POLYCRYSTALLINE GRAIN CONTROLLED CASTINGS

FOR ROTATING COMPRESSOR AND TURBINE COMPONENTS

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Summary

Allison evaluations of integrally cast superalloy components have shown that the Grainex and Microcast X processes developed by the Howmet Turbine Components Corporation offer substantially refined macrostructures and improved microstructural uniformity over conventional castings. Both processes offer improved tensile properties and the potential for reduced data scatter. Of the two processes, the Microcast X castings showed grain sizes that were on the order of ASTM 3 to 5, compared with ASTM 0 for the Grainex product. It was determined that the Microcast X process offered the best potential for achieving maximum tensile property response and that Microcast X IN-792 + Hf, Inconel 718, and AF 95 alloys offer attractive mechanical properties for moderate temperature/stress applications. With additional work it may be possible to selectively utilize near-net-shape Microcast X castings in static and rotating turbine applications as substitutes for forgings.

Introduction

Integrally cast compressor and turbine rotors were introduced by Allison into the 317 shaft horsepower (shp) T63 engine design in the early 1960s. Since that time the use of integrally cast rotors at Allison has spread to several additional small engine designs ranging from 300 shp to 850 shp for vehicular, fixed wing, and rotary wing applications.

When Allison first introduced integrally cast 17-4PH compressor and Inco 713C turbine rotors, there were virtually no grain control restrictions placed on the casting process. Nevertheless, early experiences at Allison were generally very favorable, and thus as more powerful derivative designs developed, integrally cast components were incorporated. With the exception of hot isostatic press (HIP) processing, which was first applied to selected Model 250 17-4PH compressor components to heal microshrinkage and maximize casting yields, there were for a number of years no major changes made to the basic casting processes that had been introduced with the early T63 engine development program.

In the early 1980s, Allison evaluations were initiated on a new second-generation casting process that was under development by the Howmet Turbine Components Corporation. This proprietary process, which is being used in selected production applications, carries the Howmet designation Grainex®*. In this process the casting is agitated during solidification to shear dendrites and initiate multiple nucleation sites, which subsequently lead to a uniform refined grain size. Because microshrinkage is typically present in the as-cast Grainex product, HIP processing is required to fully densify the cast product. The advantages of this more structurally uniform product include increased strength levels and decreased property scatter. A comparison of conventionally cast and Grainex cast Mar-M247 turbine rotors is shown in Figure 1 and illustrates the grain refinement achievable via the Grainex process.

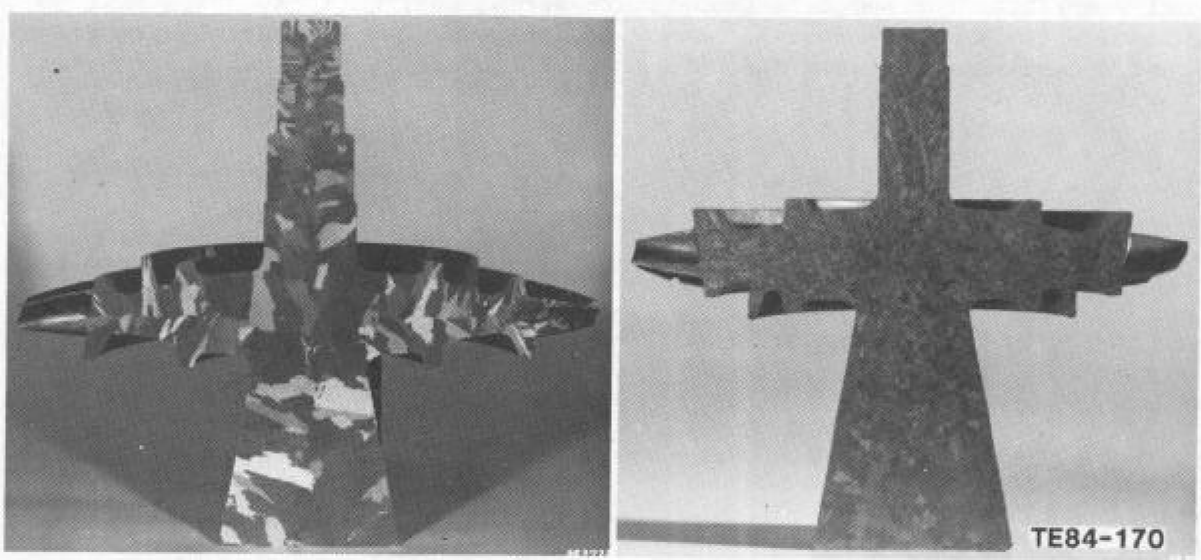

Figure 1. Model 250-C34 turbine rotors cast by conventional casting techniques (left) and the Grainex process (right).

* Grainex is a registered trademark of the Howmet Turbine Components Corporation.

In 1983, Howmet introduced a third-generation casting process with the potential for effecting further refinements in the grain size of integrally cast components. This process, which is in its early stages of development, is referred to as Microcast X and offers the potential for producing integrally cast rotor components with a grain size in the ASTM 3 to 5 range. In comparison with Grainex castings, which exhibit a dendritic structure with grain size in the ASTM 0 category, the Microcast X microstructures exhibit a cellular type of structure with grain sizes that are competitive with those developed in wrought superalloy components. Figure 2 shows an example of an AF 95 Microcast X microstructure cast as a test bar 2.5 inches in diameter by 7 inches long. By comparison, the coarser and more dendritic microstructure typical of a Grainex casting is shown in Figure 3.

Producing the highly refined cast structures represented by the proprietary Microcast X process involves very fast cooling rates subsequent to casting. To ensure that the castings are fully dense, HIP processing is routinely utilized. Because of the very fine grained structures in a wide variety of shapes and sizes that are achievable by the Microcast X process, Allison has been involved in evaluations focusing on relatively low temperature integrally cast rotor and blade applications as well as preforms that can be subsequently forged into disk-type configurations.

Second Generation Grainex Process Evaulations

During the development of the advanced technology Model 280-C1 turboshaft engine, it became apparent that conventional casting techniques resulted in a highly undesirable macrostructure in the relatively large IN-792 power turbine rotors. Despite repeated attempts with conventional

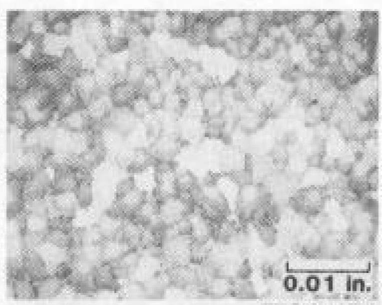

Figure 2. Microcast X AF 95 microstructure.

Figure 3. Grainex Mar-M247 turbine rotor microstructure.

casting practices, yields and anisotropic property response remained as issues of concern.

The initial Grainex casting efforts at Howmet with the third-stage turbine rotor configuration were made with the Mod 5A alloy (see Table I). Following the casting of several rotors, the results were encouraging; an impressive degree of grain refinement was developed. In addition, X-ray and zyglo quality were found to be satisfactory.

Subsequently, Grainex as well as conventionally cast Mod 5A rotors that had been made for baseline purpose were HIP processed and heat treated. Mechanical property tests that were performed on the rotors to assess their potential for moderate temperature power turbine applications are summarized in Table II. These tests indicated that the Grainex rotors possessed improved tensile and stress rupture capabilities over conventionally processed rotors. From a burst standpoint, which ultimately sizes these rotors, the tensile strength advantage exhibited by the Grainex rotors was significant.

In terms of low-cycle fatigue (LCF) results, the strain controlled tests failed to show any significant improvement over the conventionally cast product. However, had the data been evaluated considering the role of each specimen's modulus of elasticity, a comparison would have yielded a different conclusion. Specifically, had each strain range value been converted to pseudo or neuber stress (as is commonly done at other engine manufacturers), the Grainex curves represented as a function of either of these parameters would have been higher. This would have occurred by virtue of the higher modulus characteristics inherent in the Grainex product. This is supported by a program in which modulus data were generated from conventionally and Grainex cast Mar-M247 turbine rotors in a Model 250 configuration. In this program, the dynamic modulus of the material was determined as a function of orientation within the rotor over a temperature

Table I.
Alloy compositions.

Alloy	Ni	Cr	Co	Mo	W	Ta	Cb	Al	Ti	Fe	Mn	Si	C	B	Zr	Other
IN-792	61	12.4	9.0	1.9	3.8	3.9	--	3.1	4.5	--	--	--	0.12	0.020	0.10	--
Mod 5A	61	12.6	9.0	2.0	4.0	4.0	--	3.4	4.1	--	--	--	0.09	0.015	0.11	--
IN-792 + Hf	61	12.4	9.0	1.9	3.8	3.9	--	3.1	4.5	--	--	--	0.12	0.020	0.10	1.0 Hf
AF 95	61	14.0	8.0	3.5	3.5	--	3.5	3.5	2.5	--	--	--	0.04	0.010	0.05	--
Inconel 718	52.5	19.0	--	3.0	--	--	5.1	0.5	0.9	18.5	0.2	0.2	0.04	--	--	--

Table II.
Mechanical property comparisons for cast Mod 5A.

		Tensile			
Condition	Test temp--°F	0.2% YS--ksi	UTS--ksi	El--%	RA--%
Conventionally cast	70	121.5	136.8	6.2	12.9
Grainex cast	70	131.4	154.9	5.4	5.7
Conventionally cast	1200	107.7	139.3	6.8	10.0
Grainex cast	1200	115.1	158.4	6.0	7.9

	1400°F/95 ksi Stress Rupture			900°F LCF (K_t = 1, A = 1)	
Condition	Life--hr	El--%	RA--%	Total strain--%	Cycles
Conventionally cast	23.3	5.4	18.3	0.65	8524
Grainex cast	103.8	3.8	6.7	0.65	7834

range from 70°F to 1800°F. As can be seen in Table III, the modulus values for the Grainex material were generally higher and much more consistent than for the conventionally cast material. This reflects the superior isotropic behavior of the Grainex material and implies reduced scatter and higher statistical minimum properties.

Overall, Allison evaluations to date with integrally cast rotors produced by the Grainex process have been most encouraging. Best applications of the technology appear to be moderate temperature applications such as power turbine rotors, in which the fine grained airfoils are not creep rupture limited and sizing is often limited by tensile strength related burst requirements.

Third Generation Microcast X--Process Evaluations

Interest in the relatively new Microcast X process has focused heavily on latter-stage turbine blades for Model 571 turboshaft and turbine disks for T56-A-427 turboshaft engine applications. These components were selected because of the modest stress/temperature environment in these applications. The potential for cost reduction is considerable by the substitution of near-net-shape investment castings for the bill-of-material Waspaloy and Inconel 718 forgings.

To evaluate the Microcast X product, fourth-stage Model 571 turbine blades and test bars were procured from Howmet in the IN-792 plus hafnium composition. In addition, Howmet supplied full-scale third-stage T56-A-427 turbine disks, which were cast into a near-net-shape sonic configuration. The alloys selected for the disk evaluations were Inconel 718 and AF 95. Compositions of the IN-792 plus hafnium, Inconel 718, and AF 95 alloys are presented in Table I.

IN-792-Plus-Hafnium Turbine Blade Evaluations

The turbine blades supplied by Howmet were a uniformly fine grained ASTM 3 to 5, as shown in Figure 4. Extensive examination of the castings revealed slight areas of microshrinkage in airfoil locations which in the future will require modification in casting parameters. No evidence of surface recrystallization or extensive segregation was noted in the material, which was characterized by large amounts of small eutectic gamma islands, a heavy volume fraction of cooling gamma prime, and small discrete MC carbides randomly distributed throughout the matrix.

Based on heat treat studies, selected blades and test bars were solution heat treated at 2200°F/2 hr and aged to a 1550°F/4 hr + 1400°F/16 hr

Table III.
Dynamic modulus results for Mar-M247 integral wheels.

Casting process	Specimen orientation	Dynamic longitudinal modulus ($x10^6$ psi)					
		70°F	800°F	1200°F	1400°F	1600°F	1800°F
Grainex	Axial	31.0	27.6	25.5	24.2	22.8	21.4
	Tangential	31.4	27.6	25.8	24.8	23.3	22.0
	Radial	31.1	27.6	25.5	24.1	23.1	21.5
Conventional	Axial	21.5	19.0	17.4	16.6	15.5	14.1
	Tangential	25.1	21.6	20.0	19.1	17.9	16.6
	Radial	29.3	25.9	23.8	22.8	21.5	19.9

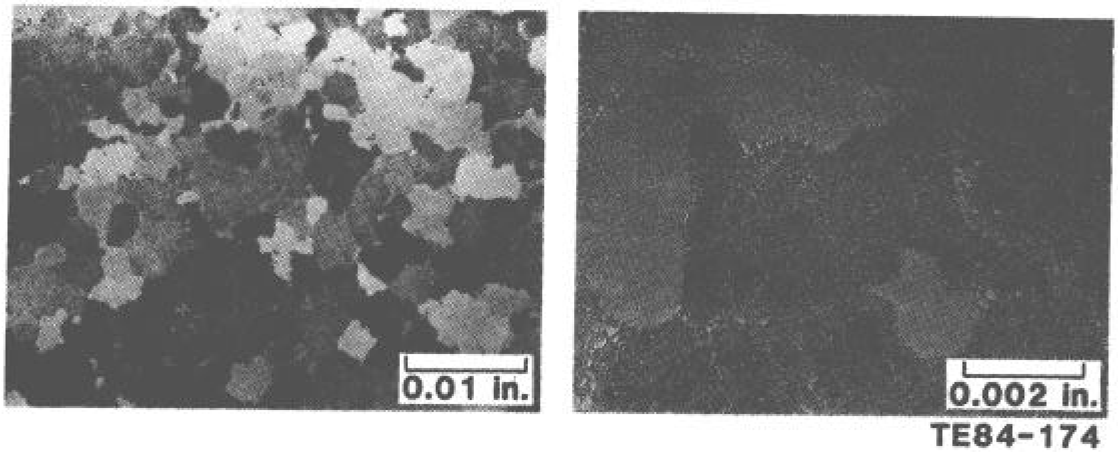

Figure 4. Cast plus hot isostatically pressed microstructure of Microcast X IN-792 plus Hf turbine blades.

cycle. Subsequently, the blades were evaluated for tensile and stress rupture capability. A summary of the results along with comparisons to wrought Waspaloy and conventionally cast IN-792 are shown in Table IV. As indicated, the Microcast X IN-792 shows a substantial tensile strength/temperature advantage over the other alloys. From a stress rupture standpoint, the IN-792 Microcast X blade material shows a strength advantage over wrought Waspaloy, although it is inferior to conventionally cast superalloys, apparently as a result of its ultrafine grain size.

These results must be considered preliminary; much additional work in the casting and postcasting process area is needed to firmly establish the capabilities of the new casting process in moderate temperature applications. It is clear, however, that if high-cycle fatigue characteristics follow the trends indicated by ultimate tensile strength, then new application areas which to date have been monopolized by forgings may open up to castings with attendant significant acquisition cost savings.

Table IV.
Mechanical property results for candidate turbine blade alloys.

Tensile

Alloy	Test temp--°F	0.2% YS--ksi	UTS--ksi	El--%	RA--%
IN-792 (Microcast X)*	70	164.8	179.8	4.0	5.9
Waspaloy (wrought bar)	70	115.0	115.0	25.0	---
IN-792 (conventionally cast)	70	145.0	168.0	6.4	---
IN-792 (Microcast X)	1200	155.8	192.4	4.7	6.7
Waspaloy (wrought bar)	1200	100.0	162.0	34.0	---
IN-792 (conventionally cast)	1200	132.0	179.0	7.6	---

1400°F/75 ksi Stress Rupture

Alloy	Hours to failure	El--%
IN-792 (Microcast X)**	119.0	4.3
Waspaloy (wrought bar)	18.0	15.0
IN-792 (conventional cast)	1000.0	5.0

*Specimens machined from blades
**Specimens machined from cast test bars

AF 95 and Inconel 718 Turbine Disk Evaluations

In the current T56-A-427 engine, Inconel 718 forgings are bill-of-material; consequently, several of the disks were cast in Inconel 718 so that a direct comparison could be made between the Microcast X product and the baseline 718 forgings. In addition, because alloy effects on the process and resulting mechanical properties are relatively unknown, several AF 95 disks were also cast. In all cases the castings were HIP processed following casting in an attempt to heal residual microshrinkage. A photograph showing typical macroetched cross sections representative of each of the two alloys are shown in Figure 5. Noted in the Inconel 718 casting are localized areas of relatively coarse recrystallized grains. Major metallographic observations and the results of mechanical testing performed on the castings follow.

Inconel 718 Turbine Disk Evaluations. Metallographic examination of the disks revealed them to be uniformly fine grained (ASTM 3-5). With the exception of localized areas in the hub and spacer, the castings were free of microshrinkage and heavy segregation. Unique to the segregated areas were relatively heavy concentrations of dark etching Fe_2Cb Laves particles. Also noted in the segregated areas were dark etching precipitation free areas. By comparison, the microstructures in the nonsegregated areas were free of Laves particles and generally exhibited a more uniform distribution of light etching MC carbides. Significantly, all the structures observed were nondendritic in nature as opposed to conventionally cast and Grainex processed castings.

In general terms, the structural phase morphology of the Microcast X material is similar to that observed in other Inconel 718 castings. Specifically, MC carbide and Laves phases were the predominate phases observed in the castings, being located both within the matrix and grain boundaries. Also observed were areas of delta Ni_3Cb phase and double gamma prime, as shown in Figure 6.

Subsequent to the microstructural characterization of the Microcast X Inconel 718 disks, sections were homogenized at 2075°F/10 hr, solution heat treated at 1900°F/2 hr, and aged at 1350°F/10 hr + 1150°F/8 hr. As is shown in Figure 7, extensive grain coarsening was encountered in the disk sections, due apparently to residual strains from the casting operation, postcasting cleanup techniques, or both.

Shown in Table V are the results of tensile and stress rupture tests performed on disk sections. Compared with baseline data for fine grained wrought Inco 901, which is a conventional disk material, the tensile results for Microcast X Inconel 718 were reduced. Tensile ductilities for

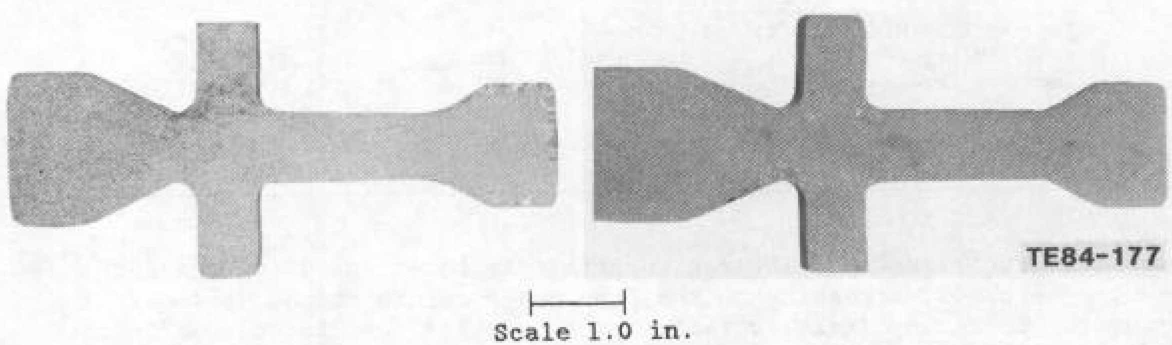

Figure 5. Macroetched Microcast X Inconel 718 (left) and AF 95 (right) disk castings.

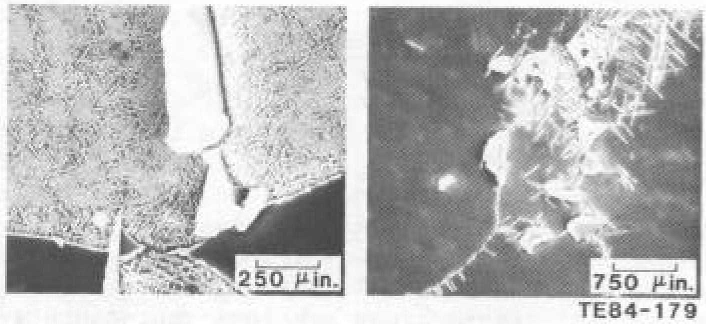

Figure 6. Areas of Ni_xCb gamma double prime (left) and delta Ni_3Cb phase (right) observed in Microcast X Inconel 718 turbine disks.

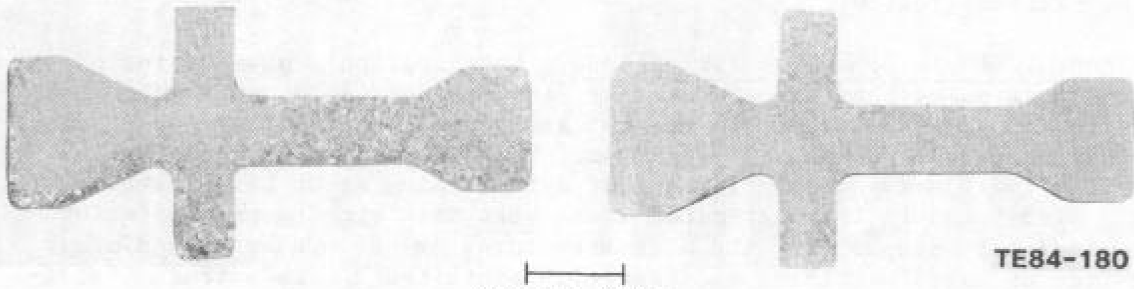

Figure 7. Macroetched slices from homogenized and heat treated Microcast X Inconel 718 (left) and AF 95 (right) disk sections.

Table V.
Mechanical property test results for candidate disk materials.

Tensile

Alloy	Test temp--°F	0.2% YS--ksi	UTS--ksi	El--%	RA--%
Inconel 718 (Microcast X)	70	136.9	161.0	26.6	39.5
AF 95 (Microcast X)	70	146.8	176.3	13.0	18.1
Inco 901 (wrought)	70	128.0	176.0	15.0	19.0
Inconel 718 (Microcast X)	1200	106.6	126.0	22.0	36.1
AF 95 (Microcast X)	1200	126.2	167.2	9.6	12.6
Inco 901 (wrought)	1200	115.0	145.0	20.0	28.0

Stress Rupture

Alloy	Test temp--°F	Stress--ksi	Hours to failure	El--%
Inconel 718 (Microcast X)	1200	90	72.8	8.0
AF 95 (Microcast X)	1200	100	1341.1*	--
Inco 901 (wrought)	1200	90	81.6	17.1

*Test discontinued

the Microcast X Inconel 718 were surprisingly in excess of values for wrought Inco 901, attesting to the fine grain nature of the Microcast X product. Correspondingly, stress rupture results for Microcast X Inconel 718 were typical of a fine grain product and equivalent to Inco 901.

Strain controlled LCF results at 800°F for Microcast X disks are shown in Figure 8. When superimposed over baseline wrought Inco 901, the Microcast X Inconel 718 compares very favorably.

AF 95 Turbine Disk Evaluations. As with the Inconel 718 Microcast X disks, the grain size observed in the as-processed AF 95 disks was a fine ASTM 3-5. A general microstructural review of these castings showed localized areas of segregation and surface-connected porosity in basically the same hub and spacer areas as was observed in the Inconel 718 castings. The segregated areas of the Microcast X AF 95 were characterized by small amounts of a columbium-rich plate-like phase (see Figure 9), which has been termed the "O'Hare" phase[1]. The overall structure of the AF 95 castings was characterized by the presence of columbium-rich MC carbides, eutectic gamma prime, and aging gamma prime. In addition, a small amount of a high parameter M_3B_2 boride phase was observed. With respect to the aging gamma prime, there was a smaller sized concentration found within the center of grains and a concentration of larger gamma prime outlining grain boundaries.

Following homogenization at 2175°F/4 hr, solution heat treatment at 2050°F/2 hr, and aging at 1600°F/1 hr and 1400°F/16 hr, specimens were removed from the casting, and tensile, stress rupture, and stain-controlled LCF tests were performed.

Tensile and stress rupture results of Microcast X AF 95 are shown in Table V. Preliminary data have shown that tensile properties of Microcast

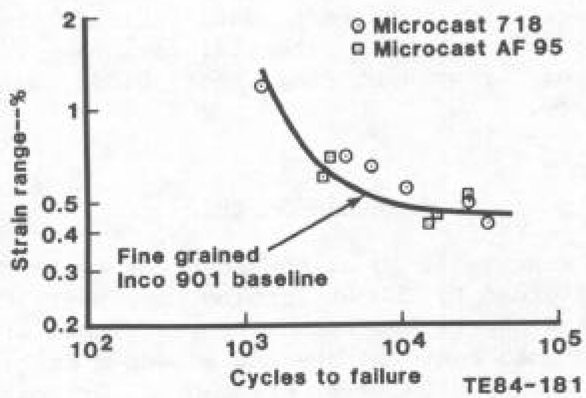

Figure 8. Results of 800°F strain controlled low-cycle fatigue tests for Microcast X AF 95 and Inconel 718.

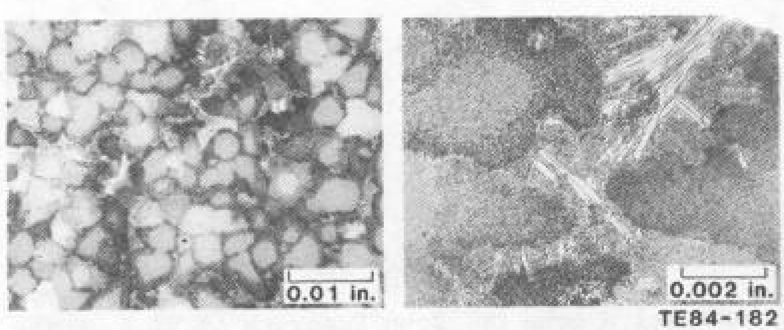

Figure 9. Photomicrographs of Microcast X AF 95: general microstructure (left) shows dark-etching coarse gamma prime surrounding fine gamma prime in grain center; plate (right) is columbium-rich O-Hare phase.

X AF 95 are generally superior to baseline Inco 901 at room temperature and 1200°F. Good ductilities were measured at both temperatures. Stress rupture properties of the Microcast X AF 95 were higher than those of Microcast X Inconel 718 and baseline Inco 901, which is consistent with the higher alloying content and associated gamma prime aging response. Strain controlled LCF results of Microcast X AF 95, shown in Figure 8, were comparable with both Microcast X 718 and Inco 901.

Conclusions

- Superalloy investment cast integrally bladed turbine rotors can now be cast by the Grainex process into uniform fine grained structures that offer the promise for increased burst margins and reduced property scatter in fatigue limited applications.

- In comparison with the Grainex process, the newer Microcast X casting process offers the potential for further substantial refinements in grain size, which carries the potential for additional improvements in burst margin and reduced property scatter.

- The use of grain refined components appears to be best suited for moderate temperature static and rotating applications in which creep rupture characteristics are not demanding. In integral rotor applications in which maximum airfoil creep rupture characteristics are required, alternative fabrication concepts should be considered.

- The mechanical properties generated to date indicate that Microcast X investment cast products have the potential for being highly cost effective substitutions for wrought ring, case, blade, disk, spacer, and blisk type components.

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References

(1) Private communication from Dr. John Radavich to B. A. Ewing