelted 20" diameter ingot. Typical VAR ingot chemistry is shown in Table I. For both materials, the ingot is press forged at temperatures slightly in excess of 2000F to the 13" to 16" diameter range to provide a preform for subsequent GFM forging.

Table I. Typical Composition of "Direct Aged" Shafts

Fe	Cr	Mo	Ti	Al	Nb+Ta	B	C	Ni
18.3	17.8	2.90	1.00	.70	5.40	.004	.035	53.0

The press forged preform is radial forged to size on a Model 55 GFM machine. For fine grain 718, all processing is conducted at temperatures slightly in excess of the delta solvus. The direct age product is radial forged similar to the fine grain 718 process to an intermediate size prior to forging to the final size of approximately 6" diameter at a temperature of 1825F, slightly below the delta solvus. This lower temperature processing results in a slightly finer grain microstructure for the direct aged material. It is also necessary to retain residual strain imparted to the material by water quenching within three minutes after start of the final forging pass. For an early trial with a quench delay of four minutes, a difference of 10 ksi from lead to tail end of the bar was observed. To consistently achieve a maximum quench delay time of three minutes, bar lengths were limited to less than 30′. Material was aged using the standard cycle of 1350F/8 hours, furnace cool 100F/hour to 1125F/8 hours followed by air cooling.

In order to assure that a fine grain structure and maximum mechanical properties are achieved, tight controls on furnace temperature and radial forging parameters are necessary. Also, rigid controls must be imposed on chemistry variation and pre-GFM billet structure.

A three dimensional finite element model is being developed for radial forging to predict strains, strain rates and temperatures for various radial forging parameters. This will allow further refinement of the radial forging process which will utilize the consistency offered by the GFM forging machine to a greater extent.

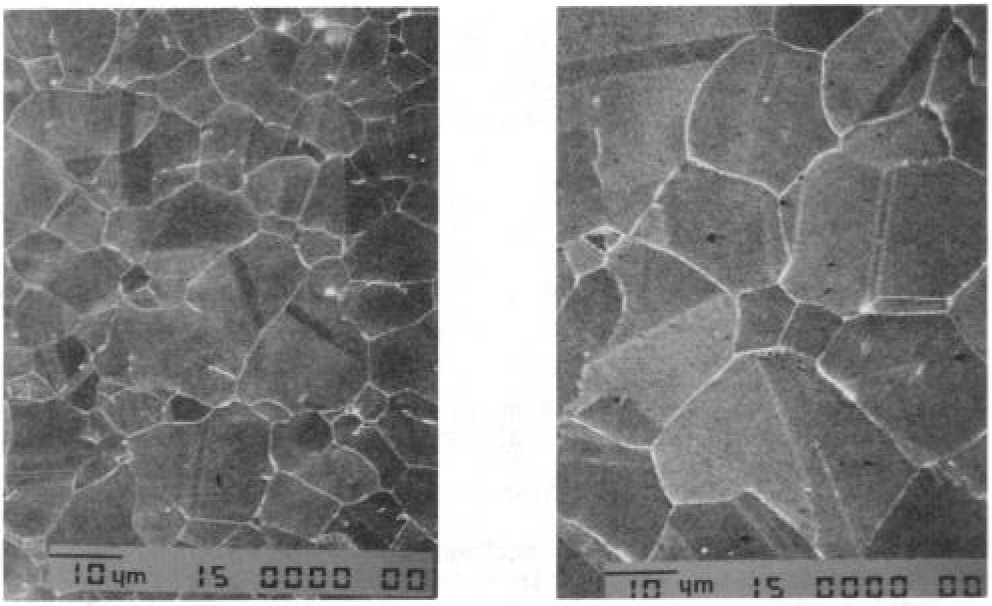
Material Evaluation

Mechanical property and metallographic specimens were cut from both ends and mid-length of each direct aged bar. Tensile properties were measured in the longitudinal direction at surface, mid-radius and bar center and in the tangential direction at only the mid-radius due to bar diameter limitations. Tensile specimens had a gage diameter of 0.252" and a gage length of 1.0". Tensile tests were performed at room temperature, 500F and 1200F.

Low cycle fatigue properties were measured in the longitudinal direction at the bar mid-radius location. Smooth, cylindrical LCF specimens, with a gage diameter of 0.200", were utilized. LCF testing was performed in axial-axial strain control (A = 1.0) at 500F over the strain range from .55% to 1.05%.

Material Structure and Mechanical Property Test Results

Microstructural evaluation was performed at surface, mid-radius and center of each end and mid-length of the DA718 bar stock. Typical microstructures are shown in Figure 1. Fine grain recrystallized structures, with minimal delta precipitation, were achieved at all locations with ASTM 9 or finer at the surface and ASTM 7/8 at bar mid-radius and center. Occasional, isolated, unrecrystallized grains as large as ASTM 2/4 were present. No variation in microstructure was observed along the length of the bar stock. Table I summarizes the microstructural evaluations.



1a 1b

Figure 1 - Typical SEM microstructure at bar surface (1a) and center (1b)

Table I. DA718 Grain Structure Summary

Location	Bar Position	Orient.	Recrystallized Grain Size	Isolated Grain Size	
				Average	Maximum
Surface	Top	Long.	9 or finer	6	2/3
Surface	Mid-Length	Long.	9 or finer	6	2.5
Surface	Bottom	Long.	9 or finer	6	3
Mid. Rad.	Top	Long.	7/8	5.5	4.5
Mid. Rad.	Mid-Length	Long.	7/8	5	4
Mid. Rad.	Bottom	Long.	7/8	5	4
Center	Top	Long.	7/8	5	4
Center	Mid-Length	Long.	7/8	5	4

Tensile test data is listed in Tables II, III and IV for room temperature, 500F and 1200F, respectively.

Table II. Room Temperature Tensile Properties

Bar End	Location	Orientation	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (%)	R.A. (%)
Top	Surface	Longitudinal	208	223	18	43
Bottom	Surface	Longitudinal	206	222	18	44
Top	Mid. Rad.	Longitudinal	190	210	22	47
Bottom	Mid. Rad.	Longitudinal	187	209	22	47
Top	Mid. Rad.	Tangential	186	204	17	31
Bottom	Mid. Rad.	Tangential	184	203	17	31
Top	Center	Longitudinal	185	206	24	45
Bottom	Center	Longitudinal	184	205	24	46

Table III. 500F Tensile Properties

Bar End	Location	Orientation	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (%)	R.A. (%)
Top	Surface	Longitudinal	195	208	16	43
Bottom	Surface	Longitudinal	192	206	17	43
Top	Mid. Rad.	Longitudinal	174	194	21	47
Bottom	Mid. Rad.	Longitudinal	173	194	21	47
Top	Mid. Rad.	Tangential	171	190	16	32
Bottom	Mid. Rad.	Tangential	170	189	16	32
Top	Center	Longitudinal	169	191	23	45
Bottom	Center	Longitudinal	168	191	22	47

Table IV. 1200F Tensile Properties

Bar End	Location	Orientation	0.2% Y.S. (ksi)	U.T.S. (ksi)	Elong. (%)	R.A. (%)
Top	Surface	Longitudinal	176	190	20	56
Bottom	Surface	Longitudinal	171	189	21	57
Top	Mid. Rad.	Longitudinal	157	176	26	58
Bottom	Mid. Rad.	Longitudinal	156	176	25	57
Top	Center	Longitudinal	154	173	26	57
Bottom	Center	Longitudinal	153	173	26	56

The data represents the product of five 20" VAR ingots. Properties were uniform from end to end of each bar with decreasing strength as a function of distance from the bar surface. Tests in the longitudinal orientation exhibited higher ductilities than for the tangential direction. For comparison, tensile properties for 5" diameter solution and aged (SA718) barstock (ASTM grain size 6/7) as well as the DA718 data is shown in Table V. At all test conditions, the DA processed barstock was significantly higher in strength than the SA718 material while maintaining comparable ductility.

Table V. DA718 / SA718 Shaft Tensile Property Comparison

Temp. (F)	Test Dir.	Test Loc.	.2% YS (ksi) DA718	.2% YS (ksi) SA718	TS (ksi) DA718	TS (ksi) SA718	EL (%) DA718	EL (%) SA718	RA (%) DA718	RA (%) SA718
R.T.	L	Surf.	207	175	222	206	18	21	43	40
R.T.	L	M.R.	189	169	209	200	22	22	47	39
500	L	Surf.	193	164	207	188	16	21	43	42
500	L	M.R.	173	157	194	181	21	22	46	42
1200	L	M.R.	157	144	176	162	25	22	58	50

Axial-axial strain controlled low cycle fatigue test results at 500F for both DA718 and SA718 processed barstock are shown in Figure 2.

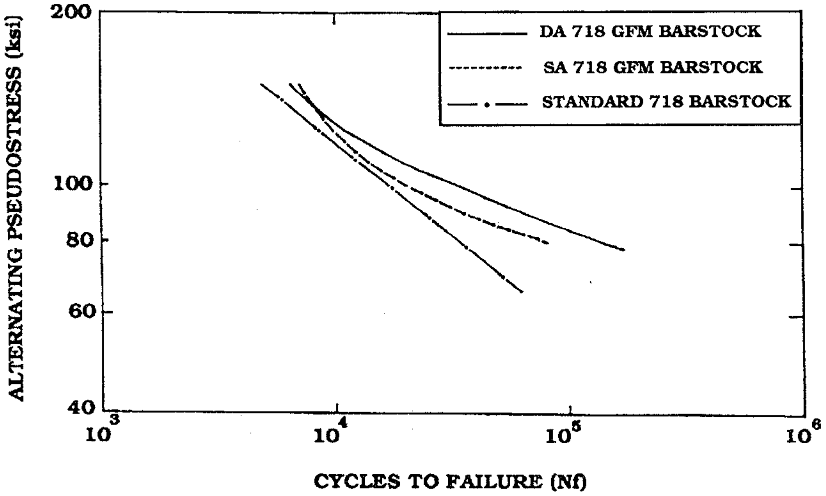


Figure 2 - Direct Age Versus Solution + Age Low Cycle Fatigue Comparison

The higher strength and finer grained DA material exhibited a significant improvement in cyclic life capability. At an alternating pseudostress of 80 ksi, a life improvement greater than 50% was realized.

Discussion

The application of "Direct Age" processing to barstock for aircraft engine shafting application resulted in a significant increase in strength and low cycle fatigue capability compared to solutioned and aged barstock. At the mid-radius location, an increase of 10-13 ksi .2% yield strength and 13-20 ksi in ultimate tensile strength was realized over the temperature range from 75F to 1200F. Slightly greater gains were observed at the surface location. Tangential tests were slightly lower in strength (2-3 ksi) and ductility than longitudinal tests. In addition, greater than 50% improvement in low cycle fatigue life at 500F was observed. The increase in strength and low cycle fatigue was achieved while maintaining comparable ductilities to solution and aged material. Properties were uniform over the length of the barstock processed and no variations were observed from top to bottom of ingot.

The increase in material properties is greater than could be attributed to grain size differences alone indicating that the water quench and direct age process stabilizes the dislocation substructure produced during hot forming and increases aging response. This is consistent with the microstructures shown in figure 1 and with the strength differences observed for longer quench delays. Close control of forging reductions and temperatures was required to achieve a fine grain fully recrystallized microstructure with uniform γ'' distribution. Of particular importance is the final pass time on the GFM and water quench delay time after forging. Excessive times for either operation results in material recovery and lower properties. Optimum length of bars produced by the DA process was in the 20′ to 25′ range and quench delay times were three minutes maximum to achieve the desired properties.

Conclusions

1. Direct Age processing of IN718 bar stock for aircraft engine application resulted in increased strength and low cycle fatigue capability compared to solutioned and aged fine grain barstock.
2. Uniform microstructure and mechanical properties were achieved for barstock processed in lengths up to 28 feet. Specimens oriented longitudinally in the barstock exhibited slightly higher properties than tangentially oriented specimens.
3. The consistency resulting from GFM forged barstock combined with direct aged processing produces a product that will increase the tensile and low cycle fatigue allowables in Inconel 718 aircraft engine shafts.

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