THE DEVELOPMENT OF IMPROVED PERFORMANCE PM UDIMET® 720 TURBINE DISKS

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Abstract

Udimet® 720 is an important alloy because it exhibits an outstanding balance of strength, temperature, and defect tolerance characteristics (Ref. 1). In its cast and wrought alloy form, it is employed for turbine disk components utilized in a large number of civil and military propulsion systems. In its powder metal (PM) alloy form, which has been shown to be very cost competitive with its cast and wrought counterpart, Udimet 720 exhibits superior alloy homogeneity that provides an opportunity to develop the uniform and controlled microstructures desired for advanced designs (Ref. 2). Because it was recognized that Udimet 720 compositions developed for cast and wrought applications were not necessarily the best for PM processing, it was decided to study PM Udimet 720 chemistry, processing, and mechanical property relationships. The goal of this effort was to determine if an improved balance of performance characteristics could be developed for advanced turbine disk applications. For this work, four Udimet 720 chemistry modifications involving boron, zirconium, and hafnium additions were made to the baseline composition. Also represented in the program, for reference, was a contemporary baseline PM Udimet 720 composition.

To produce materials for evaluation, powder representative of each of the five compositions was argon atomized and screened to a -150 mesh powder fraction and consolidated by hot isostatic pressing (HIP) technique into 30 lb billet preforms. The HIP processed billets were then isothermally forged at two different forging temperatures into pancakes. After forging, selected pancakes were subsolvus and supersolvus solution heat treated to achieve target grain sizes, respectively, of ASTM 11 and ASTM 9. Cut-up evaluations were then performed on fully heat treated disks representative of each grain size and chemistry combination. This included tensile, creep rupture, fatigue crack growth (FCG), and low cycle fatigue (LCF) testing at temperatures and conditions of interest for gas turbine disk applications.

Test results showed supersolvus processing to an ASTM 9 target grain size resulted in attractive reductions in 1200°F FCG rate relative to both the subsolvus processed ASTM 11 PM alloys and cast and wrought Udimet 720 disk product subsolvus processed. Significant improvements in both 1200°F LCF life and 1350°F creep rupture capability were also achieved for material processed to the ASTM 9 grain size. It was observed that the higher boron and boron/zirconium levels in the coarse grained PM alloys enhanced these properties. By comparison, tensile testing did not show trends that could be attributed to the chemistry modifications, but 0.2% tensile yield strengths for the ASTM 9 material were reduced on the order of 10 ksi relative to the ASTM 11 material.

From this work it was found that selected chemistry modifications, when combined with appropriate grain size control, can yield an improved balance of FCG resistance, LCF capability, creep strength, and tensile properties relative to the baseline PM alloy as well as traditional cast and wrought Udimet 720 that is subsolvus processed. In particular, this work has shown promise for PM Udimet 720 alloy forms exhibiting boron and boron/zirconium levels that exceed baseline PM and cast and wrought Udimet 720 target levels. Based on these results, it should be possible to greatly extend the performance capabilities of PM Udimet 720 turbine disks.

*® Udimet is a registered trademark of Special Metals Corporation.

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Introduction

Early cast and wrought Udimet 720 compositions used for disk forgings were susceptible to chemical segregation, causing wide variability in grain size and heat treatment response. As a result, extensive homogenization and billet working practices had to be developed to improve alloy homogeneity. Problems were also encountered with the formation of boride and carbide stringers that can act as nucleation sites, which lead to early fatigue cracking and premature component failure. These stringer problems were related to the alloying constituents required to promote grain boundary strengthening.

Due to these difficulties, several changes were made to the melt practices and chemistry used for Udimet 720 disk components. As an example, melt practices were changed from a vacuum induction melt plus vacuum arc remelt double melt practice to a vacuum induction melt plus electroslag remelt plus vacuum arc remelt triple melt practice to improve cleanliness and structure. Elements that can lead to stringer formation were also adjusted; specifically, carbon and boron were reduced. Due to the lower carbon levels, chromium content was reduced as well to develop a chromium/carbon balance to minimize, if not eliminate, the formation of a deleterious chromium rich sigma phase. A comparison of first and current generation cast and wrought compositions reflecting these changes is presented in Table I.

Overall, the cast and wrought processing methods developed for Udimet 720 have been very successful in managing the segregation related issues associated with the manufacture of relatively small cast and wrought disks. These disks typically require forging multiple weights of up to 150 lb, and utilize 4 to 6-in. diameter billet. As a result, 4 and 6-in. diameter cast and wrought Udimet 720 billet is routinely being used to produce turbine disk forgings used in a number of Rolls-Royce Corporation engine applications. These include AE 3007 turbofan engines powering the Embraer RJ 135/145 and Citation X aircraft, the AE 2100 turboprop engine powering the C-130J and Saab 2000 aircraft, the AE 1107 turboshaft engine used on the V-22 Osprey tiltrotor, and the Light Helicopter Turbine Engine Company (LHTEC) T800 turboshaft engine powering the Comanche RAH-66 helicopter.

Unfortunately, as disk size increases beyond that accommodated by 6 to 8-in. diameter billet, segregation problems and related microstructural control issues become significantly more difficult to manage. For example, turbine disks for turbofan engines powering modern wide-bodied aircraft require large 1000-lb 12-in. diameter billet. As a result of increased billet size, the microstructural control and quality levels desired are very difficult to achieve using conventional cast and wrought methods and processing complexity is dramatically increased. For these applications the use of PM processing affords the opportunity to produce cost-effective, high quality homogeneous billet product with uniform microstructural characteristics (Ref. 3).

Because of the opportunities PM billet processing provides for the improved microstructural control demanded by new disk designs, as well as the recognition that the compositions developed for cast and wrought applications were not necessarily the best for PM processing, it was decided to study PM Udimet 720 chemistry, processing, and mechanical property relationships. The goal of this effort was to determine if an improved balance of performance characteristics could be developed for advanced turbine disk applications.

To achieve an improved balance of defect tolerance, LCF resistance, creep strength, and tensile strength relative to cast and wrought Udimet 720, the work focused on two key aspects of disk manufacturing: a) chemistry modifications and b) isothermal forging/heat treat practices. The approach involved evaluating subscale disk forgings produced by a HIP consolidation and isothermal forging processing route. Crucible Materials Corporation produced and consolidated the powders and the Ladish Company produced and heat treated the forgings to target grain sizes of ASTM 9 and ASTM 11.

Udimet 720 Chemistry Modification

For this work, four Udimet 720 chemistry modifications involving boron, zirconium, and hafnium additions were made to the baseline composition (Table II). Also represented in the program, for reference, was a standard PM Udimet 720 composition (Alloy 1). Of the four compositions, Alloy 2 was designed to evaluate hafnium effects relative to the baseline Alloy 1, whereas Alloys 3 and 5 were formulated to evaluate the effect of higher boron. Alloy 4 was designed to evaluate the effect of increased boron and zirconium. This alloying approach was taken as a result of previous work performed by both Rolls-Royce Corporation and Rolls-Royce plc.

Powder Production and HIP Compaction

The powder for the program was produced at the Crucible Research Division of the Crucible Materials Corporation by conventional vacuum induction melting and argon atomization. Two heats were made for each composition. The heats were analyzed individually for major alloying elements and then blended. Powder characterization included scanning electron microscope (SEM) examination of the surface characteristics and optical examination of the as-atomized powder microstructures.

Table I. Evolution of cast and wrought Udimet 720 alloy chemistries.

Alloy	Alloy compositions (weight percent)										
	C	Cr	Co	Mo	Ti	Al	W	Zr	B	Hf	Ni
First generation	0.035	18.0	14.75	3.0	5.0	2.5	1.25	0.035	0.035	-	Bal.
Current generation	0.015	16.0	14.75	3.0	5.0	2.5	1.25	0.035	0.017	-	Bal.

Table II. Target alloy compositions for PM Udimet 720 alloy/process modification program.

Alloy	Target alloy compositions (weight percent)										
	C	Cr	Co	Mo	Ti	Al	W	Zr	B	Hf	Ni
Alloy 1 (baseline Udimet 720)	0.025	16.0	14.75	3.0	5.0	2.5	1.25	0.035	0.02	-	Bal.
Alloy 2	0.025	16.0	14.75	3.0	5.0	2.5	1.25	0.035	0.02	0.75	Bal.
Alloy 3	0.025	16.0	14.75	3.0	5.0	2.5	1.25	0.035	0.03	-	Bal.
Alloy 4	0.025	16.0	14.75	3.0	5.0	2.5	1.25	0.070	0.03	-	Bal.
Alloy 5	0.025	16.0	14.75	3.0	5.0	2.5	1.25	0.035	0.04	-	Bal.

Water elutriation was also conducted on -150 mesh powder from each of the compositions. The results of these evaluations indicated chemistry requirements were satisfied. SEM and water elutriation results were acceptable and considered as typical of Crucible's powder product produced by their laboratory equipment.

Nominal inside dimensions for the steel HIP containers were 4 5/8 in. diameter by 8 3/8 in. long. The cans filled with -150 powder were first outgassed at room temperature and then heated to 350°F under vacuum the ensure removal of water vapor. After outgassing, the cans were sealed off by pressure welding the stems and tungsten inert gas (TIG) welding the ends. The parameters used for HIP consolidation of the compacts were 2065°F and 15 ksi for 4 hr. Following HIP, the can material was removed, compacts were centerless ground, and were ultrasonically inspected. No anomalies were found in either the ultrasonic inspection results or the microstructural reviews conducted on the material.

The thermal induced porosity (TIP) response of the baseline Udimet 720 composition was determined by exposing the 50 g samples at temperature for 1 hr and measuring densities. The exposure at 2160°F resulted in a density decrease of 0.03 to 0.10% and at 2260°F resulted in a density decrease of 0.48 to 0.55%. These results are typical of -150 mesh powder.

Forging and Heat Treatment Development

Prior to isothermal forging of the HIP consolidated compacts, the forging characteristics of as-HIP material were evaluated by performing compression tests on baseline Udimet 720 material. The testing involved isothermally upsetting 3/8-in. diameter by 5/8-in. button specimens at six temperatures (Table III). The strain rate used for all tests was 0.003/in./in./sec. All specimens were forged to 70% upset. Selection of these parameters was based on previous Ladish experience with PM superalloys. Following upset, the specimens were cut into four quadrants. One was saved to preserve the forged microstructure and two were, respectively, solution heat treated to temperatures 115°F (2000°F) and 50°F (2065°F) below the 2115°F gamma prime solvus temperature for this material. One of the quadrants was also solution heat treated to 25°F (2140°F) above the gamma prime solvus temperature. All four quadrants were prepared for microstructural and grain size evaluations. Grain sizes varied from as fine as ASTM 13 to as coarse as ASTM 6 (Table III).

In general, there was little significant influence of forging/upset temperature on as-forged grain size. Relative to heat treatment, there was little grain size difference between the as-forged structure and the 2000°F heat treated material. Comparing the 2000 to the 2065°F heat treatment showed coarsening into the grain size regime of interest. Comparing the 2065°F heat treated material to the 2140°F material showed additional coarsening, with material from the lower forging temperatures showing the best overall coarsening response.

Table III. As-forged and heat treated PM Udimet 720 grain sizes.

Forging* temp—°F	Predominant ASTM grain sizes as a function of heat treatment			
	As-forged	2000°F/ 2 hr	2065°F/ 4 hr	2140°F/ 2 hr
2085	12	11	10.5	6
2065	12	12	11	6
2040	13	12.5	11	7.5
2015	13	13	11.5	8.5
1990	12	12.5	11	8.5
1965	12	12	11.5	8.5

*Gamma prime solvus temperature is 2115°F

Following a review of the microstructures and grain sizes obtained, two forging temperatures were selected for further study. Specifically selected were 2065°F, which is near the 2115°F solvus temperature, and 1990°F, which is near the current forging temperature. The 2065°F forgings were solutioned at 2065°F to obtain a target subsolvus grain size of ASTM 11 and the 1990°F forgings at 2140°F to obtain a target grain size of ASTM 9. Interest in these grain sizes was based upon previous work that showed an attractive balance of mechanical properties in forgings processed to these grain size conditions.

For each alloy, one 9-in. diameter by 1.25-in. thick pancake forging was made at 2065°F and another at 1990°F. Forging response of the alloys was generally good. Forgings made at 2065°F received a subsolvus solution heat treatment of 2065°F/2 hr and forgings made at 1990°F received a supersolvus solution heat treatment of 2140°F/4 hr. Cooling from solution heat treatments was by fan air quenching to develop an approximate cooling rate of 275°F/min. Further heat treatment included stabilization at 1400°F/8 hr/air cooled (AC) and aging at 1200°F/24 hr/AC for both subsolvus and supersolvus materials. Subsequently, it was determined that the subsolvus processing resulted in a relatively uniform grain size of ASTM 11 and the supersolvus processing resulted in a relatively uniform grain size of ASTM 9.

Mechanical Property Evaluations

Since the purpose of this investigation was to examine the effects of boron, zirconium, and hafnium additions and thermal-mechanical processes on the mechanical property behavior of PM Udimet 720, a wide range of mechanical property tests were performed. As shown in Table IV, these included tensile, creep rupture, LCF, and FCG rate tests at temperatures and conditions of interest for gas turbine disk applications. By selecting these conditions, it was also possible to compare the results to cast and wrought Udimet 720 properties from a Rolls-Royce Corporation database for full-scale disks representative of several production heats that have been subsolvus processed to a predominant ASTM10 grain size condition and oil quenched to maximize tensile capabilities.

Average tensile results of duplicate tests for subsolvus and supersolvus PM alloys are listed in Tables V and VI, respectively, along with cast and wrought Udimet 720 properties. Tensile testing did not show trends that could be attributed to the chemistry modifications; however, 0.2% tensile yield strengths of the supersolvus ASTM 9 materials were on the order of 10 ksi lower than subsolvus ASTM 11 material. The lower tensile yield strengths offered by supersolvus coarse grained material is an expected superalloy material behavior. By comparison to subsolvus processed cast and wrought Udimet 720, the subsolvus processed PM alloys generally exhibited slightly lower yield

Table IV. Test Matrix for PM Udimet 720 alloy modifications.

Property	Test conditions
Tensile	Room temperature (RT), 800°F, and 1200°F
0.2% creep-rupture	1250°F/115 ksi and 1350°F/70 ksi
FCG	800°F and 1200°F/R = 0.05/with and without a 5- min dwell
LCF	800°F,R = 0.0,strain range = 0.9% 1200°F,R = 0.0, strain range = 0.8%

strengths. This is attributable to the faster cooling rates associated with the manufacture of the disks used to generate the cast and wrought database.

Creep capability of the candidate compositions was evaluated by testing duplicate specimens and comparing the time to 0.2% creep strain at 1250°F/115 ksi and 1350°F/70 ksi test conditions (Figures 1 and 2). As expected, the coarser grain supersolvus processed alloys showed superiority over the finer grain subsolvus processed alloys. It ranged from an approximate 4X advantage in life at the 1250°F test condition to as much as 30X advantage in life at the 1350°F test condition. Relative to cast and wrought performance, the subsolvus processed PM alloys exhibited creep characteristics that were slightly better at 1250°F and comparable at 1350°F. From a PM alloy compositional viewpoint, the subsolvus processed material appeared to be relatively insensitive to compositional variations irrespective of test conditions. However, for the supersolvus processed material there appeared to be a significant influence of boron and boron/zirconium additions on creep life for the specimens tested at 1350°F. The improved creep capability at 1350°F for supersolvus processed Alloys 3, 4, and 5 is likely associated with the beneficial effects of these additions on grain boundary strength. With respect to hafnium, its addition appeared to be most beneficial to stress rupture life of subsolvus material tested at both 1250 and 1350°F (Figure 3). Tests on supersolvus treated material were discontinued after 0.2% creep strain, therefore, stress rupture lives could not be plotted.

The elevated temperature LCF capability of the candidate compositions was evaluated by comparing the cycles to crack initiation on four to six specimens tested at a strain range of 0.9% with 20 cpm and R = 0 at 800°F (Figure 4) and for a strain range of 0.8% with 20 cpm and R = 0 at 1200°F (Figure 5). The results of the LCF testing showed a significant effect of both grain size and composition at both 800 and 1200°F test conditions.

In particular for the 800°F condition, it was shown that LCF lives for the subsolvus processed material were superior to those for supersolvus processed material. In addition, at the 800°F test condition, a trend developed for the subsolvus processed material in which LCF lives appeared to increase with increasing boron and boron/zirconium content (Alloys 1, 3, and 4), with a peak in performance being reached for Alloy 4 (0.03B/0.07Zr). However, at 800°F this effect was not evident in the supersolvus processed material. Relative to subsolvus processed cast and wrought material, the 800°F capabilities of the PM alloys were very attractive, with subsolvus processed Alloy 4 exhibiting an approximate 6X advantage in cyclic life.

Relative to the 1200°F testing, it was shown that the supersolvus processed alloys generally showed higher cyclic lives than the subsolvus processed alloys. This was the opposite of what was observed in the 800°F testing. One exception to this was Alloy 2,the hafnium bearing alloy. After reviewing individual specimen results and identities, it is still unclear as to why the supersolvus form of this alloy did not perform better. The 1200°F testing also showed trends similar to those observed in the 800°F testing in that cyclic life appeared to increase as a function of increasing boron and boron/zirconium content to a peak in performance for Alloy 4 (0.03B/0.07Zr). However, the alloying trend was far more pronounced in the supersolvus processed material than in

Table V. Subsolvus heat treated tensile data.

Forging serial no.		C/W Udimet 720	PM Alloy 1 Udimet 720	PM Alloy 2	PM Alloy 3	PM Alloy 4	PM Alloy 5
Solution heat treat ASTM grain size		Subsolvus 10	Subsolvus 11	Subsolvus 11	Subsolvus 11	Subsolvus 11	Subsolvus 11
Temp—°F	Properties						
RT	U.T.S.	233.9	239.3	243.3	240.3	240.0	240.3
RT	0.2% Y.S.	175.9	170.7	170.8	170.5	170.7	170.7
RT	% El.	17.1	19.0	19.0	20.7	18.0	19.3
RT	% RA	18.4	20.7	20.0	22.3	18.3	21.0
800	U.T.S.	224.4	226.0	228.5	226.5	227.5	226.0
800	0.2% Y.S.	167.6	163.5	164.0	164.0	164.0	163.5
800	% El.	18.2	18.0	20.0	20.5	18.0	19.5
800	% RA	18.7	20.0	23.0	23.5	21.0	21.5
1200	U.T.S.	214.0	198.7	202.7	199.7	199.3	200.3
1200	0.2% Y.S.	165.6	155.3	157.4	156.5	156.5	157.0
1200	% El.	18.1	21.3	27.3	31.0	19.0	17.7
1200	% RA	19.4	22.0	26.0	32.0	20.0	19.0

Table VI. Supersolvus heat treated tensile data.

Forging serial no.		PM Alloy 1 Udimet 720	PM Alloy 2	PM Alloy 3	PM Alloy 4	PM Alloy 5
Solution heat treat ASTM grain size		Supersolvus 9	Supersolvus 9	Supersolvus 9	Supersolvus 9	Supersolvus 9
Temp—°F	Properties					
RT	U.T.S.	230.0	234.7	229.3	229.7	230.0
RT	0.2% Y.S.	160.7	159.0	158.4	158.7	157.7
RT	% El.	15.3	17.3	17.3	17.0	17.3
RT	% RA	17.3	18.7	18.7	17.3	19.3
800	U.T.S.	219.0	221.5	221.0	220.0	217.5
800	0.2% Y.S.	155.5	154.0	155.5	155.0	155.5
800	% El.	13.5	16.5	15.5	16.0	16.5
800	% RA	19.5	18.5	16.5	17.0	16.0
1200	U.T.S.	207.0	207.3	205.7	207.3	207.7
1200	0.2% Y.S.	146.0	145.3	143.7	146.3	145.7
1200	% El.	25.3	31.0	28.0	23.7	23.3
1200	% RA	25.7	29.7	27.7	24.3	25.0

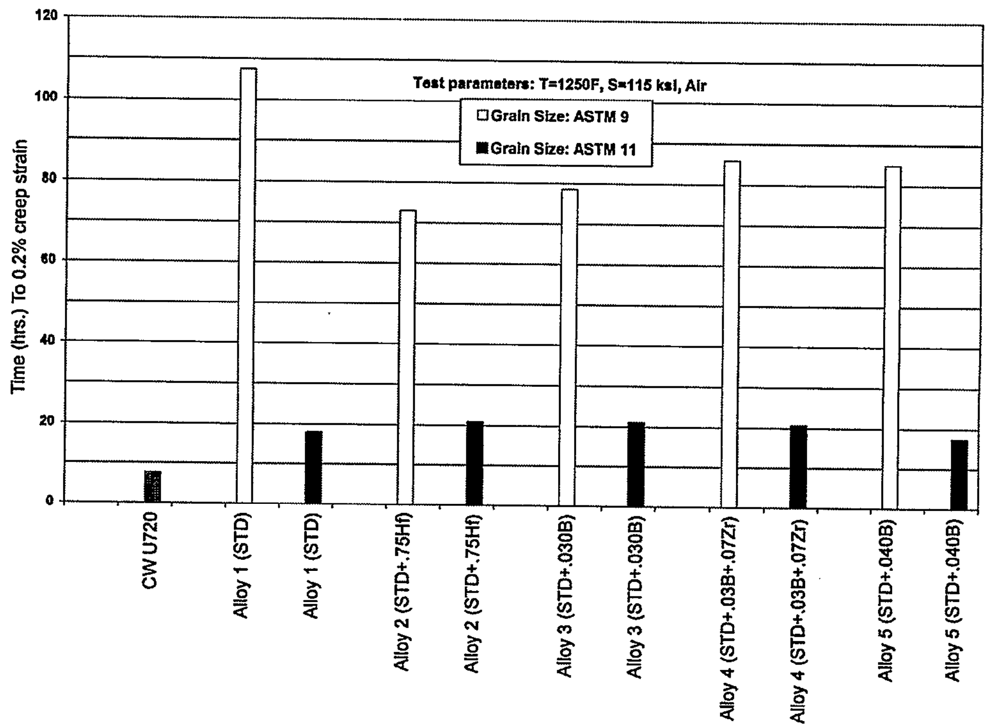

Figure 1. Effect of PM Udimet 720 alloy modifications and solution temperatures (grain sizes ASTM 9 and 11) on 1250°F/115 ksi creep behavior.

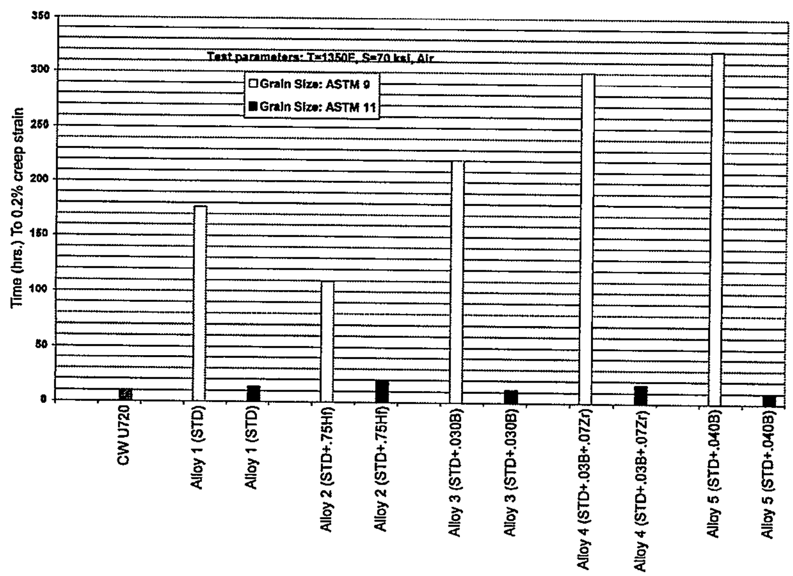

Figure 2. Effect of PM Udimet 720 alloy modifications and solution temperatures (grain sizes ASTM 9 and 11) on 1350°F/70 ksi creep behavior.

the subsolvus material. By comparison to subsolvus processed cast and wrought Udimet 720, all of the PM compositions offered superior lives, with the greatest advantage being noted for supersolvus processed materials at 1200°F. For example, supersolvus processed Alloy 4 exhibited 70,000 cycles average life versus 11,000 cycles average life for subsolvus processed cast and wrought Udimet 720.

To develop an improved understanding of the LCF test results, the fracture surfaces of failed LCF bars were examined; they generally showed the 800°F bars to be transgranular in nature and the 1200°F bars to be intergranular in failure mode. As might be expected, there were occasional failure origins associated with the presence of ceramic particles, although little scatter was noted on the multiple tests conducted.

To evaluate the crack growth rate capability of the candidate compositions, 1200°F fatigue crack growth tests were conducted on compact tension specimens with 5-min dwell and without dwell at peak load (Figures 6 and 7) and without dwell at 800°F

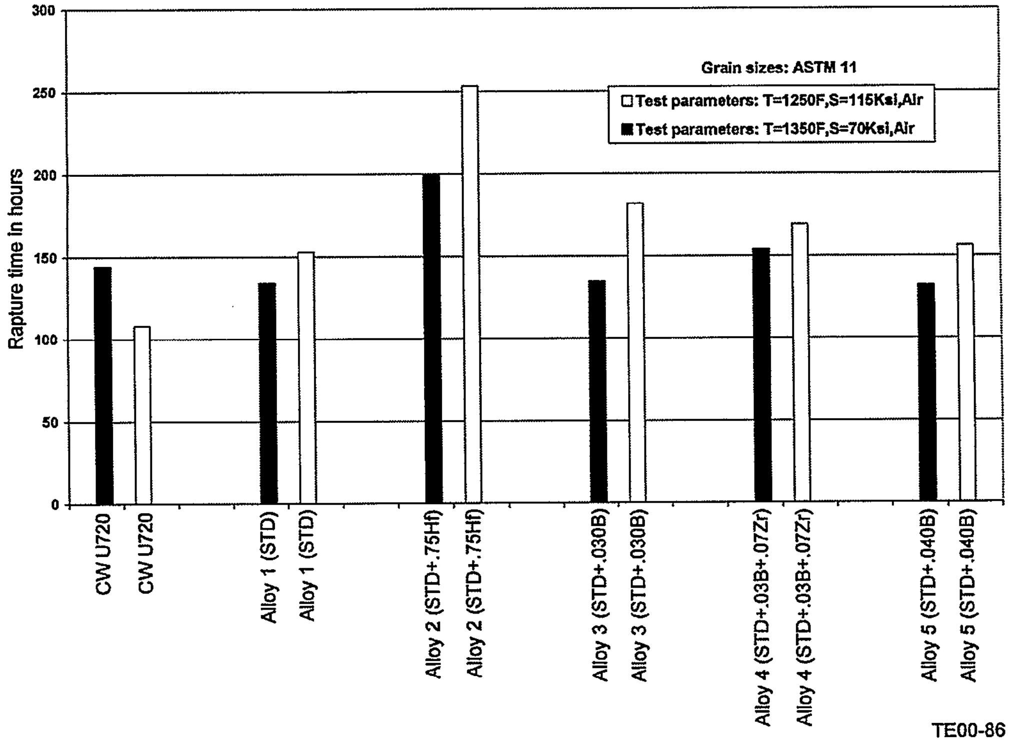

Figure 3. Effect of PM Udimet 720 alloy modifications on 1250°F/115 ksi and 1350°F/70 ksi stress rupture behavior of subsolvus heat treated (grains size ASTM 11) material.

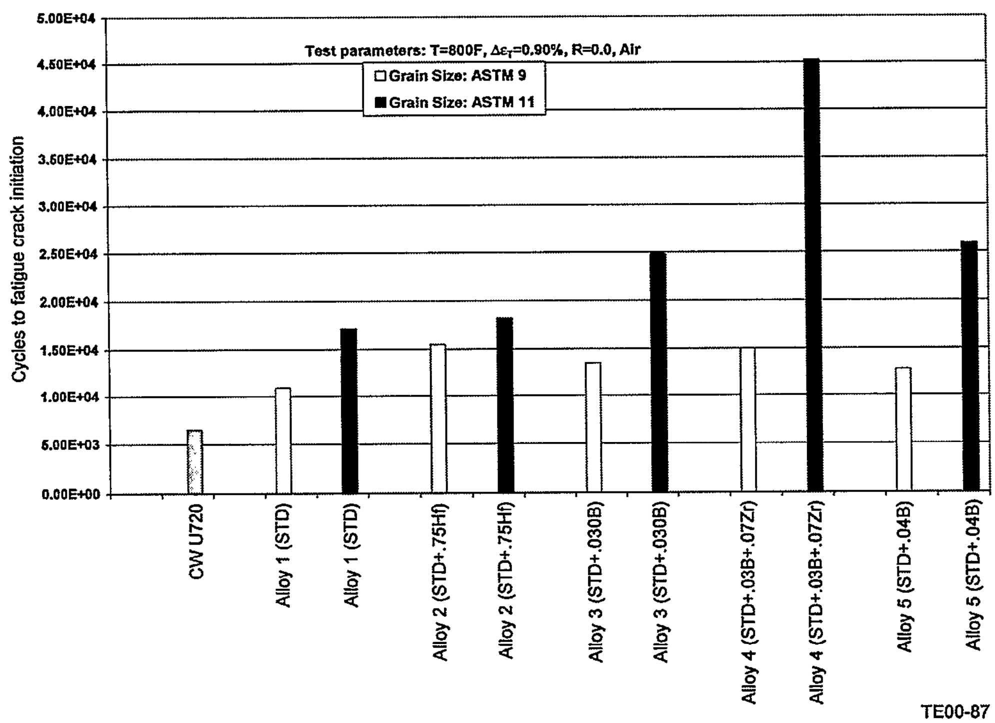

Figure 4. Effect of PM Udimet 720 alloy modifications and solution temperatures (grain sizes ASTM 9 and 11) on 800°F strain controlled LCF behavior ($\Delta\varepsilon_T$=0.9%, R=0.0, F=20CPM).

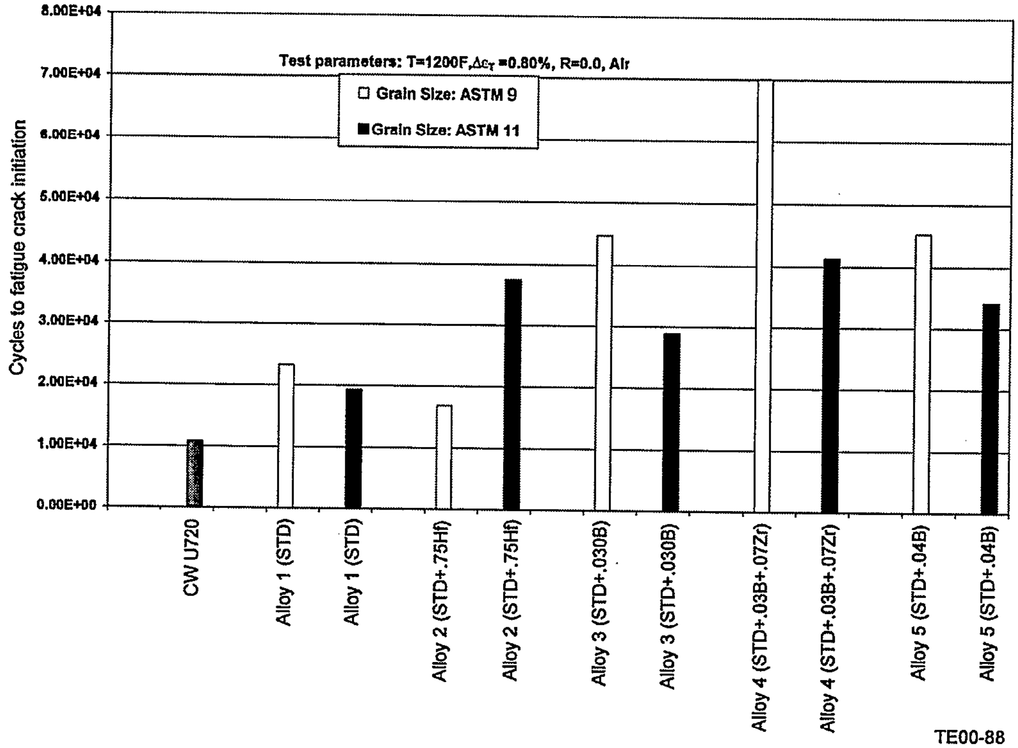

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Figure 5. Effect of PM Udimet 720 alloy modifications and solution temperatures (grain sizes ASTM 9 and 11) on 1200°F strain controlled LCF behavior ($\Delta\varepsilon_T$=0.8%, R=0.0, F=20CPM).

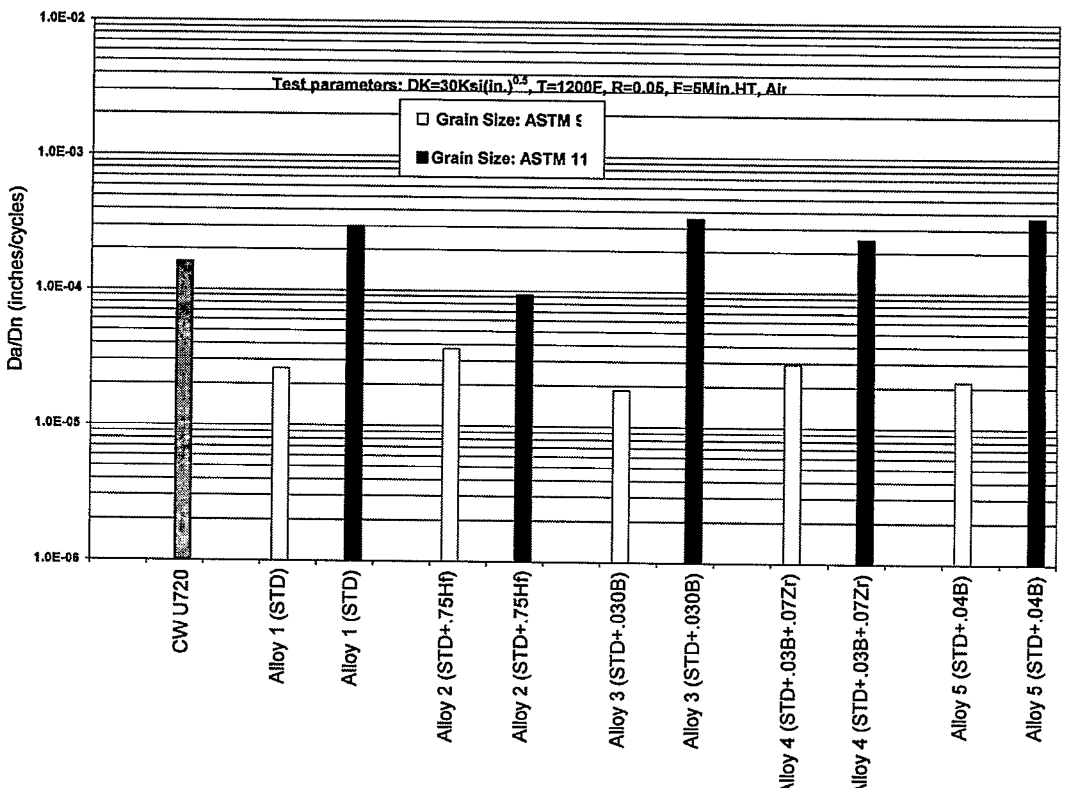

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Figure 6. Effect of PM Udimet 720 alloy modifications and solution temperatures (grain sizes ASTM 9 and 11) on 1200°F/5-min hold FCG rate (Da/Dn) behavior (ΔK=30 ksi-in$^{1/2}$ R=0.05).

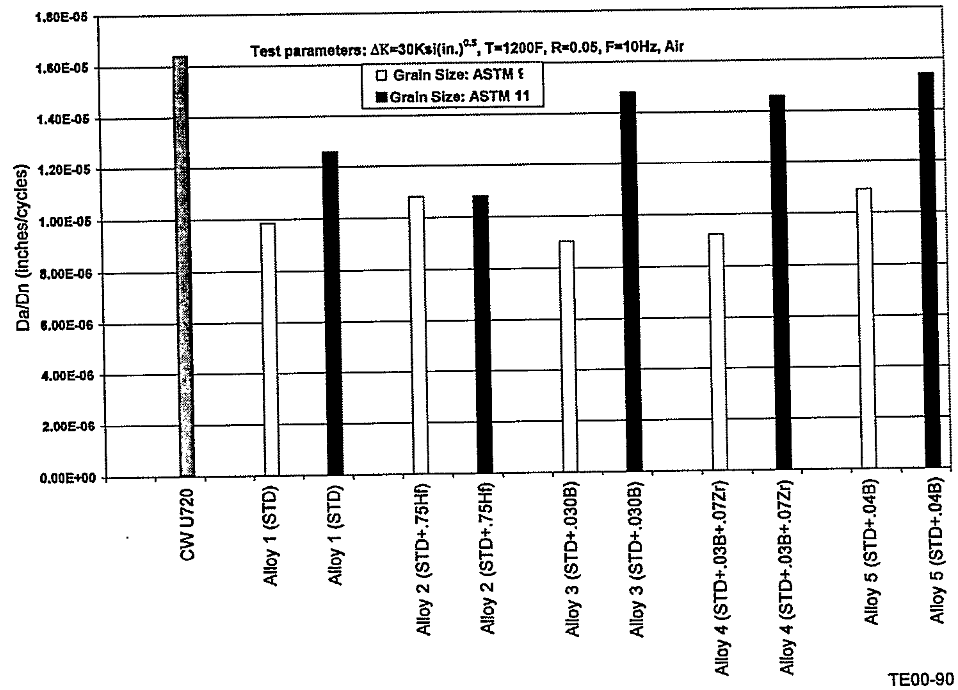


Figure 7. Effect of PM Udimet 720 alloy modifications and solution temperatures (grain sizes ASTM 9 and 11) on 1200°F FCG rate (Da/Dn) behavior (ΔK=30 ksi-in$^{1/2}$ R=0.05, Freq=10Hz).

(Figure 8). Duplicate tests were conducted on both subsolvus and supersolvus processed materials and average crack growth rates were plotted at ΔK = 30 ksi-in.$^{1/2}$

The dwell test is important because the rim of a turbine disk is at high temperature for several minutes when the engine is at takeoff power. Thus, the crack growth rate due to high temperature dwell must be minimized to ensure disk damage tolerance. As shown in Figure 6, the supersolvus processed candidate alloys had greatly decelerated crack growth rates when tested under dwell conditions at 1200°F. It was also observed that, with the exception of subsolvus processed hafnium modified Alloy 2, the crack growth rate characteristics of the modified alloys were similar. In the case of subsolvus processed Alloy 2, the hafnium addition appeared to offer an advantage over the other subsolvus processed nonhafnium bearing alloys.

With respect to 1200°F and 800°F nondwell tests, the data (Figures 7 and 8) indicated an overall trend in which the crack growth resistance characteristics of supersolvus processed alloys were improved over the subsolvus processed alloys. It was also noted that the crack growth resistance seemed to be relatively insensitive to compositional modifications.

Microstructural Observations

Microstructural review verified the target grain sizes of ASTM 11 for the subsolvus processed material and an ASTM 9 for the supersolvus processed material were achieved. It was also found that the grain sizes were very uniform from location to location within a forging. Additionally, microstructural appearances for a given target grain size were generally very similar from alloy to alloy. Photomicrographs representative of the PM Udimet 720 modifications are shown in Figure 9.

Examination of the microstructures representative of the ASTM 11 and ASTM 9 processed material found the grain boundaries were decorated with gramma prime, M_3B_2, and $M_{23}C_6$ particles (Figure 10). Also, random ZrO_2 and HfO_2 particles were found in matrix areas of both subsolvus and supersolvus processed material away from grain boundaries. Relative to the morphology of the gamma prime in the alloys, there was evidence of residual overaged gamma prime phase in the subsolvus processed material. Also, the aging gamma prime in the supersolvus processed material tended to be slightly coarser than that seen in the subsolvus material (Figure 11).

Overall, it was not possible to clearly pinpoint grain boundary decoration characteristics and matrix microstructural features as a function of the chemistry modifications made in this program. However, a significant influence of both chemistry and grain size on mechanical properties was observed. Future work is needed to thoroughly understand the 800 and 1200°F LCF, 1200°F FCG, and 1350°F creep property relationships involved with the boron, zirconium, and hafnium chemistry modifications evaluated in this program.

Summary of Results

- Zirconium and boron modifications resulted in significant improvements in 800 and 1200°F LCF life:
  - 0.03B/0.07Zr LCF life was approximately 2.5X better than baseline PM Udimet 720 at 800°F for subsolvus processed material and approximately 3X better for supersolvus processed material at 1200°F.
  - 0.03B/0.07Zr LCF life was approximately 6X greater than cast and wrought Udimet 720 at both 800°F for subsolvus processed and 1200°F for supersolvus processed material.

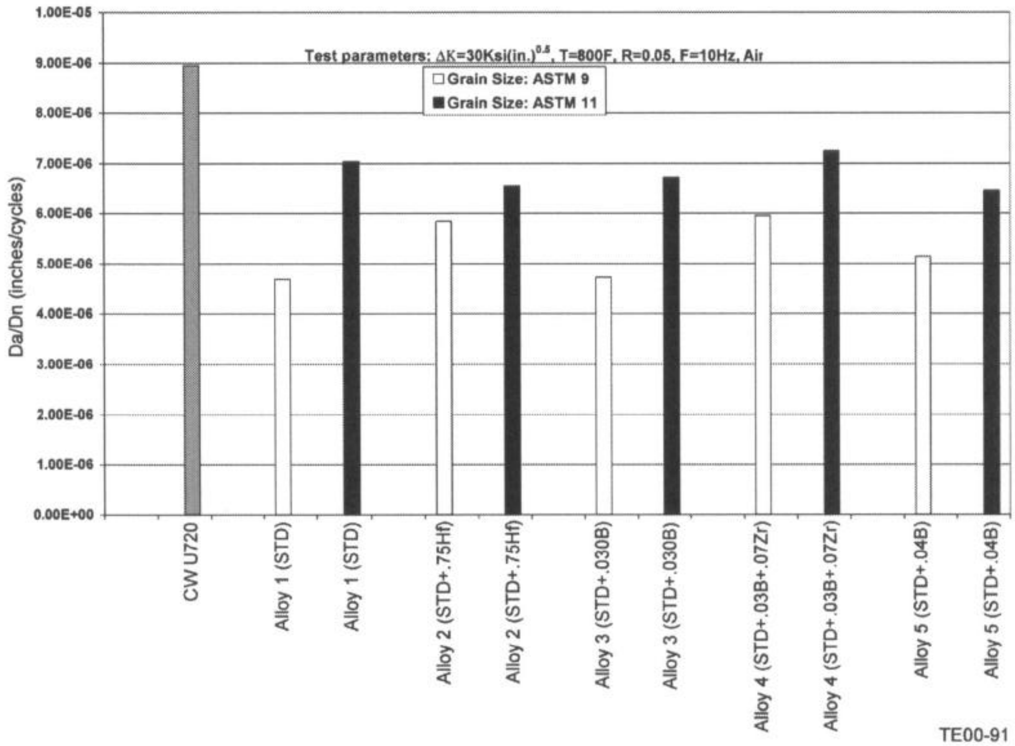


Figure 8. Effect of PM Udimet 720 alloy modifications and solution temperatures (grain sizes ASTM 9 and 11) on 800°F FCG rate (Da/Dn) behavior (ΔK=30 ksi-in$^{1/2}$ R=0.05, Freq=10Hz).

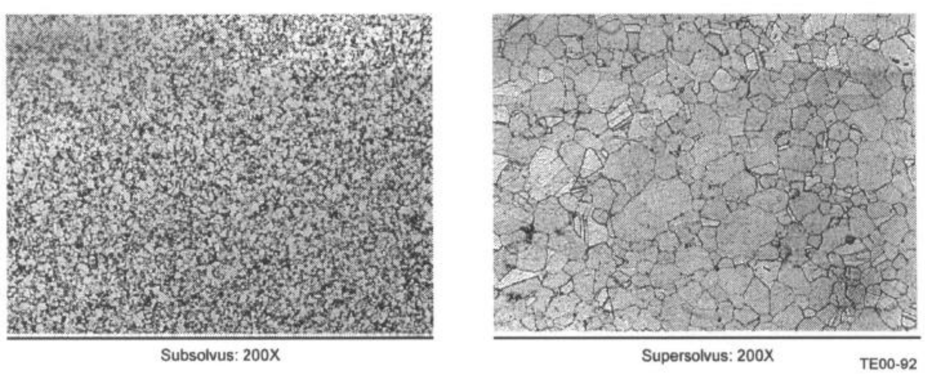


Figure 9. Typical low magnification microstructures observed for subsolvus and supersolvus processed PM Udimet 720 alloys.

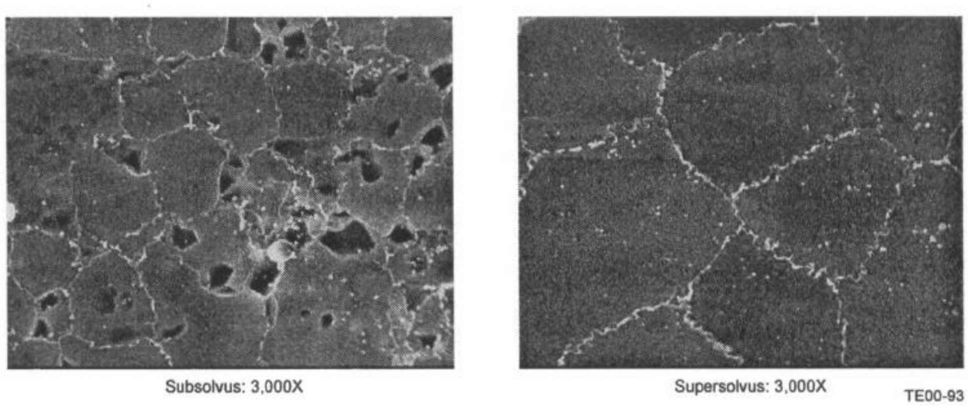
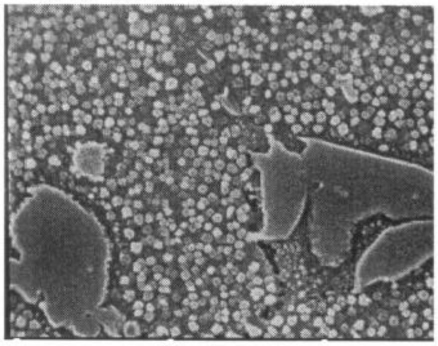


Figure 10. Typical grain boundary microstructures observed for subsolvus and supersolvus processed PM Udimet 720 alloys.



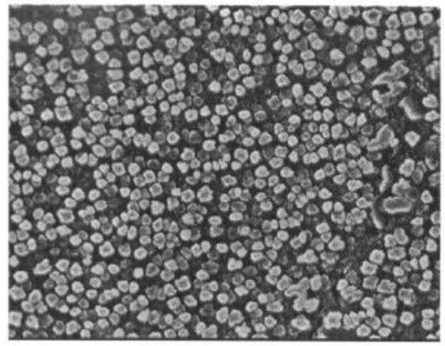


Figure 11. Typical gamma prime microstructures observed for subsolvus and supersolvus processed PM Udimet 720 alloys.

- Subsolvus processed (ASTM 11) material generally yielded the best 800°F LCF results; supersolvus material generally yielded the best 1200°F LCF results.
- Grain size had the greatest impact on FCG resistance at 800 and 1200°F:
    - Supersolvus (ASTM 9) material was significantly better than subsolvus processed material.
    - The FCG rates of the modified alloys were similar to one another; however, they had better (lower) FCG rates than cast and wrought Udimet 720 at 800 and 1200°F.
- Of the modified compositions in the subsolvus processed condition, the hafnium modified alloy appeared to offer the best overall FCG resistance at 1200°F.
- No significant effect of Udimet 720 alloy modifications was noted in tensile results:
- The 0.2% tensile yield strength of supersolvus processed material was reduced on the order of 10 ksi compared to subsolvus processed material.
- Little influence of alloy modifications was observed for the 1250°F creep results, but strong boron and boron/zirconium trends were noted for the 1350°F tests:
    - The best 1350°F results were noted for 0.03B/ 0.07Zr modifications.

Conclusions and Recommendations

The results of this program have shown that the compositions developed to manage segregation issues with cast and wrought Udimet 720 are nonoptimum from a mechanical property viewpoint for PM Udimet 720 alloy forms. This is because PM processing offers the ability to increase alloying elements such as boron and zirconium to levels beyond those that can ordinarily be tolerated with traditional cast and wrought processing. Additional work is recommended to further define the optimum alloy composition for PM Udimet 720 and to scale the effort to larger commercial heat sizes.

Additionally, the concept of developing a dual microstructure PM Udimet 720 disk featuring a coarse grained rim and a fine grained bore should be considered. This is because the results of this work have shown the coarse grained microstructures can develop very attractive creep rupture, crack growth rate, and LCF capabilities at elevated temperature conditions such as might be required by rim locations in advanced disk designs. Similarly, the fine grained structures investigated in this program have shown tensile and LCF capabilities that are attractive for lower temperature bore regions. Therefore, by combining these two structures into a single disk design, it may be possible to develop an overall performance capability greater than what could be developed by a disk processed to a single microstructural condition.

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