CHARACTERIZATION OF VACUUM DIE CAST INCONEL 718 AND DERIVATIVES (PWA 1472/PWA 1473)

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Abstract

Vacuum die casting is an advanced metal fabrication process being developed to produce premium quality parts for critical aerospace applications. As part of an extensive development effort, detailed microstructural and mechanical property characterization of vacuum die cast Inconel 718 and Inconel 718 derivatives (PWA 1472 - high strength alloy and PWA 1473 – low Laves alloy) was completed. Thermal cycles (including HIP) were defined to produce a uniform, homogeneous microstructure and material was subsequently evaluated for mechanical property response. Tensile, stress rupture, impact and fatigue testing showed that vacuum die cast Inconel 718 and PWA 1473 exhibited properties approaching premium grade rotor material. Vacuum die cast PWA 1472 showed superior strength and fatigue capability but exhibited a substantial reduction in tensile ductility and impact energy. All material exhibited a propensity for notch stress rupture failures. The vacuum die cast material shows the potential for use in critical aerospace applications although additional work needs to be conducted aimed at developing an improved balance of properties, particularly HCF and stress rupture capability.

Superalloys 718, 625, 706 and Various Derivatives
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Introduction

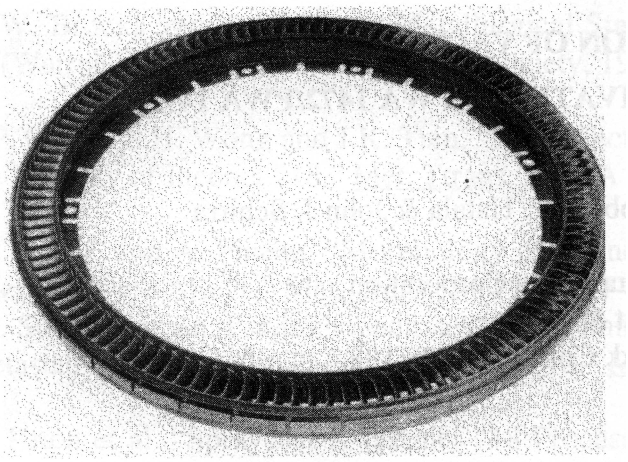

Figure 1 : Typical Cast Inconel 718 Integral Compressor Stator Ring Assembly.

Since its original development and introduction, Inconel 718 has made extensive inroads into turbine applications as static and rotating components. The alloy possesses an attractive combination of low cost, good intermediate temperature property balance and robust processing paths which all combine to promote use in the high compressor, burner and turbine modules of contemporary turbine engines. Material engineers quickly recognized the good weldability and unique characteristics associated with Inconel 718's use of Nb as the principal strengthening element and its sluggish precipitation kinetics. This resulted in the successful application of Inconel 718 to complex wrought, welded assemblies such as the diffuser case for P&W's (Pratt & Whitney) JT9D engine. Development and evaluation of investment cast Inconel 718 as a processing alternative was a logical path to reduce the cost associated with complex, welded wrought assemblies. Introduction of hot isostatic pressing (HIP) technology further facilitated the use of Inconel 718 as investment cast structural components such as diffuser (F100, PW2037, PW4000) and TOBI (tangential on board injection) cases. It was during the development of investment cast structural applications that several technical issues were identified including the development of brittle intermetallic phases such as Laves due to Nb segregation as well as the presence of post HIP porosity due to the presence of surface connected shrinkage in the as cast components. Homogenization heat treatments have been developed to minimize the impact of the as cast segregation, however technology to eliminate the impact of surface connected porosity has yet to be developed. Significant advancements in solidification and casting process modeling have contributed to reducing both the presence of as cast porosity and segregation, further improving the quality of cast Inconel 718 components.

In addition to enhancing the quality of cast components, much of the development activity has focused on improving the properties of cast Inconel 718 to approach the levels exhibited by wrought Inconel 718. One approach has been alloy development to increase strength such as P&W's PWA 1472 alloy. Major processing technologies explored include Osprey processing (sprayforming) [1], low super heat casting, mold agitation and centrifugal casting techniques [2]. Each of these process technologies are aimed at refining the casting grain structure, reducing as cast segregation and minimizing surface connected shrinkage porosity. Characterization of material fabricated using these processes has shown the product to exhibit properties approaching wrought and in the instance of sprayformed material equivalent to wrought. These advanced processing techniques have found aerospace applications including the production of integral high compressor stator ring assemblies (Figure 1). Stator components present a particularly challenging application in that not only must structural integrity be maintained, but complex aerodynamic geometries as well.

A rapidly growing application of Inconel 718 is as forged airfoils for use in the high compressor. The good forgeability of Inconel 718 enables the fabrication of complicated airfoil shapes while the alloy possesses the required property balance as replacement for titanium due to higher operating temperatures. Demand for increased operating efficiency and the availability of rapid aerodynamic analytical tools based on computational fluid dynamics has provided the motivation for and given the designers the tools they need to create airfoil configurations that are pushing the limits of Inconel 718 airfoil forging capability. The increased usage of Inconel 718 airfoils and the demand for a lower cost fabrication process capable of producing the required complex airfoil configurations provided the motivation for Pratt & Whitney to evaluate alternative fabrication techniques. Particular emphasis was on adapting the well established die casting process to higher temperature, reactive material processing.

Pratt & Whitney conducted a joint development program with Howmet Corporation to develop and apply the vacuum die casting process to the fabrication of Inconel 718 airfoils and assess the characteristics of the resultant product relative to the current bill of material forged application. By integrating high integrity vacuum melting and pouring systems with conventional horizontal die casting equipment, Howmet had provided a means of transitioning the process for use with reactive alloys. The vacuum die casting process offers many advantages [3-4] such as the ability to achieve good dimensional reproducibility (due to casting into a large metal die and use of pressurized injection), very refined grain structure (rapid solidification due to the large metal dies), minimal porosity (due to vacuum casting and pressurized injection), and high volume production. Combined, these advantages make vacuum die cast Inconel 718 a viable alternative to forged Inconel 718 for airfoil applications. This paper will present a summary of the characterization activity conducted by Pratt & Whitney as part of the joint development program. During the development activity, the microstructural and mechanical behavior response of vacuum die cast Inconel 718 and Pratt & Whitney's Inconel 718 derivatives PWA 1472 (high strength alloy) and PWA 1473 (low Laves alloy) were assessed and results are summarized here.

Details

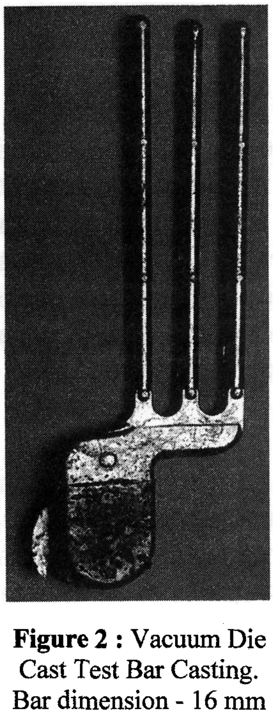

Figure 2 : Vacuum Die Cast Test Bar Casting. Bar dimension - 16 mm dia. by 305 mm length.

All casting trials were conducted using the prototype vacuum die casting machine located at Howmet's Operhall research center located in Whitehall, MI. Test material was produced by remelting small charges (about 3.6 kg) of alloy and producing cast test bars for subsequent processing. As part of the Inconel 718 evaluations, a series of castings were produced looking at a range of casting parameters including melt superheat and shot speed. Over the range of parameters utilized no significant differences in structure or properties were observed. Each casting produced three oversize test bars nominally 16 mm in diameter by 305 mm in length (Figure 2) for subsequent processing and evaluation. Over 20 castings were produced from Inconel 718 with five produced from PWA 1472 and one from PWA 1473. The as cast structure was characterized for each of the test bars using standard metallographic techniques. While the use of vacuum die casting significantly reduces the amount of shrinkage porosity that is present, it does not completely eliminate it. As such, HIP is expected to be an integral part of the processing sequence for critical applications such as airfoils. To define the optimum HIP cycle (heal porosity, homogenize the casting and retain the fine as cast grain size) a series of simulated HIP cycles were evaluated via thermal exposure. The initial trials were conducted on the cast Inconel 718 test bars. Segments were sectioned from the test bars and processed over the temperature range 982°C to 1066°C (in 10°C increments) and for times of one, four and eight hours. After heat treatment the samples were processed using standard metallographic techniques and evaluated for microstructural uniformity (segregation) and grain size. Results from this study suggested that a 4 hour cycle would be sufficient for homogenization and an additional heat treat study (in 10°C increments) over the temperature range 1010°C to 1093°C for 4 hours was conducted. The HIP cycle selected was 1024°C/172.4 MPa/4 hours which was applied to each of the vacuum die cast materials. After HIP each material was processed through their respective standard heat treat processes (Table I). Tensile and combination (smooth and notch <Kt = 3.8>) stress rupture specimens were machined from all materials. In addition, Charpy impact, smooth fatigue and notch fatigue specimens were machined from the Inconel 718 and PWA 1472 test bars. Testing was conducted over a range of temperatures and stresses and the test conditions are summarized in Table II. Post test metallographic and fractographic characterization was conducted on selected test specimens.

Table I : Post HIP Heat Treatment Parameters for Die Cast Inconel 718 and Derivatives

Alloy	Solution Cycle	Precipitation Cycle
Inconel 718	954°C /1 hr + Air Cool	718°C /8 hrs – 38°C/hr – 621°C /8 hrs
PWA 1472	1010°C /1 hr + Air Cool	760°C /4 hrs – 38°C/hr – 663°C /2 hrs
PWA 1473	954°C /1 hr + Air Cool	732°C /8 hrs – 38°C/hr – 663°C /8 hrs

Table II : Mechanical Property Test Matrix for Die Cast Inconel 718 and Derivatives

	Tensile			Stress Rupture	Impact		Fatigue
Alloy	20°C	455°C	650°C	650°C / 724 MPa	20°C	455°C	455°C
Inco 718	X	X	X	X	X	X	X
PWA 1472	X	X	X	X	X	X	X
PWA 1473		X		X			

Results

Chemical and Microstructural Characterization. Chemistry for each of the die cast materials is presented in Table III and shows that the castings easily conform to specification requirements for each of the alloys with the exception of Nb + Ta content which tended to be at or outside the low end of the specification. In general the measured Nb + Ta level in the casting was consistently lower than the charge level during the casting characterization. No physical basis for the Nb + Ta fade was identified. The other observation relative to the casting chemistry was that there tended to be oxygen pickup in the castings relative to the charge composition.

The general as cast structure for each of the cast alloys was similar with only subtle variations (primarily segregation related) existing among the alloys. The predominant structure consisted of a fine, equiaxed cellularly solidified grain structure (ASTM 8 to 9) with areas of intercellular segregation (Figure 3). There also tended to be regions of very fine as cast grains at or near the casting surface (due to the rapid solidification rates caused by the metallic dies) as well as cellularly solidified regions generally free of segregation. In general the greatest amount of as cast segregation tended to be observed for the PWA 1472 material, followed by the Inconel 718 castings and then the low Laves alloy PWA 1473.

Table III : Measured Chemistry (wt %) for Die Cast Inconel 718 and Derivatives

	Inconel 718			PWA 1472			PWA 1473		
Element	Min	Max	Actual[1]	Min	Max	Actual[1]	Min	Max	Actual[1]
Nb + Ta	5.15	5.5	5.0	5.75	6.25	5.66	4.75	5.25	4.94
Al	.4	.8	.53	.4	.8	.46	.4	.8	.46
Ti	.65	1.15	.97	1.75	2.25	1.93	.65	1.15	.98
Cr	17	21	19.2	11	13	12.6	11	13	12.2
Mo	2.8	3.3	3.15	2.8	3.3	3.14	2.8	3.3	2.99
Fe		19	17.8	17	21	17.9	17	19	18
C	.02	.04	.064	.02	.06	.055	.02	.06	.042
B	.002	.006	.002		.005	.002		.005	.002
O			.006			.013			.007
P		.015	.003		.015	.007		.015	.012

[1] Balance nickel.

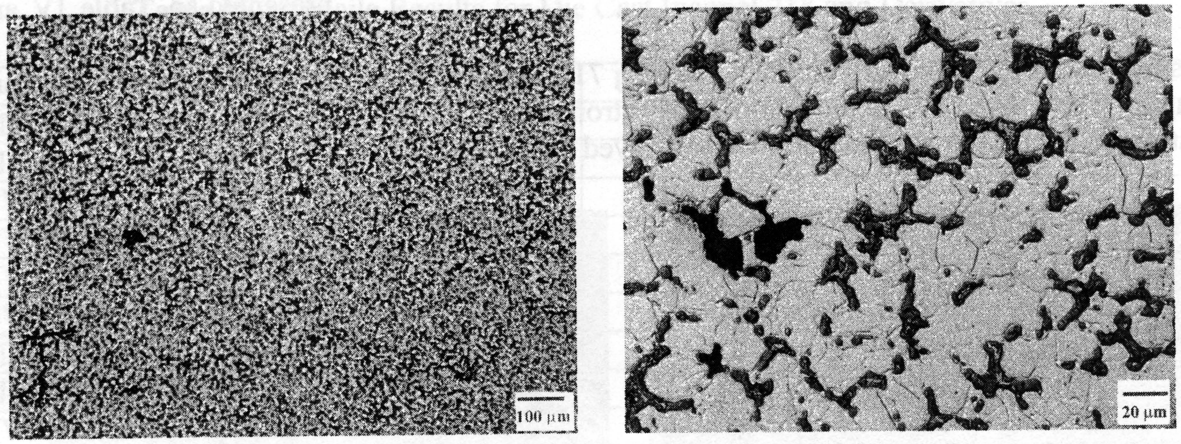

Figure 3 : Typical As Die Cast Inconel 718 Microstructure

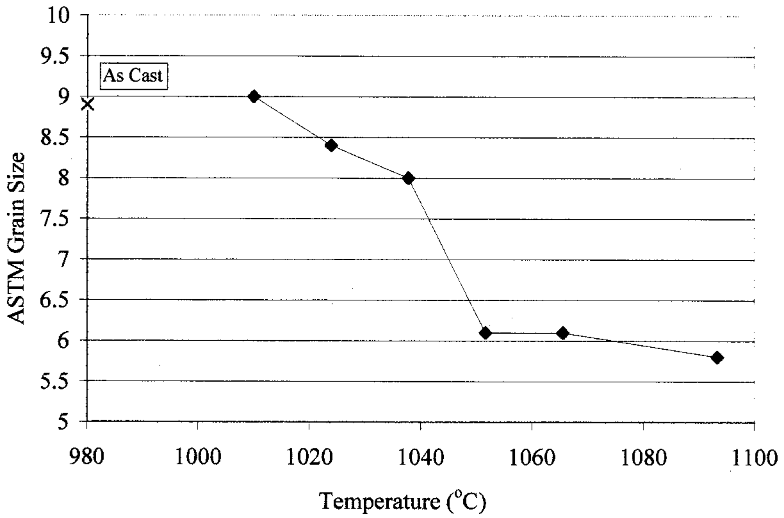

Figure 4 : Effect of a 4 hour thermal exposure on the grain size of die cast Inconel 718.

Measured grain sizes from the heat treat studies are presented in Figures 4 and 5. As cast, the average grain size typically ranged from ASTM 8 to 9 and coarsened slightly over the temperature range studied for exposures of 4 hours (Figure 4). This trend was verified on the refined heat treat study (Figure 5). In addition to verifying the grain coarsening behavior, review of the cast structures showed most of the as cast segregation was eliminated after the 4 hour exposure at 1024°C and completely eliminated at 1062°C. Based on the combination of the retained fine grain size and adequate homogenization, the test material was HIP processed at 1024°C and then heat treated per the processes listed in Table I. Consistent with the heat treatment development

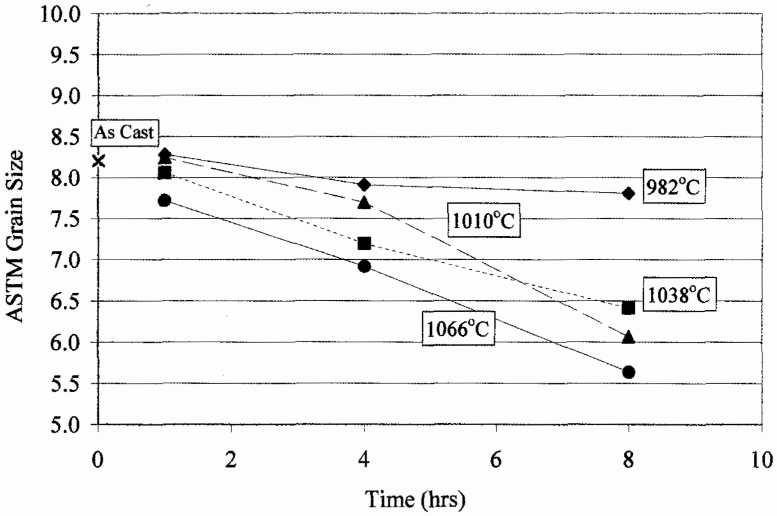

Figure 5 : Effect of a time and temperature on the grain size of die cast Inconel 718.

trials, the test material exhibited a relatively fine grain size with the casting segregation significantly reduced. Typical microstructures for the fully processed materials are presented in Figures 6 (Inconel 718), 7 (PWA 1473) and 8 (PWA 1472). Hardness ranged from 40 to 42R$_C$ and is typical for the materials.

<u>Mechanical Test Results.</u> Tensile results are presented in Table IV and show that, similar to investment casting behavior, die cast Inconel 718 and PWA 1473 exhibit equivalent tensile strengths with PWA 1472 being significantly stronger. In general, there was very little scatter in the strength results but with more scatter observed in the tensile ductility results.

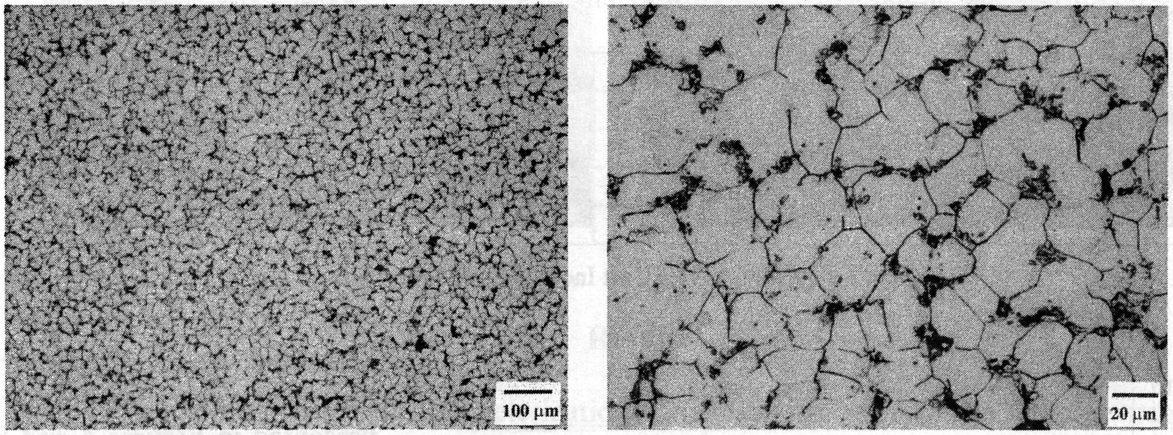

Figure 6 : Typical Microstructure of Fully Processed Die Cast Inconel 718.

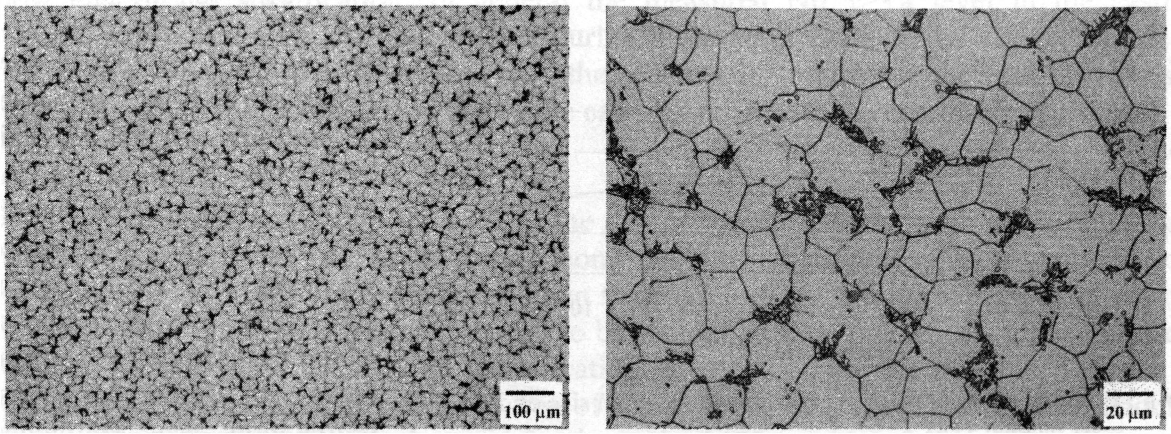

Figure 7 : Typical Microstructure of Fully Processed Die Cast PWA 1473.

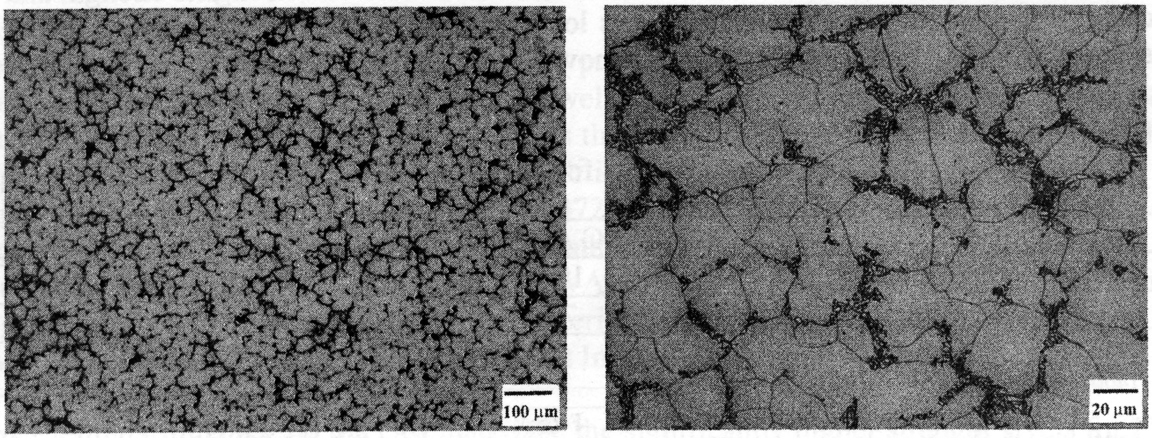

Figure 8 : Typical Microstructure of Fully Processed Die Cast PWA 1472.

Table IV : Tensile Results for Die Cast Inconel 718 and Derivatives

Alloy	Temp	YS (MPa)	UTS (MPa)	% EL	% RA
Inco 718	20°C	991	1253	11.1	14.3
Inco 718	20°C	1011	1293	20.6	25.5
PWA 1472	20°C	1207	1407	6.5	9.4
PWA 1472	20°C	1228	1464	10.9	13.9
PWA 1473	455°C	847	1107	18.8	28
PWA 1473	455°C	847	1117	20.1	33.3
Inco 718	455°C	855	1116	22.7	33.8
Inco 718	455°C	876	1138	18.9	19
PWA 1472	455°C	1087	1287	14.2	14.6
PWA 1472	455°C	1102	1316	17.8	27.7
Inco 718	650°C	825	1042	21.6	26.3
Inco 718	650°C	844	1026	13.2	15.4
PWA 1472	650°C	1034	1213	5.8	10.9
PWA 1472	650°C	1074	1232	6.3	8.6

Stress rupture results are presented in Table V. All testing was conducted at 650°C with stresses of 724 or 758 MPa. Each of the alloys exhibits some degree of notch sensitivity. PWA 1472 showed the most notch rupture sensitivity while Inconel 718 and PWA 1473 were slightly better and comparable to each other.

Table V : Combination Smooth/Notch ($K_t = 3.8$) Stress Rupture Results for Die Cast Inconel 718 and Derivatives

Alloy	Stress (MPa)	Notch Life	Smooth Life	% EL	% RA
PWA 1473	724	n/a	22.9	5.5	5.3
PWA 1473	724	.6	13.3	5.2	12.9
Inconel 718	758/724	1.9	4.1[1]/ 29.8	-[1]/6.3	-[1]
Inconel 718	758	n/a	13.1	4.4	9.3
PWA 1472	758	.1	.9[1]	-[1]	-[1]
PWA 1472	758	0	.4[1]	-[1]	-[1]

[1] Failed in threads upon reloading. Smooth life indicated is cumulative (notch and smooth) life.

Charpy impact results are summarized in Table VI. Consistent with its higher strength and lower ductility levels, die cast PWA 1472 exhibits lower impact resistance than die cast Inconel 718. Testing of PWA 1473 was not conducted, however results would probably be similar to those measured for Inconel 718.

Table VI : Charpy Impact Results for Die Cast Inconel 718 and PWA 1472

Alloy	20°C Impact (J)	20°C Avg. (J)	455°C Impact (J)	455°C Avg. (J)
Inconel 718	17,18.3,20.3,22.4	19.5	26,27.8,41,42.7	34.4
PWA 1472	6.1,6.8,8.1,10.2	7.8	10.8,12.2,13,14.2	12.5

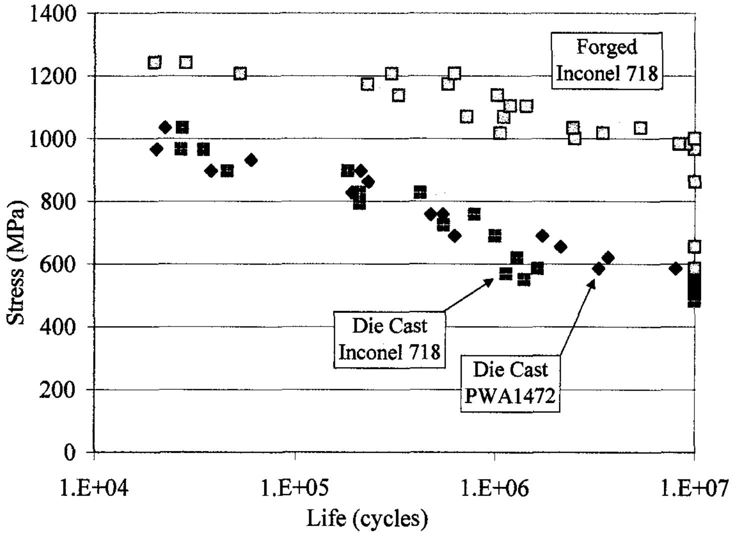

Figure 9 : Comparison of the 455°C smooth fatigue capability of forged and die cast Inconel 718 and die cast PWA 1472.

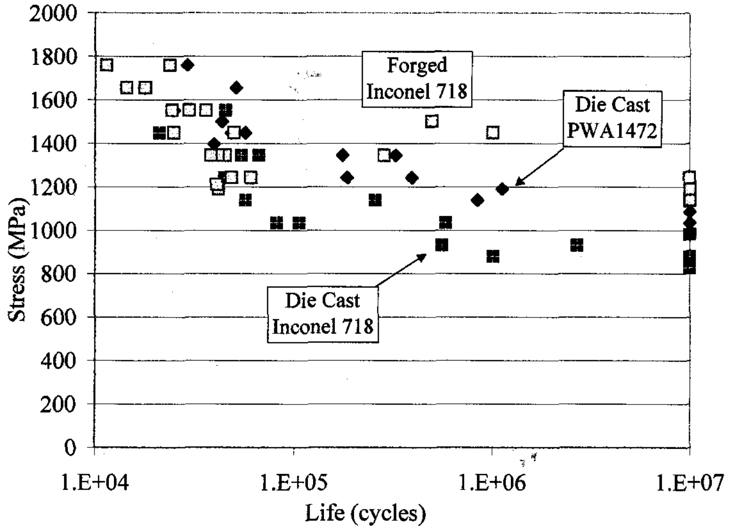

Figure 10 : Comparison of the 455°C notch (K_t=3) fatigue capability of forged and die cast Inconel 718 and die cast PWA 1472.

Smooth and notch fatigue results are presented in Figures 9 and 10, respectively. Testing was conducted at 455°C and S-N curves were generated for each condition. Notch testing was conducted with a stress concentration factor of 3 and the data is plotted at the concentrated stress values. Forged Inconel 718 baseline material was tested as well and results are also plotted with the die cast results. The results clearly show that die cast Inconel 718 and PWA 1472 exhibit similar smooth fatigue capability (both low and high cycle) despite the significant strength differences between the two materials. At an equivalent smooth cyclic life, forged Inconel 718 shows a 200 to 400 MPa advantage over both die cast materials under both low and high cycle conditions. Post test failure analysis indicated that defect (oxide) and defect free related fatigue failures were equally interspersed throughout the die cast material results indicating that casting defects are not the source of the reduced die cast material fatigue capability.

Review of the notch results (Figure 10) shows that the die cast PWA 1472 and forged Inconel 718 exhibit equivalent fatigue capability (low and high cycle). The die cast Inconel 718 show comparable low cycle capability but slightly lower high cycle capability.

Discussion

A comparison of the room temperature tensile properties of Inconel 718 (and its derivatives) produced using various casting techniques as well as premium forged material is presented in Figure 11. Review of Inconel 718 results shows that both the fine grain investment cast and die cast product exhibit similar yield strengths, both improved over conventional cast material and inferior to forged capability and cast PWA 1472. With respect to ultimate strength, die cast Inconel 718 shows increased capability over both conventional and fine grain investment cast material and approaching the level of cast PWA 1472. Die cast PWA 1472 shows ultimate strength equivalent to forged. The die cast material exhibits improved ductility over their cast equivalents with both fine grain cast and die cast Inconel 718 comparable to forged material.

Comparing the results for the die cast materials, the significantly higher strength levels for PWA 1472 indicate that additional improvements in die cast Inconel 718 strengths could be achieved by increasing the Nb content of the alloy. However the increased Nb content must be balanced against reduced ductility. As has been the case for its adaptation to other manufacturing processes, optimization of the Inconel 718 chemistry would be required to achieve an improved balance of properties.

It is interesting to note that even with the very fine solidification rates present in the die casting process (>1650°C/minute), segregation (as manifested by the presence of Laves phase and delta phase concentrations) was observed in each of the die cast materials. This highlights the strong segregation propensity of the alloy. However, the thermal trials showed the die cast segregation homogenized at significantly lower temperature and time exposures than conventionally cast material, probably due to the finer grain size/increased grain boundary area enhancing diffusion. This indicates that while increasing the Nb level to improve strength more segregation should result, it would be readily homogenized. In addition, the die cast grain size stays relatively stable at higher than expected temperatures relative to forged material. This behavior is critical to enable a heat treat window sufficient to achieve homogenization without losing the property benefits provided by the finer grain size. The grain size stability of the die cast material could be due to both the absence of forging strain reducing the driving force for grain growth as well as the presence of a dispersion of fine carbides restricting grain coarsening.

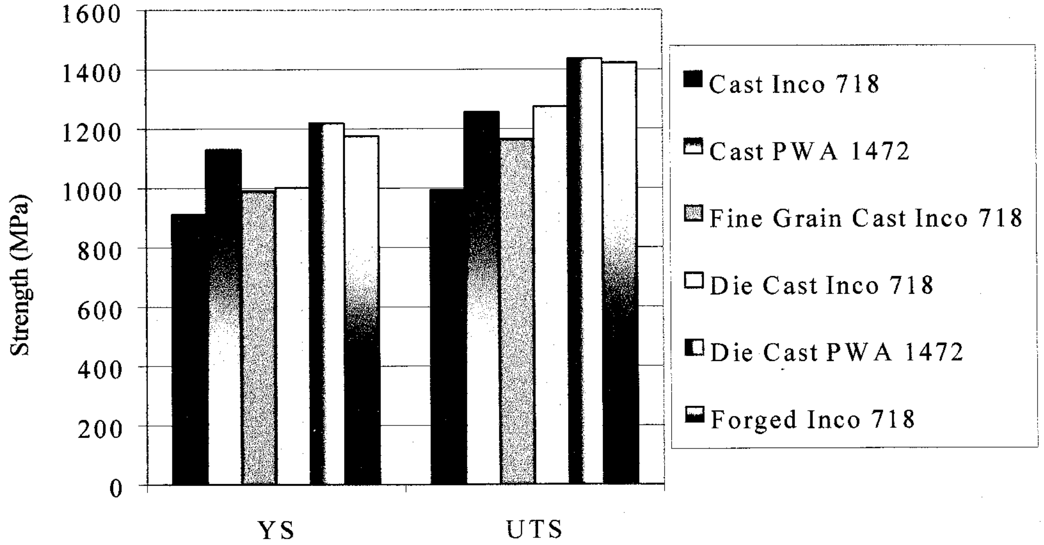

Figure 11 : Comparison of Typical Room Temperature Tensile Properties of Inconel 718 and it's High Strength Derivative (PWA 1472) Produced Using Various Techniques.

In summary, this evaluation indicates that Inconel 718 and its derivatives are readily adaptable to the die casting process although additional refinement and optimization is required. A generally uniform, refined grain structure is achieved in the die cast and HIP + heat treated product. While a reasonably good balance of properties is achieved, work needs to be conducted to improve the notch stress rupture resistance of the die casting material. When Inconel 718 is adapted to new fabrication processes, this is often encountered and has traditionally been addressed primarily through heat treatment optimization and with some alloy refinement. It is expected that this approach would be successful in producing a notch ductile die cast material. For critical rotating applications such as airfoils, additional improvements in smooth fatigue capability must also be achieved. Based on the observation that die cast PWA 1472 and die cast Inconel 718 exhibit comparable smooth fatigue capabilities, increasing strength alone will not be sufficient to improve the smooth fatigue capability. Additional work is required to identify the development path for improved smooth fatigue capability.

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