MECHANICAL PROPERTIES AND MICROSTRUCTURE OF FINE GRAIN, CENTRIFUGALLY CAST ALLOY 718

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Abstract

Solidification under high pressure with proper control over process parameters produces an equiaxed, fine grain structure, typically ASTM 4-6.5, with a minimum of localized segregation and little if any microporosity. The mechanical properties and microstructure of centrifugally cast, fine grain Alloy 718 material in various precipitation hardened conditions are presented. Room and 1200°F (648°C) tensile as well as 1200°F/ 90 ksi (648°C/621 MPa) stress rupture properties far exceeded minimum specification values for all age conditions. Improvements due to a standard HIP cycle can be attributed to high temperature homogenization.

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Introduction

The use of high temperature alloys such as Alloy 718 is limited by microstructural aspects which are usually artifacts of the particular manufacturing process employed to produce a component. For example, optimum low cycle fatigue properties, as obtained through high temperature deformation during forging operations, result from a fine, fully dense equiaxed grain structure. Unfortunately, extensive machining is required to produce the final component.

To cost effectively produce components to near-net shape, a cast technology is the process alternative. Precision investment casting, under static conditions, enables shaping but presents problems in controlling grain size, grain uniformity and nonmetallic inclusions. To produce a fine equiaxed grain structure, in the absence of mechanical working, a casting process utilizing high heat removal rates from liquid metal of low superheat is necessary. Various attempts at producing fine grain equiaxed structures have resulted in microporosity associated with localized solidification contraction (1, 2). Hot isostatic pressing (HIP) may be utilized to reduce the effect of microporosity but this often results in grain growth and subsequent mechanical property degradation. By combining the shaping technologies of precision casting with solidification under high pressure in centrifugal casting, the microporosity associated with the low pressure mode of solidification is avoided.

In centrifugal casting, molten metal is fed into a mold that is rotating about either the vertical or horizontal axis. Centrifugal force drives the metal to the mold wall by radial acceleration forces. The magnitude of the centrifugal force increases proportional to the square of the radius of rotation. This centrifugal force can be described in terms of a gravitational constant, g, a multiple of static pressure. In high pressure centrifugal casting solidification occurs under conditions of 'g' greater than 35. In these circumstances, higher density metal is forced against the mold sidewall with lower density components migrating to the casting inner diameter (ID). In practice, these lower density components include metal oxides, sulfides, gas and other impurities which would otherwise have been entrapped in the component.

Centrifugal force applied on the metal as it solidifies limits the presence of microporosity typically associated with the intersection of equiaxed grain boundaries. This results from the pressure exerted by the applied centrifugal force, which effectively prevents the microporosity formation associated with equiaxed grain bridging (2). The combinations of impurity migration to the ID, directional solidification, and solidification under pressure, results in a casting that has a defect distribution and soundness equal or superior to that which can be obtained by investment casting.

This paper presents verification of the benefits of centrifugal casting in the production of fine grain Alloy 718 components.

Experimental Procedure

For the purpose of this study, typical gas turbine components were produced by vacuum induction melting (VIM) Alloy 718 and centrifugally casting in vacuum into a specially designed production mold. Product chemistry analysis, as conducted on material removed from the castings are shown in Table I. The casting configuration used in this evaluation is represented in Figure 1.

The various heat treatments employed in this program were conducted on segments from the castings and are summarized in Table II. After heat treatment, 0.252 inch (6.35 mm) diameter test bars oriented circumferencially with respect to the casting axis of rotation, were removed and prepared in accordance with ASTM E8, E21, and E139 specifications. To ensure uniformity in the specimen surfaces, low stress crush grinding was employed. All data shown represent numerical means of three or more tests.

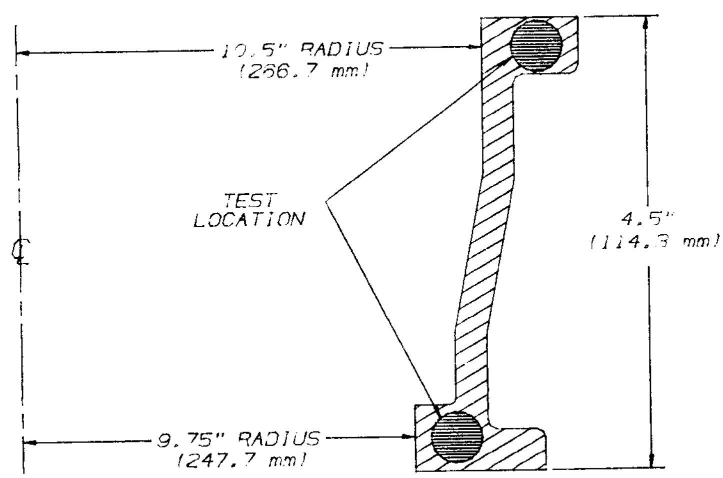


Figure 1

Schematic of casting cross section. Mechanical test coupons taken circumferentially at the locations indicated.

Table I. Centrifugally Cast Alloy 718

Chemical Composition, weight percent

Casting Number	C	Si	Cr	Ni	Mo	Cb+ Ta	Ti	Al	B	Fe
AMS 5383 Spec.	0.10 Max.	0.35 Max.	17.00 21.00	50.00 55.00	2.80 3.30	4.75 5.50	0.65 1.15	0.40 0.80	0.006 Max.	Bal
1	0.032	0.06	18.40	53.00	3.05	5.07	0.95	0.55	0.003	Bal
2	0.039	0.09	18.76	51.97	3.03	5.10	0.93	0.57	0.003	Bal
3	0.046	0.12	18.56	53.60	3.01	4.96	0.95	0.63	0.004	Bal
4	0.043	0.16	18.13	53.49	3.29	5.11	1.03	0.45	0.004	Bal
5	0.049	0.14	18.33	52.88	3.25	5.00	0.97	0.46	0.003	Bal
6	0.057	0.08	19.04	52.02	2.92	4.41	0.98	0.54	0.003	Bal
7	0.057	0.11	18.98	52.78	2.92	4.47	1.02	0.60	0.004	Bal

Table II. Heat Treatment Conditions and Descriptions

Designation	Condition	Casting Numbers
A	As Cast	1,4,5
B	Conventional Heat Treatment 2000°F(1093°C) - 1-1/2 hr 1750°F(953°C) - 1 hr 1325°F(717°C)/1150°F(620°C) - 18 hrs	4,5
C	HIP + Conventional Heat Treatment 2050°F(1121°C) - 3 hrs/14.750 ksi(101.7 MPa) 2000°F(1093°C) - 1-1/2 hr 1750°F(953°C) - 1-1/2 hr 1325°F(717°C)/1150°F(620°C) - 18 hrs	4,5,6,7
D	HIP + Modified Heat Treatment 2050°F(1121°C) - 3 hrs/14.750 ksi(101.7 MPa) 1925°F(1050°C) - 1 hr 1400°F(760°C) - 5 hrs	2,3
E	Homogenization + Modified Heat Treatment 2050°F(1121°C) - 3 hrs 1925°F(1050°C) - 1 hr 1400°F(760°C) - 5 hrs	1

Metallographic specimens were removed from the gripper end of room temperature tensile test bars. Standard mechanical polishing techniques with an electrolytic final polish were used to prepare the specimens for final etching. A polishing solution consisting of 20 parts sulfuric acid and 80 parts methanol was utilized for the final polish operation (3). Polished specimens were then electrolytically etched in a solution of 12 parts phosphoric, 41 parts nitric, and 47 parts sulfuric acid. Comparative grain size uniformity tests were conducted on casting cross sections using a macroetch solution of 10 parts hydrogen peroxide, 10 parts water, and 80 parts hydrochloric acid.

Microstructure and mechanical properties were the two subjects of interest in this study. The influence of heat treatment on the microstructure was determined using optical and scanning electron microscopy. Room and elevated temperature tensile and stress rupture tests were used to evaluate heat treatment influence on mechanical properties. Low cycle fatigue and notched stress rupture testing is ongoing but not available at the time of this writing. Because the strength in polycrystalline alloys is contingent on the condition of the grain boundaries, the microstructural analysis for this study will focus primarily on boundary microconstituents as effected by heat treatment (4). Not discussed here are precipitation hardening events which are well documented in other works from these proceedings.

Results

Microstructure

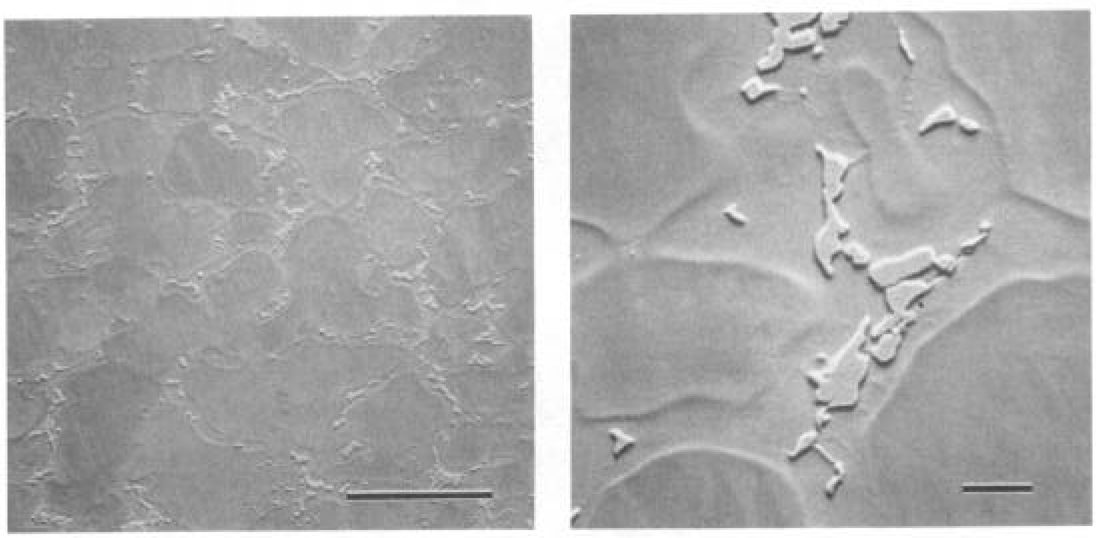
Condition A: As cast. The typical microstructure of as cast centrifugally cast Alloy 718 is shown in Figure 2. The average ASTM grain size number for this condition is 6.5. A complete summary of all grain size measurements is shown in Table III. The unheat-treated microstructure contained moderate amounts of Laves phase and niobium-rich carbides aligned along equiaxed grain boundaries. Also evident were discrete carbides within the grain matricies.

Condition B: Conventional Heat Treatment (AMS 5383). This microstructure (Figure 3) exhibits significant reduction in Laves phase with little or no effect on carbide distribution. Concentrations of delta phase are evident along the grain boundaries. Average ASTM grain size for this condition is 6.5.

Condition C: HIP plus Conventional Heat Treatment. The average grain size is 4.5, which is a moderate increase over the previous conditions. Laves phase has been essentially eliminated from the microstructure and delta phase significantly reduced as a result of this treatment (Figure 4). Carbide and semicontinous delta phase are moderately dispersed along grain boundaries.

Condition D: HIP plus Modified Heat Treatment. Neither Laves phase nor microporosity are evident (Figure 5). In contrast to the previous treatment, grain boundary delta phase was not observed. Average grain size for this condition is ASTM No. 4.5.

Condition E: Homogenization plus Modified Heat Treatment. The microstructure of this condition (Figure 6) is similar to the Condition D material. Occasional micropores, less than 1.2 x 10^{-5} square inches in size, are evident in the microstructure. The average grain size is ASTM No. 4.



200X 100 microns 1000X 10 microns

Figure 2

Condition A, As cast - scanning electron photomicrographs.

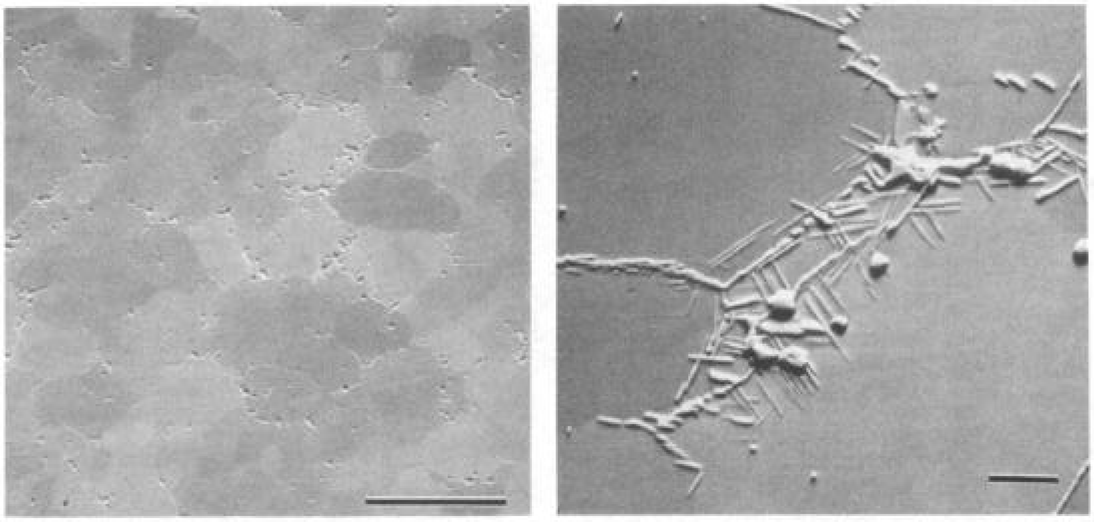


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Figure 3

Condition B, Conventional heat treatment (AMS 5383).

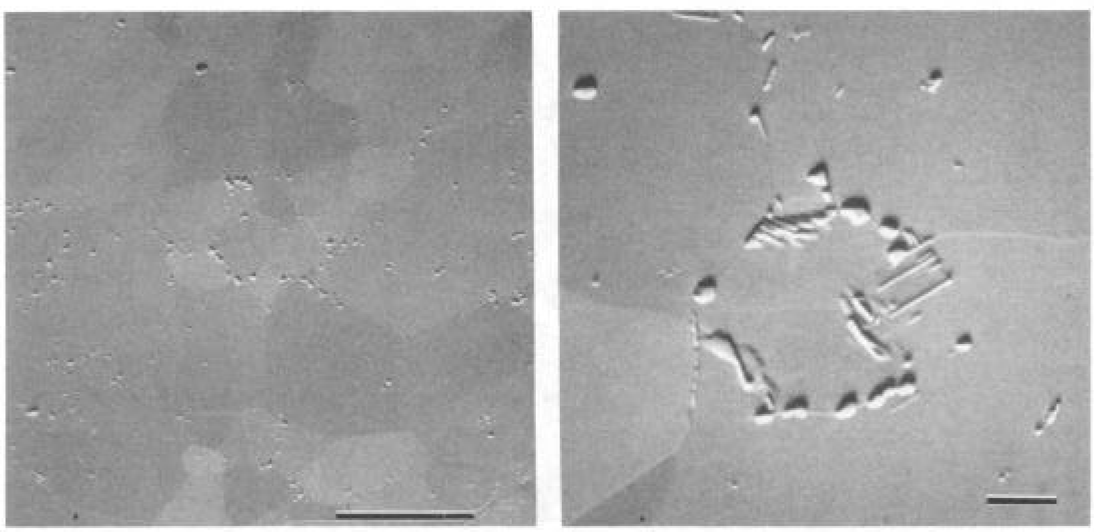

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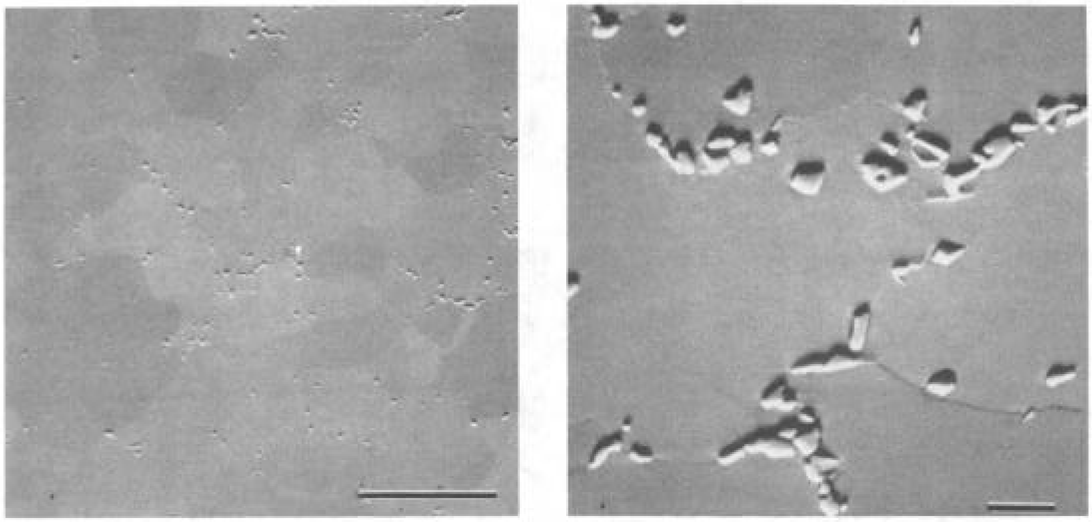
Figure 4

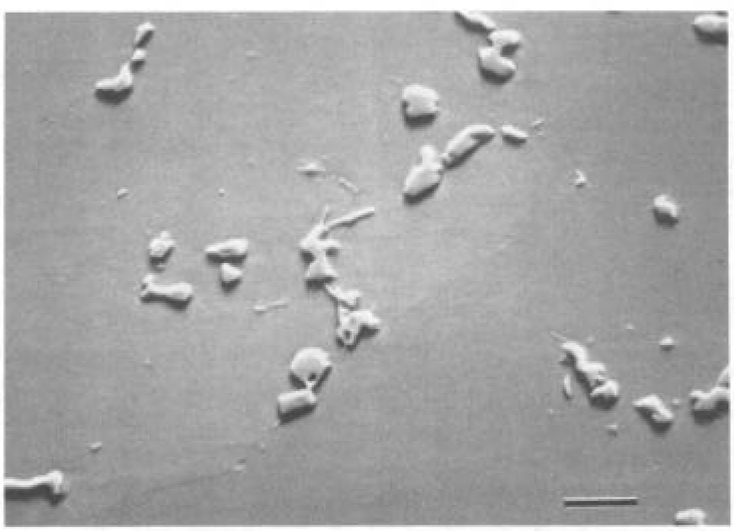
Condition C, HIP plus conventional heat treatment.



200X 100 microns 1000X 10 microns

Figure 5

Condition D, HIP plus modified heat treatment.



1000X 10 microns

Figure 6

Condition E, Homogenize plus modified heat treatment.

Table III. ASTM Grain Size

(Mean values obtained by standard comparative method)

Condition		Grain Size ASTM Number
A	As Cast	6.5
B	Conventional Heat Treatment	6.5
C	HIP + Conventional Heat Treatment	4.5
D	HIP + Modified Heat Treatment	4.5
E	Homogenization + Modified Heat Treatment	4

Mechanical Properties

The mechanical properties obtained from the various heat treatment conditions are summarized in Tables IV, V, and VI. Results obtained for all heat treatments were found to be substantially higher than those required by AMS 5383 as well as by private industry casting specifications for Alloy 718.

Significant difference was noted between the HIP'ed and nonHIP'ed conventionally heat treated material. Room temperature ductility of the HIP'ed and the homogenized materials were higher than that observed in the conventional 1325°F/ 1150°F age condition. Similarly, the 1200°F/90 ksi (648°C/621 MPa) stress rupture life also improved in the HIP'ed material.

A comparison of the aging effect can be made between the HIP'ed material aged at 1325°F/1150°F versus 1400°F. Significant difference was evident in the 1200°F/90 ksi (648°C/621 MPa) stress rupture life where the HIP plus 1400°F aged material had a substantially greater life than the HIP plus 1325°F/1150°F aged condition.

Stress rupture testing for Condition E as well as notched stress rupture testing for all condtions is ongoing and were unavailable at the time of publication.

Table IV. Tensile Properties 70°F(21°C)

Condition	Yield Strength, ksi (MPa)	Ultimate Strength, ksi (MPa)	Elongation (%)	Reduction of Area (%)
B Conventional Heat Treatment	147.6 (1017.9)	174.2 (1201.4)	13	16
C HIP + Conventional Heat Treatment	149.1 (1028.3)	178.1 (1228.2)	23	28
D HIP + Modified Heat Treatment	150.1 (1035.2)	180.9 (1247.6)	24	25
E Homogenized + Modified Heat Treatment	142.1 (980.0)	172.7 (1191.0)	27	31
Typical Specification Minimum Requirements	110.0 (758.6)	125.0 (862.1)	5	10

Table V. Tensile Properties 1200°F(648°C)

Condition	Yield Strength, ksi (MPa)	Ultimate Strength, ksi (MPa)	Elongation (%)	Reduction of Area (%)
B Conventional Heat Treatment	122.4 (844.1)	143.9 (992.4)	12	16
C HIP + Conventional Heat Treatment	123.0 (848.3)	139.7 (963.5)	19	23
D HIP + Modified Heat Treatment	127.8 (881.3)	145.7 (1004.8)	13	16
E Homogenized + Modified Heat Treatment	126.3 (871.0)	142.5 (982.7)	14	17
Typical Specification Minimum Requirements	80.0 (551.7)	100.0 (689.7)	7	Report

Table VI. Stress Rupture

1200°F/90 ksi(648°C/621 MPa) Properties

Condition	Life (Hrs)	Elongation (%)	Red. of Area (%)
B Conventional Heat Treatment	494.7	13	14
C HIP + Conventional Heat Treatment	717.4	10	13
D HIP + Modified Heat Treatment	957.8	8	10
Typical Specification Minimum Requirements	23	3.0	--

Summary and Conclusions

1. High pressure centrifugal casting of Alloy 718 parts, produced under carefully controlled conditions, results in a fine grain microstructure essentially free of microporosity with limited segregation effects.

2. The grain structure for all material conditions was found to be uniform equiaxed throughout the casting envelope. Grain size variation was found to be approximately one grain size number.

   A grain size of ASTM 6.5 was developed in conventional AMS 5383 aged material. The largest grain size, ASTM 4-4.5, was observed in material which was HIP'ed or homogenized at 2050°F for 3 hours.

3. Room and 1200°F tensile as well as 1200°F/90 ksi stress rupture properties far exceeded minimum specification values for all age conditions.

4. The conventional AMS 5383 (1325°F/1150°F age) heat treatment cycle proved unsuccessful in completely eliminating Laves phase from the microstructure. Inclusion of a 2050°F high temperature treatment as a part of the heat treatment cycle did however eliminate Laves phase from the microstructure. Occasional micropores less than 1.2×10^{-5} square inches in size were observed in material homogenized at 2050°F - 3 hours.

5. Significant stress rupture life increase, resulting from more extensive homogenization, was experienced after the HIP plus various age treatments compared to that following the conventional age heat treatment. A moderate increase in yield strength, independent of aging temperature, was observed in HIP'ed material.

References

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