Mechanical Properties of Fine-Grain Microcast-X® Alloy 718 Investment Castings for SSME, Gas Turbine Engine, and Airframe Components

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ABSTRACT

The mechanical properties of fine grain Microcast-X® investment cast Alloy 718 Space Shuttle Main Engine (SSME) turbopumps, gas turbine engine, and airframe components are compared to the test bar data from cast-to-size bars and slab data generated in 1987-88. The SSME structural components made by P&W are now being used during shuttle flights, and gas turbine engine components (for aero and land-base engines) are now in process development. Airframe components of varying thickness (simulated with cast slabs) have also been evaluated by Boeing. Tensile, stress rupture, and high and low cycle fatigue properties of these components in the temperature range of -320F to 1000F (-196C to 538C) are discussed with regard to the Microcast-X Alloy 718 process capability.

INTRODUCTION

The Microcast-X® process (abbreviated MX®), first reported in 1984 [1], produces a cellular (non-dendritic) grain with a micro-grain size range of ASTM 3-5. This fine-grain process utilizes traditional investment casting methods, but requires improved mold preheat temperature and melting controls. Standard alloys can generally be used with the MX process, with a chemistry within the applicable specification range. A U.S. patent for the MX process was issued to Howmet researchers in 1989 [2], which was then followed by several publications describing the process advantages, limitations, and mechanical properties [3-7]. These publications generally utilized data generated from oversize test bars and slabs, whereas reference [8] and the current paper utilizes properties from test bars machined from production-cast components.

After roughly eight years of development and production experience, some basic characteristics of the MX process are worth summarizing. The limiting parameters for fine grain Alloy 718 are filling thin sections and controlling Laves phase segregation. Due to the low superheat at casting, flow in the mold is reduced, and filling is

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achieved by increasing minimum wall thickness where necessary and raising mold temperatures as required. However, large structural castings having a wall thickness approaching 0.080 in. (2 mm) have been made with the MX process. Smaller structural castings have been produced with walls approaching 0.060 in. (1.5 mm) thick.

Laves phase in MX castings is all intergranular and may create brittle grain boundaries. This has the effect of reducing tensile and fatigue properties, although the precise influence of Laves has been difficult to document [3,9]. A similar effect in conventional castings is masked somewhat by the typically large variation in mechanical properties due in part to a much larger grain size and grain orientation effect. The greatest effect from Laves phase is almost always near gating or areas with very slow solidification rates. Since test bars are usually extracted from the thickest sections, the test data are believed to represent the maximum variation. Microcast-X castings have now demonstrated consistent mechanical property enhancements on a production basis. Selection of MX casting parameters in the low superheat environment, including welding and non-destructive inspection (NDI) procedures, are also routinely used in several Howmet production foundries to meet customers design expectations at minimal cost.

Since these fine-grain MX cast components have smaller grain sizes, and higher tensile, fatigue, and stress rupture properties compared to standard investment castings, new applications have been developed. Three component areas have been successfully addressed: liquid fuel rockets, gas turbine engines and, to a limited extent, aircraft airframe components. Rocket parts, particularly turbopump components, have been well developed in the SSME program. Currently, five key components including high pressure housings have been in production for several years and approximately 30 engine sets have been delivered. These parts benefit from the high tensile strength of MX Alloy 718 especially in the cryogenic region.

Gas turbine engine components, which always require a balance of properties usually at elevated temperatures, have benefited to a lesser degree from MX casting technology. The main limitation to the incorporation of MX processing into critical structural parts has been relatively poor crack growth resistance. Fine grained castings are no worse than wrought components, but they are not as good as conventionally made castings. However, parts that are designed with LCF properties in mind have been the most successful, as fatigue capabilities near standard wrought components are possible with near net shapes as well.

More recently, a potential application has arisen in aircraft airframe parts generally in the vicinity of the engines or auxiliary power units (APU's) where high strength is balanced against weight at temperatures above normal use temperatures for titanium. The use of Microcast-X Alloy 718 for airframe heat shields is not well developed, and the properties presented here are designed to generate further interest.

PROCEDURES AND APPROACH

The composition of the Alloy 718 components discussed in this paper are generally the same as in AMS 5383, with typical chemistries provided in [3]. Likewise, casting processes, hot isostatic pressing (HIP), solution heat treatments and ageing cycles are also similar to those discussed in [3], with the exception that all processing was conducted at Howmet LaPorte, IN., and Hampton, VA., facilities in a production environment. In addition, the mechanical properties, tested at Howmet and at customer facilities, utilized standard ASTM procedures including E8, E139, and E606 for tensile, stress rupture, and fatigue testing, respectively.

RESULTS AND DISCUSSION

Space Shuttle Main Engine Lox and Fuel Turbopumps

As part of several NASA measures to improve the overall Space Shuttle's reliability, safety, and efficiency while reducing operating costs and attaining 55 missions per component, Pratt & Whitney / Government Engine & Space Propulsion (P&W/GESP) was awarded a contract to supply line replaceable Liquid Oxygen (Lox) and Liquid Hydrogen (Fuel) turbopumps for the SSME.

The actual hardware designs were similar to the Rocketdyne pumps (which depended upon fabricated components and had initiated flights of the shuttles [10]), but also included several advantages. The P&W pumps were much simpler in that the pumps incorporated Howmet's investment cast housings, which nearly eliminated the use of fabrication welds on the Lox pump main housings, and did eliminate all fabrication welds on the Fuel pump main housings. Over 200 welds were required to fabricate the original SSME pumps, whereas four fabrication welds were required on the P&W SSME pumps. Although the overall pump design was improved, the component designs were still very complex. Volute flowpaths, "hidden" passages, massive flanges, and integrally cast airfoils and flow guides contributed to the housing complexity and appeal as Howmet MX investment castings. These P&W pumps were also designed to be line replaceable with the Rocketdyne pumps, and perform at the same power levels.

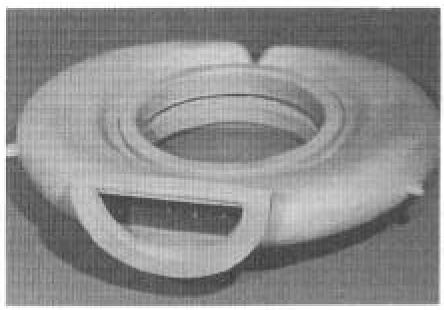
Current Status of SSME Components. To date, the SSME Alternate Turbopump Development (ATD) Lox pump program has progressed successfully. After extensive component testing, the initial development hardware was assembled into test engines. A series of pump tests were conducted at both P&W/GESP facilities in Florida and at NASA's Stennis Space Flight Engine Test Center in Mississippi. After the successful development engine test program, a Flight Certification Program was conducted. Again, the P&W SSME Lox pumps performed acceptably and were granted flight certification approval after attaining 10^3 minutes of engine test firing time (~125 missions). The first flight of a P&W Lox SSME pump occurred with the liftoff of Space Transportation System (STS) Mission 70 on July 13, 1995. One of the three main engines aboard the orbiter Discovery contained a P&W SSME Lox pump. To date, seven individual Lox pumps have flown. Two STS missions have utilized P&W Lox pumps for all three SSME's. Five additional pumps are schedule to fly in 1997. Howmet Hampton Casting has delivered approximately 18 sets of flight capable Main Lox pump hardware to date, with several more engine sets expected in the next two years. The Space Shuttle orbiters are projected to be in service beyond the year 2012.

The SSME/ATD Main Fuel Pump Program has also undergone extensive development and testing. However, the Fuel pump certification program was delayed for approximately two years due to NASA and Congressional funding considerations. All development and flight certification hardware has been delivered to P&W machining sources and three Fuel pumps will enter the flight test certification phase in October, 1997. First flight of the P&W Fuel turbopump is targeted for May, 1998.

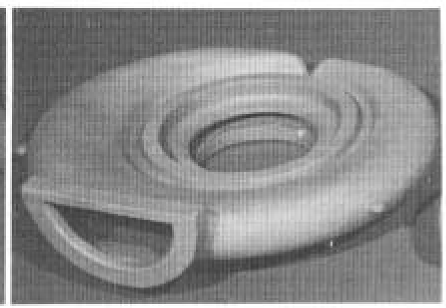
Processing of Fine Grain SSME Components. These components, several of which are shown in Figure 1, are produced similar to other Alloy 718 castings as described in [3] with some exceptions. After the casting cools, it is cleaned and given a proprietary homogenization cycle, followed by a 2050F (1121C)/4 hr. HIP cycle and a 2000F (1093C) re-solution cycle + gas fan cooling and nondestructive inspection (NDI). If gas tungsten arc weld (GTAW) reworking is necessary, the casting is re-HIP'd and re-solutioned and double aged, followed by weld blending and re-NDI. The grain size of this material was generally ASTM 3-5, with grain sizes of ASTM 1-2 allowed on gate pads. A typical microstructure from a 2 in. (50 mm) thick casting is shown in Figure 2, and a section through a fuel turbopump discharge housing is shown in Fig. 3.

Figure 1.

(Right) Components from the high pressure Lox turbopump.

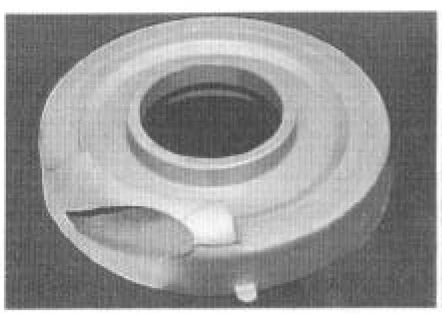


Forward Inlet Housing (~ 14 in. dia.)

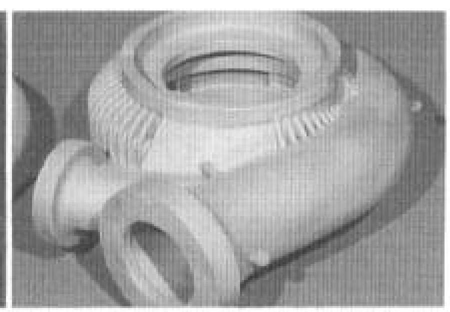


Aft Inlet Housing (~14 in. dia.)

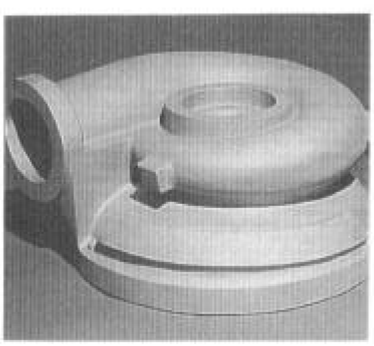
(Below) Components from the high pressure Fuel turbopump.



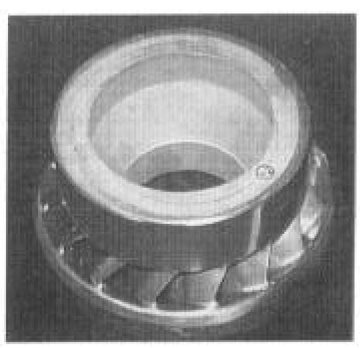
Preburner Housing (~9.5 in. dia.)



Discharge Housing (~14 in. dia.)



Inlet Housing (~20 in. dia.)



Inlet Vane Ring (~9 in. dia.)

Discharge Housing (~20 in. dia)

Tensile Properties of SSME Components. There were at least 90 cryogenic and 137 room temperature (RT) tensile tests utilized for final component qualification. All of the ultimate tensile strength (UTS), 0.2% yield strength (YS), elongation (EL), and reduction of area (RA) values are summarized with histograms in Figure 4. This data demonstrates the process capability of the Microcast-X casting process for several high-integrity components. The $\bar{x}$-3σ range of values in Table I below are compared to the average "oversize-bar" (OSB) data from [3]. The OSB data was generated from solid 0.63 in. (16 mm) diameter bars while the MFC bars were of the same final size, but came from cast sections 0.8-2 in. (19-50 mm) thick.

The histograms represent the range of MX data for the eight different parts, following casting, HIP, and heat treatment processes. The MFC tensile data compares very favorably with the OSB data produced earlier in [3], and in fact the RT MFC data exceeds the RT OSB data, in part due to the additional homogenization for SSME parts.

High Cycle Fatigue Properties of Welded and Unwelded SSME Components. The HCF properties of a fully processed SSME component were tested with and without

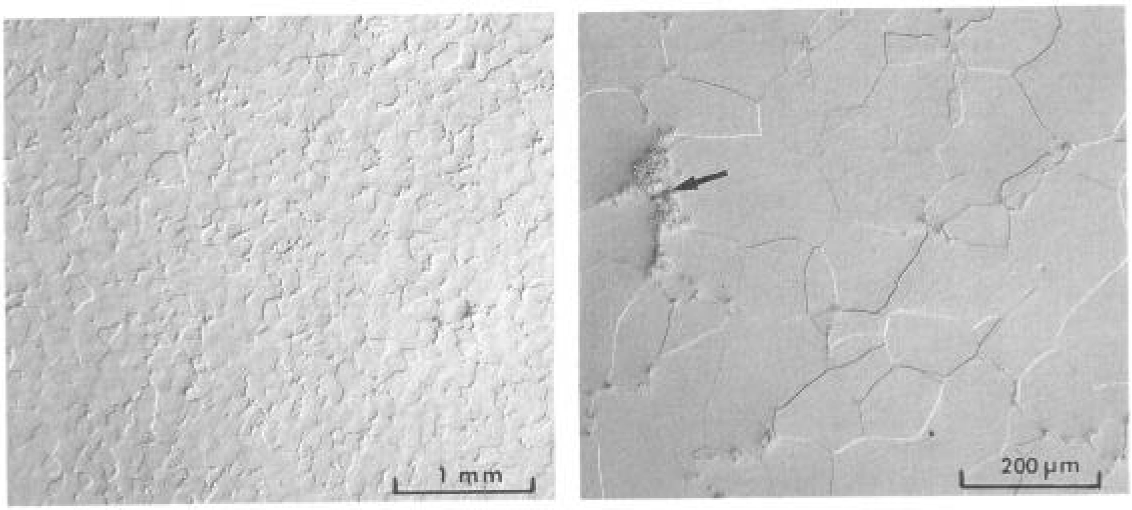


Figure 2. Microstructures from a typical MX SSME Alloy 718 component. Left, a uniform ASTM 3 grain size is shown and right, typical segregation (Laves+carbide phases).

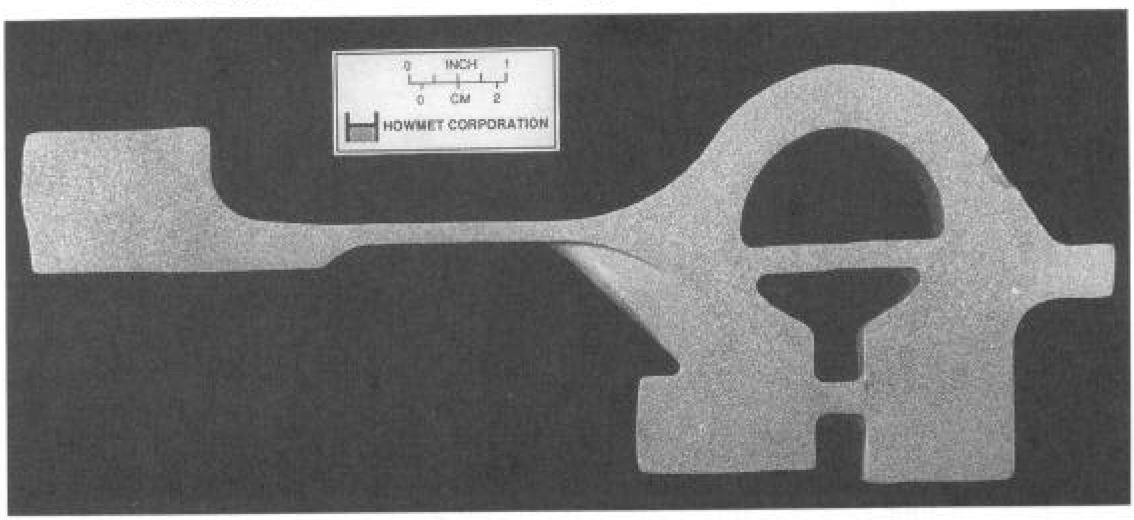


Figure 3. Cross-section through a fuel discharge housing showing a uniform fine grain size.

welds in the gauge section of the HCF bars under LN_2 at -320F (-196C) and gaseous H_2 at R.T. by P&W. This testing proved the viability of weld reworking a casting, and that welds did not reduce HCF properties of the castings. The HCF curves for these materials are shown in Figure 5. The LCF data was very similar to the HCF data.

Gas Turbine Engine Components.

Two proprietary components, one rotating and the other stationary, are being considered as MX Alloy 718 castings in gas turbine engines. The rotating component has been flight certified. The section sizes where MFC's were extracted for each of these castings were in the range of 0.5-0.8 in. (12-18 mm), and the "envelope" for the casting itself (including the gating) was approximately a 2 ft. (~610 mm) cube.

Table I - Mean Tensile Properties of Over-Sized Bar's (OSB's) from [3] Compared to SSME Component Test Bars Machined From Castings (MFC's)

	UTS		0.2% YS			
	ksi	MPa	ksi	MPa	%EL	%RA
-320F OSB $\bar{x}$	219	1509	160	1100	21	23
-320F MFC $\bar{x}$	206	1417	171	1175	15	19.4
-320F MFC $\bar{x}$-3σ	183	1258	153	1056	5	10
RT OSB $\bar{x}$	166	1146	137	945	15	23
RT MFC $\bar{x}$	167	1153	145	1000	20.3	25.8
RT MFC $\bar{x}$-3σ	156	1075	132	907	10	15

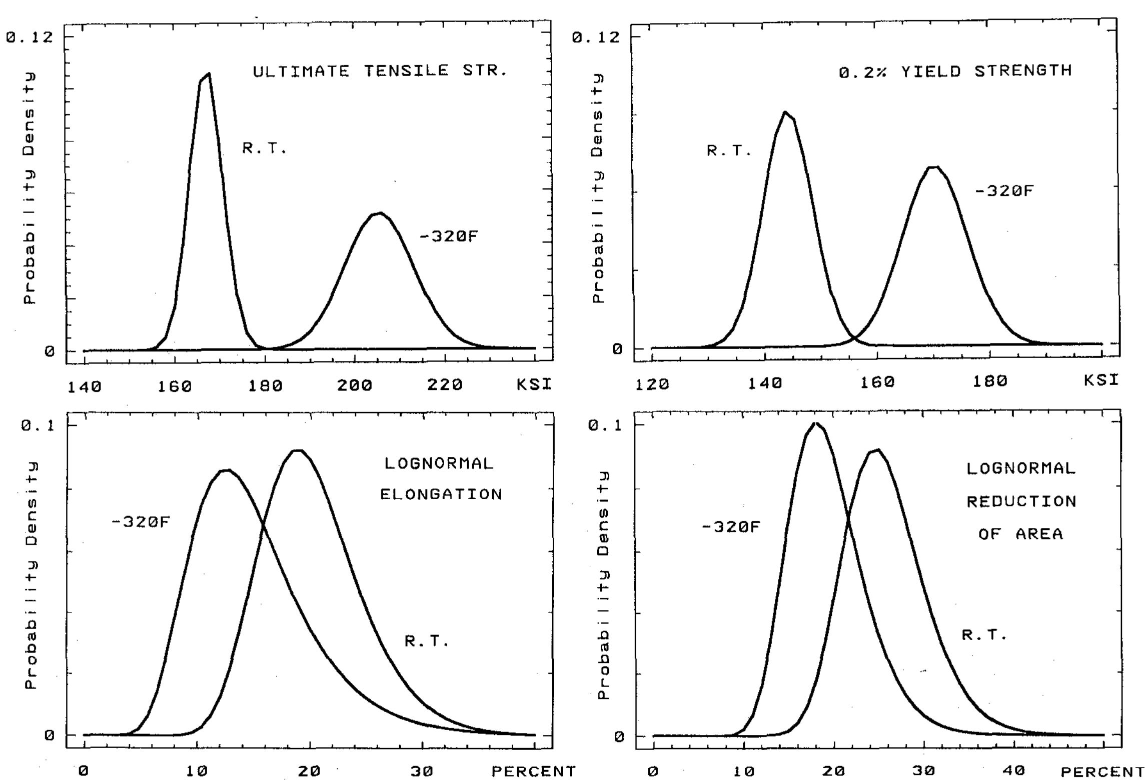


Figure 4. Histograms of tensile data at -320F (-196C) and at room temperature for eight SSME Alloy 718 Microcast-X components.

Component #1. During the initial casting trials, three amounts of "superheat" were used for pouring; 20F, 50F, and 100F (11, 28, and 55C). After standard processing including HIP and full heat treatment, duplicate RT and 800F (427C) tensile tests were conducted. Comparison of the RT tensile properties from each of these castings are given below in Table II.

These properties show the MFC data is very comparable to the OSB data generated in [3]. In addition, the data shows that significant reductions in UTS and YS occurs when the amount of superheat exceeds the Microcast-X casting range.

Component #2. This proprietary component was tested by the customer. The differences in processing includes a post-HIP 1950F (1066C) solution temperature, and 1400F/1200F (760C/649C) duplex age cycles. Tensile and stress rupture properties of the OSB's from [3] and tests using MFC's (three MFC tests were used to determine mean values) are shown below in Table III.

The UTS, YS, and S/R lives are slightly higher for the MFC's at both temperatures. However, the ductility is comparable, except for the stress rupture %RA for the MFC which is about half that for the OSB. The probable reason for the lower %RA is the absence of a 1750-1850F (954-1010C) solution cycle before ageing which has reduced the 1200F (649C) stress rupture %RA in other testing performed by Howmet.

Table II - Mean Tensile Values at RT and 800F (427C) for Three Casting Processes.

	UTS		0.2% YS			
	ksi	MPa	ksi	MPa	% EL	%RA
Nominal +20F Superheat, Grain Size ASTM 3-4 (Microcast-X process)						
RT OSB	166	1146	137	942	15	23
RT MFC	165	1140	140	965	12	18
800F OSB	151	1041	128	882	28	37
800F MFC	142	980	120	830	17	22
Nominal +50F Superheat, Grain Size ASTM 0-1 (Not Microcast-X process)						
RT MFC	144	990	121	835	10	15
800F MFC	128	880	107	740	14	17
Nominal +100F Superheat, Grain Size >1/4 in. (6 mm), (Not Microcast-X process)						
RT MFC	132	910	112	775	13	18
800F MFC	112	772	95	655	19	30

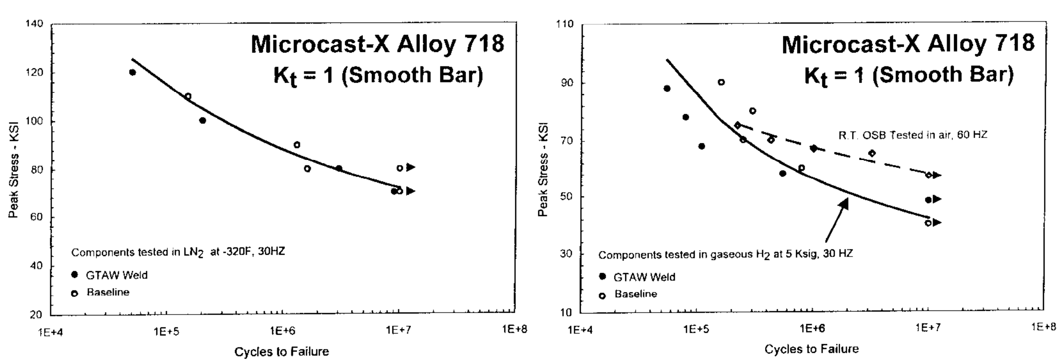


Figure 5. High cycle fatigue for welded and unwelded (baseline) Alloy 718 MX castings, at LN_2 and RT gaseous H_2 and air tests. P&W data, except air tests from [3].

Component #2 LCF tests. Strain-controlled LCF tests were conducted at RT, 400F (204C), and 1100F (593C) using MFC's. Those data, along with 900F (482C) LCF OSB data generated by Howmet in [3] is shown in Figure 6. The OSB and MFC data clearly form an uninterrupted family of LCF curves; however, degradation of LCF (most likely due to creep) is evident at 1100F (593C). The companion dynamic Modulus of Elasticity curves in Figure 7 will also allow the interested reader to convert these curves to stress vs. life curves.

Cast Slabs for Potential Airframe Components

Four slabs were cast for Boeing Commercial Airplane Co., in a single mold having four 4x6 in. (100x150 mm) slabs with a setup described by a "⊕" symbol. The "o" represents the pourcup and the " + " represents the four gates, below which were one

Table III - Average Tensile and Stress Rupture Properties for Microcast-X Alloy 718 Oversize Bars (OSB's) From [3] and Test Bars Machined From Castings (MFC's).

	Stress	Life	UTS		0.2% YS			
	ksi/MPa	hours	ksi	MPa	ksi	MPa	%EL	%RA
Tensile Properties								
RT OSB	-	-	166	1146	137	942	15	23
RT MFC	-	-	178	1225	149	1028	21	26
1000F OSB	-	-	144	992	123	848	26	38
1000F MFC	-	-	147	1016	127	875	25	35
Stress Rupture Properties								
1200F OSB	90/620	260	-	-	-	-	4	10
1200F MFC	90/620	445	-	-	-	-	4	4.9

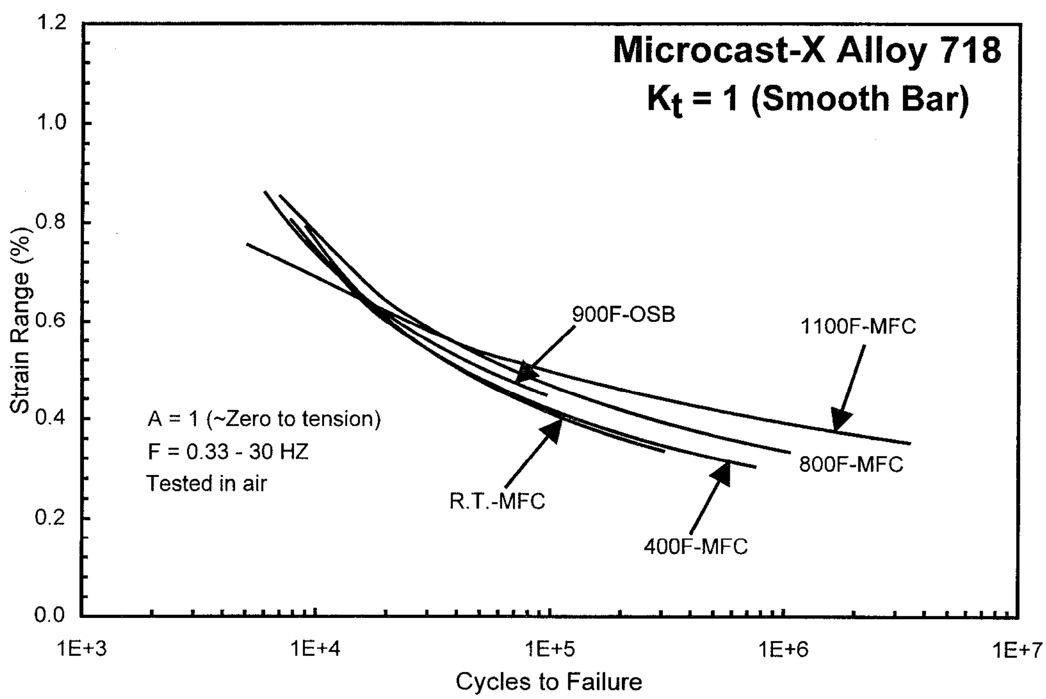


Figure 6. LCF data for Microcast-X Alloy 718 between -320F and 1100F (-196 to 593C) from P&W, [3], and another gas turbine engine manufacturer.

slab each. These slabs were cast to simulate material in the vicinity of the engines or APU's, where the local temperature would exceed the temperature capability for a titanium alloy. For the tensile tests, three test bars having a rectangular cross-section were used to test the 1/4 in. (6 mm) and 1/2 in. (12 mm) thickness, whereas 10 and 18 test bars with a round cross-section were used to test the 3/4 in. (18 mm) and 1-1/4 in. (31 mm) thick slabs, respectively. These data are shown in Table IV below:

Of particular interest were the following:

- Grain sizes of ASTM 5 were produced in the 1-1/4 in. thick slabs.
- The two thinner slabs had slightly higher strength and ductility, which shows a potential section size effect of MX castings. However, flat test bars were extracted from the smaller slabs and round test bars were extracted from the larger slabs, so a reason for this section size effect may be test bar geometry.
- There was less data scatter with the smaller slabs.

Table IV - RT Tensile Data For 1/4 in., 1/2 in., 3/4 in., and 1-1/4 in. Thick Slabs

	UTS		0.2% YS		EL	RA	ASTM
Slab Thickness	ksi	MPa	ksi	MPa	%	%	Grain Size
1/4 in. (6 mm)	176.8	1219	148.6	1024	22.3	-	5-6
$\bar{x}$-3σ	173.2	1194	142.5	982	20.6		
1/2 in (12 mm)	173.8	1198	146.5	1010	17.3	-	5-6
$\bar{x}$-3σ	169.0	1169	145.4	1002	12.7		
3/4 in (18 mm)	167.6	1155	141.7	977	15.5	19.2	5
$\bar{x}$-3σ	153.1	1055	128.5	886	7.9	6.0	
1-1/4 in. (31 mm)	167.0	1151	141.5	975	14.0	15.9	5
$\bar{x}$-3σ	151.7	1046	130.4	899	6.0	3.0	

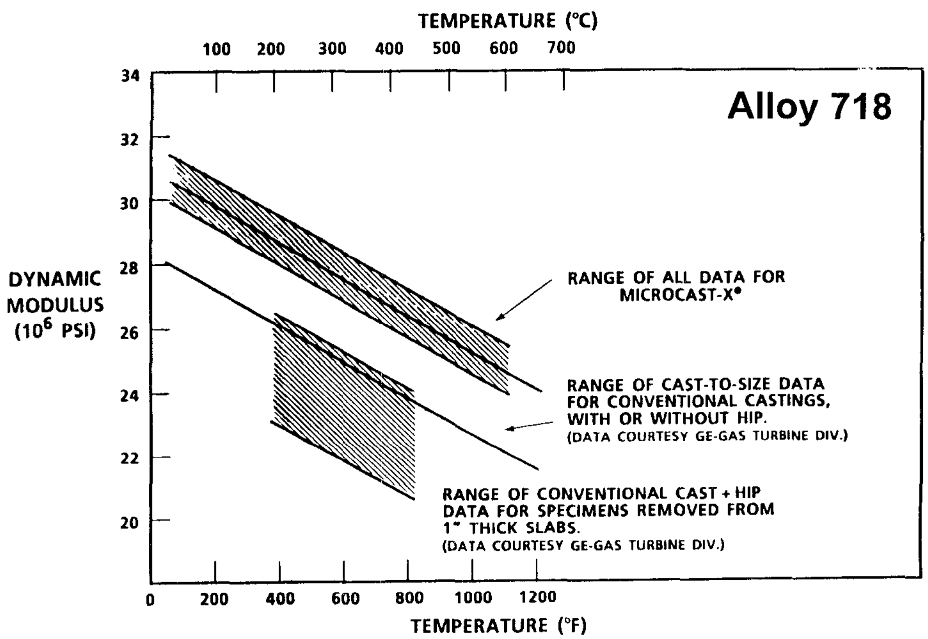


Figure 7. Dynamic Modulus of Elasticity versus temperature for investment cast + HIP Alloy 718 from [3 and 11].

SUMMARY

The fine-grained Microcast-X casting process for Alloy 718 has demonstrated tensile, stress rupture, LCF, and HCF properties from production components to be comparable to mechanical properties from oversized test bars used during the MX development phase. While the MX casting process has some limitations due to ability to fill thin sections, it is successfully used in several applications between cryogenic and ~1000F (593C) temperatures where the primary design considerations are tensile strength, LCF, HCF, and/or stress rupture properties.

ACKNOWLEDGMENTS

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