DEVELOPMENT OF DAMAGE TOLERANT MICROSTRUCTURES

IN UDIMET 720

K. R. Bain*, M. L. Gambone*, J. M. Hyzak**, and M. C. Thomas*

*Allison Gas Turbine Division of G.M.C.
P.O. Box 420, Indianapolis, IN 46206

**Wyman-Gordon Company
Worcester Street
North Grafton, MA 01536

Abstract

Developments in the design of aerospace turbine engines are changing the material service requirements. In particular, the incorporation of damage tolerant design concepts has increased the need for high strength turbine disk alloys with good high temperature crack growth properties. A program was initiated to develop a crack growth resistant microstructure in the high strength nickel-base superalloy UDIMET* 720. This alloy has excellent tensile strength and fatigue strength when produced with a fine grained microstructure (ASTM 8-12). Several alternative structures with coarser grain sizes were produced via heat treatment and supersolvus forging which exhibited significant improvements in high temperature fatigue crack growth behavior. These alternative microstructures were evaluated for their effect on a variety of mechanical properties including tensile, stress-rupture, low cycle fatigue, and fatigue crack growth at several temperatures. The effects of gamma prime size and morphology along with grain boundary structure are also related to the observed behavior.

* UDIMET is a registered trade name of the Special Metals Corporation.

Superalloys 1988
Edited by S. Reichman, D.N. Duhl,
G. Maurer, S. Antolovich and C. Lund
The Metallurgical Society, 1988

Introduction

UDIMET 720 alloy is high strength corrosion resistant superalloy which is strengthened by gamma prime, $Ni_3Ti(Al)$. A review of the development of the UDIMET 720 alloy was given by Sczerzenie and Maurer(1). The alloy was developed for use in steam turbine blade applications but has recently been recognized for its outstanding strength and fatigue resistance when used with a fine grain size in gas turbine disk applications. With billet conversion and forging aimed at producing a fine grain (ASTM 8-12) microstructure, UDIMET 720 readily achieves average property levels of 220 ksi ultimate strength and 170 ksi yield strength at 1000°F. High temperature low cycle fatigue resistance is also very good in the fine grain condition with fatigue strength at or better than RENE-95 when corrected for the lower density of UDIMET 720 (.292 lb./in.^{3}). The measured fatigue crack growth rate of UDIMET 720 alloy in the fine grain condition at 1200°F with a 5 minute dwell at maximum load is 15x slower than PM/Extruded and Isothermally forged RENE-95(2,3). This improvement is expected when one considers the research by Whitlow(4) which indicates that the chemistry and grain boundary structure of UDIMET 720 inhibits diffusion of oxygen along the grain boundaries which accelerates intergranular crack growth at elevated temperatures.

In this program the benefits in high temperature fatigue crack growth observed in the fine grain version of UDIMET 720 are extended by producing microstructures which can further reduce the fatigue crack growth rates of the alloy at elevated temperatures. Considerable research has indicated that increasing the grain size of an alloy will dramatically reduce the high temperature fatigue crack growth rate of nickel-base superalloys (2,5-7). Increasing the grain size reduces the tensile and low cycle fatigue strength of the alloy. Therefore, the goal becomes to develop a process and structure which give the best compromise between the high strength of UDIMET 720 and improved fatigue crack growth resistance. Such a material will have considerable application in damage tolerant designs which must operate at temperatures at or above 1200°F, such as advanced gas turbine disks. The present paper reports on the progress made to date in developing the UDIMET 720 alloy for just such an application.

Experimental Results

The following sections will detail the processing, microstructure and experimental results obtained in this program.

Material

A total of five different microstructures were produced and evaluated in this program. The structures were obtained by controlled forging and heat treatment of the UDIMET 720 material. The chemistry is given below:

UDIMET 720 Chemistry

Ni	Cr	Co	Mo	W	Ti	Al	C	B	Zr
Bal.	17.8	14.5	2.98	1.21	4.94	2.45	.032	.032	.030

This material was vacuum induction melted and vacuum arc remelted, homogenized and forged to billet, to give a uniform fine grain size of ASTM 8. The fine grain billet was forged on hot dies at a subsolvus temperature. The gamma prime solvus for this alloy, as determined by differential thermal analysis, is generally 2090°F. The coarser grain microstructures were produced either by forging in the supersolvus regime or by supersolvus heat treatment of fine grain forgings. For this study, the supersolvus forgings were produced isothermally. One necklace structure was also produced. The forging stock was first supersolvus annealed to coarsen the grain size, then subsolvus forged on hot dies. The resultant microstructure showed large warm worked grains outlined by a necklace of fine recrystalized grains. The processing and heat treatment is summarized in Table 1. Representative photomicrographs of the structures produced are shown in Figure 1.

Table 1
UDIMET 720 Processing/Heat Treatment Combinations

	Forging Method/Temperature	Heat Treatment*	Grain Size
1.	Hot die /subsolvus	2080°F/2 hrs/Oil Quench	ASTM 8.5 (19 um)
2.	Isothermal/supersolvus (2.0 in./in./min. rate)	2040°F/2 hrs/Oil Quench	ASTM 4 (90 um)
3.	Isothermal/supersolvus (0.2 in./in./min. rate)	2040°F/2 hrs/Oil Quench	ASTM 3 (127 um)
4.	Hot die/subsolvus	2135°F/2 hrs/Oil Quench	ASTM 0 (359 um)
5.	Hot die/subsolvus (coarse grained billet)	2040°F/2 hrs/Oil Quench	Duplex ASTM 6-10

*Age: 1400°F/8 hrs/air cool + 1200°F/24 hrs/air cool

All of the above processes produced forgings with uniform microstructures. Supersolvus forging has demonstrated previously and in this instance, the ability to produce controlled grain structures. Special processing was also used to produce a uniform necklace structure throughout the majority of the pancake forging. UDIMET 720 alloy in these conditions is very forgeable and grain coarsens in a predictable manner with solution treatment temperature.

Tensile and Stress Rupture Strengths

Tensile test specimens were taken in the chordal direction from the forgings, and were tested at both room temperature and at 1200°F. Duplicate tests were performed and the average ultimate tensile strengths and 0.2% yield strengths are presented in Figure 2. The results show the fine grained (ASTM 8.5) structure exhibited the highest strengths while the ASTM 0 microstructure had the lowest strength. The duplex structure behaved like the uniform fine structure with high strength.

Smooth bar stress rupture testing was conducted in air at 1300°F with an applied stress of 100 ksi. The results of duplicate tests are shown in Figure 3. The coarser structures had the longest lives as expected. The ASTM 0 structure had approximately 2.5x longer lives than the uniform ASTM 8.5 microstructures. The duplex microstructure, which was selected because these structures generally maintain good stress rupture properties, lasted only half as long as the uniform fine grain size. The fine recrystalized grains in the duplex forging controlled the behavior.

Low Cycle Fatigue Results

Strain controlled low cycle fatigue testing was conducted to determine the relative effects of these microstructural variations on the number of cycles to initiate a crack. Five tests were performed at the same conditions on each of the five processes. All the tests were conducted at 1200°F on smooth, Kt=1, specimens, R-ratio = 0.0, with a frequency of 20 cycles per minute in strain control at a total strain range of 0.80%. The

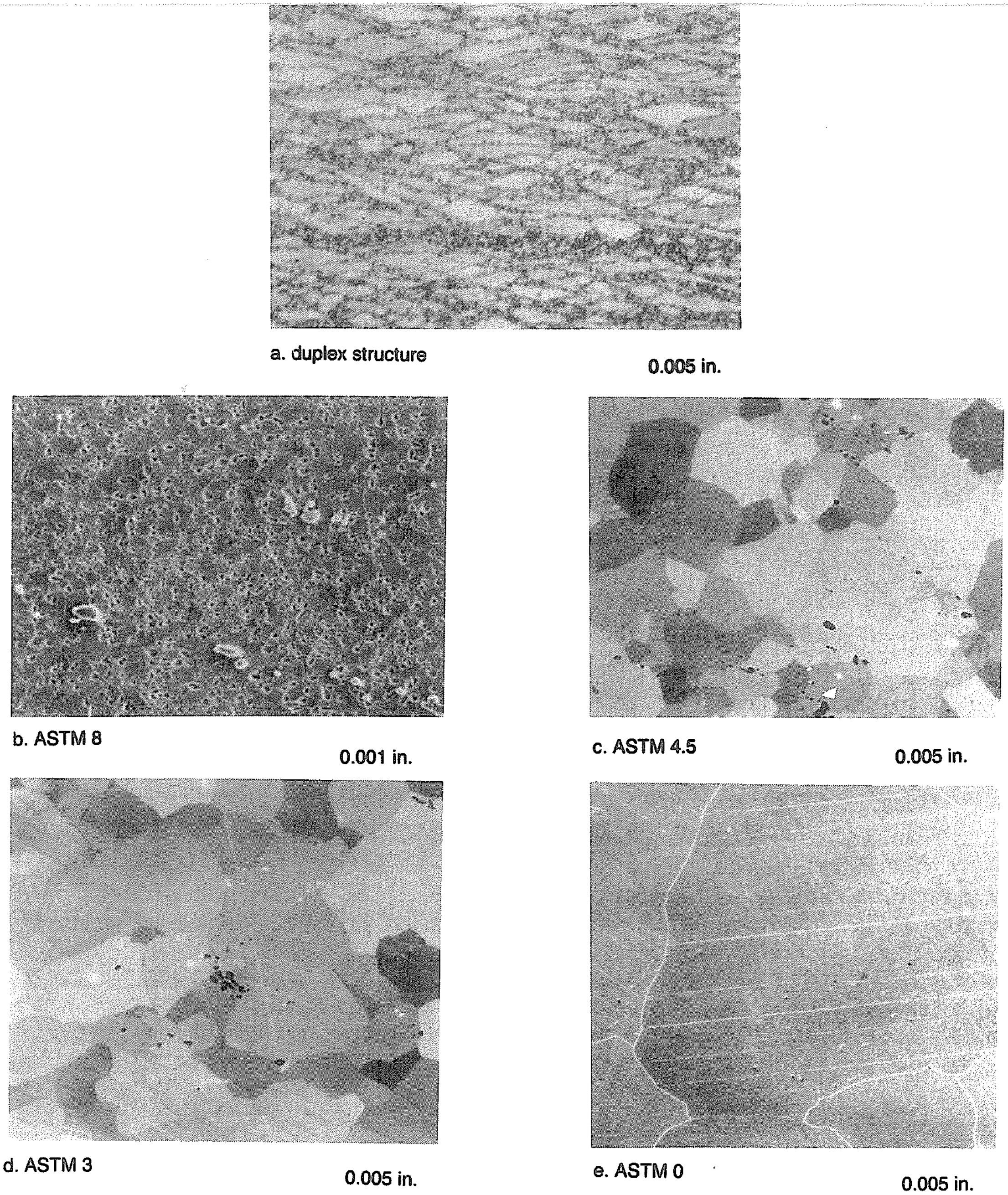

Figure 1. Microstructures of the five heat treatment/process variations of U-720 studied.

results indicated that as the grain size was decreased the fatigue lives increased. (see Figure 4) The ASTM 0 structure exhibited lives a factor of ten shorter than the fine ASTM 8.5 grain size structure. The duplex structure had low fatigue strength with the highest scatter in the results.

Fatigue Crack Growth Results

Duplicate fatigue crack growth rate tests were conducted in air on each of the five structures at two different test conditions. Duplicate tests at 800°F, R-ratio = 0.05, at 200 cpm were conducted to evaluate the lower temperature cyclic crack growth rate for each microstructure. Tests at 1200°F, R-ratio = 0.05, with a 5 minute dwell at the maximum load were conducted to evaluate the time dependent crack growth behavior of the five structures. Four of the five structures had the same 800°F crack growth rate which was similar to RENE-95 (2), but the ASTM 0 grain size process exhibited a factor of two reduction in the fatigue crack growth rate.

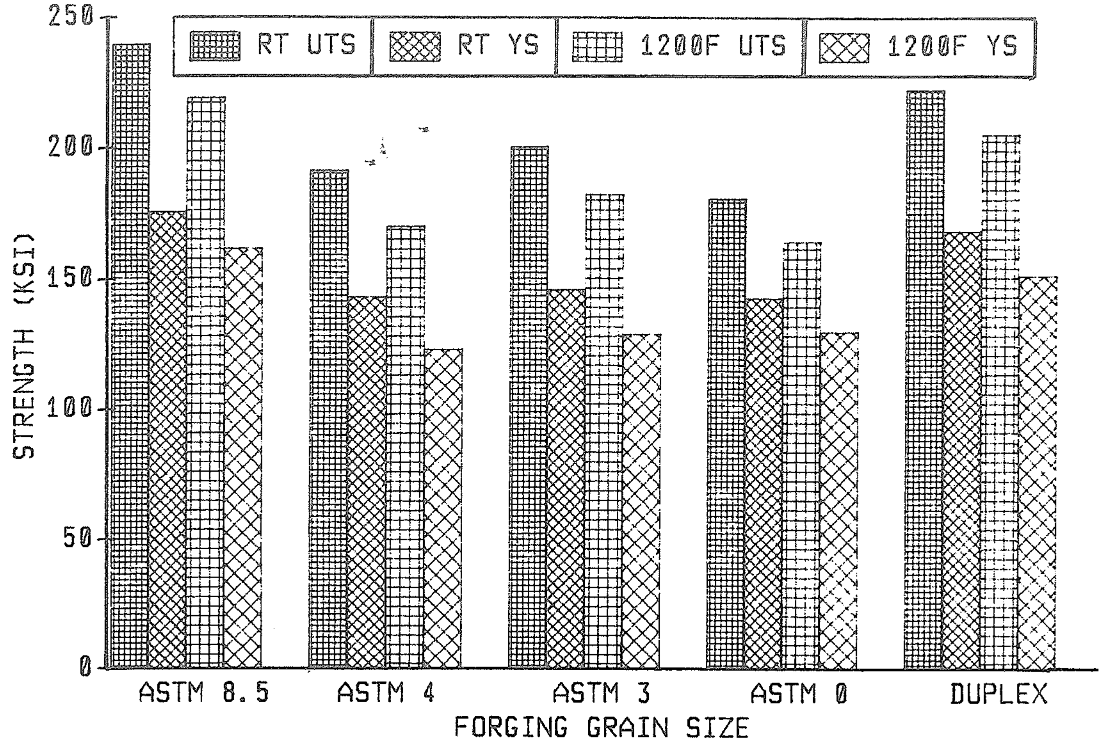

Figure 2. Tensile test results at room temperature and at 1200°f.

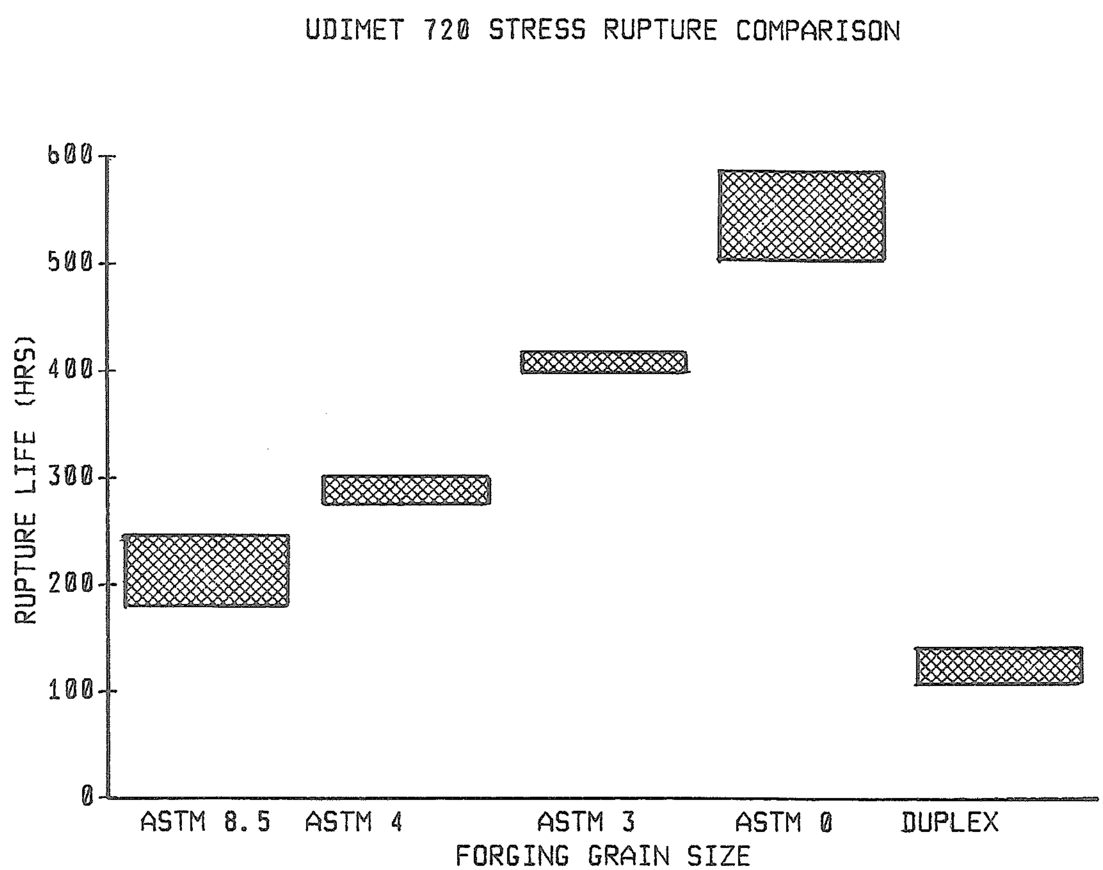

Figure 3. Range of stress-rupture results for the five microstructures tested at 1300°f/100 ksi.

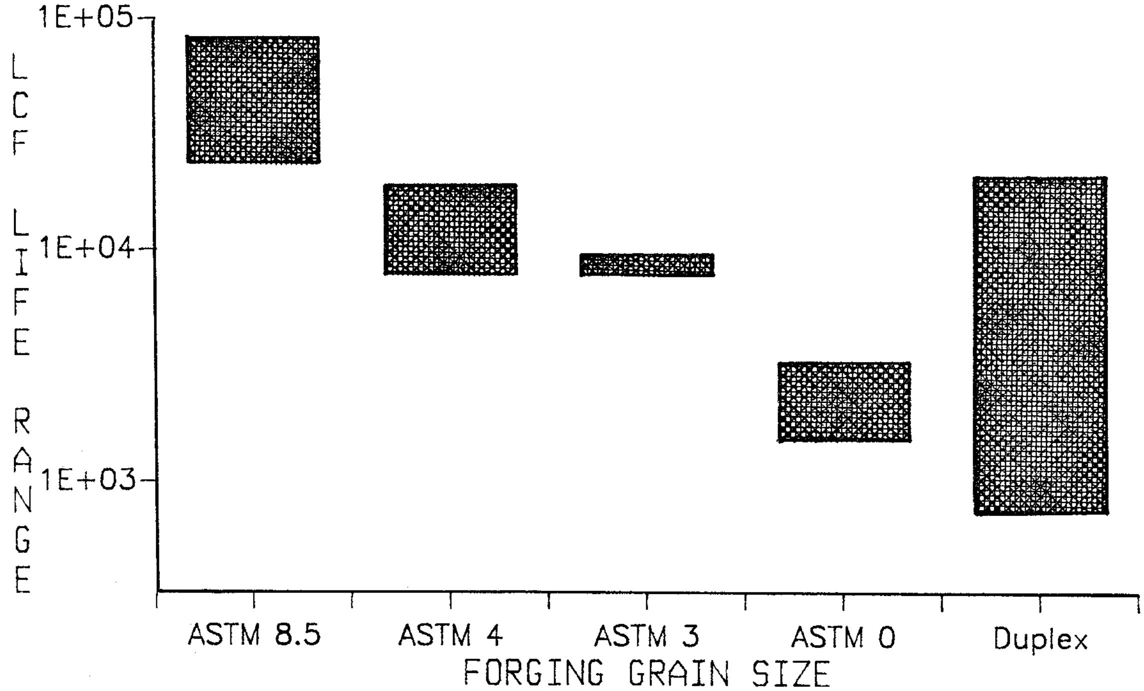

Figure 4. Low cycle fatigue test results. The results indicated that the finer structures are superior in LCF strength.

(see Figure 5). The 1200°F results are shown in Figure 6. The coarse grained microstructures had the lowest fatigue crack growth rates. The ASTM 0 structure exhibited crack growth rates four orders of magnitude lower than fine grained RENE-95 tested under similar conditions (3).

The fracture paths of each of the fatigue crack growth specimens was also examined. At 800°F Figure 7 shows that the fractures were transgranular with the fracture surface becoming very rough for the larger grain sizes. At 1200°F Figure 8 shows that the fracture paths were always intergranular as is common in time dependent crack growth tests. However, the fracture path became mixed at 1200°F for the ASTM 0 structure indicating only a slight time-dependent cracking, and this structure did show the smallest effect of hold time on crack growth.

Discussion

The results of the mechanical tests on the five microstructures produced several interesting results. The effect of grain size on tensile strength, stress-rupture, and low cycle fatigue were as expected. Increasing the grain size decreased tensile and fatigue strength, but increased the stress-rupture lives. However, the reduction in strength was greater than expected for the supersolvus forged structures. The observed gamma prime precipitates are shown in Figure 9. The supersolvus forged structures (ASTM 3 and ASTM 4 grain size) along with the duplex structure have a mixture of large and small gamma prime while the subsolvus forged structures have a uniform fine gamma prime precipitate. The duplex gamma prime is good for stress rupture but gives lower tensile strengths. All of the forgings received a standard disk aging heat treatment at 1400°F and 1200°F which resulted in heavy precipitation of grain boundary carbides and borides along the grain boundaries. The formation of continuous films in the grain boundaries can be seen in Figure 10. These films would result in lower stress rupture lives and must be avoided in future work by tailoring the heat treatments to precipitate these phases at higher temperatures. Stabilization heat treatments in the 1800°F to 1900°F have been shown to eliminate continuous grain boundary films in UDIMET 720 (1). The phases present in the grain boundary for the five microstructures studied is given in Table 2.

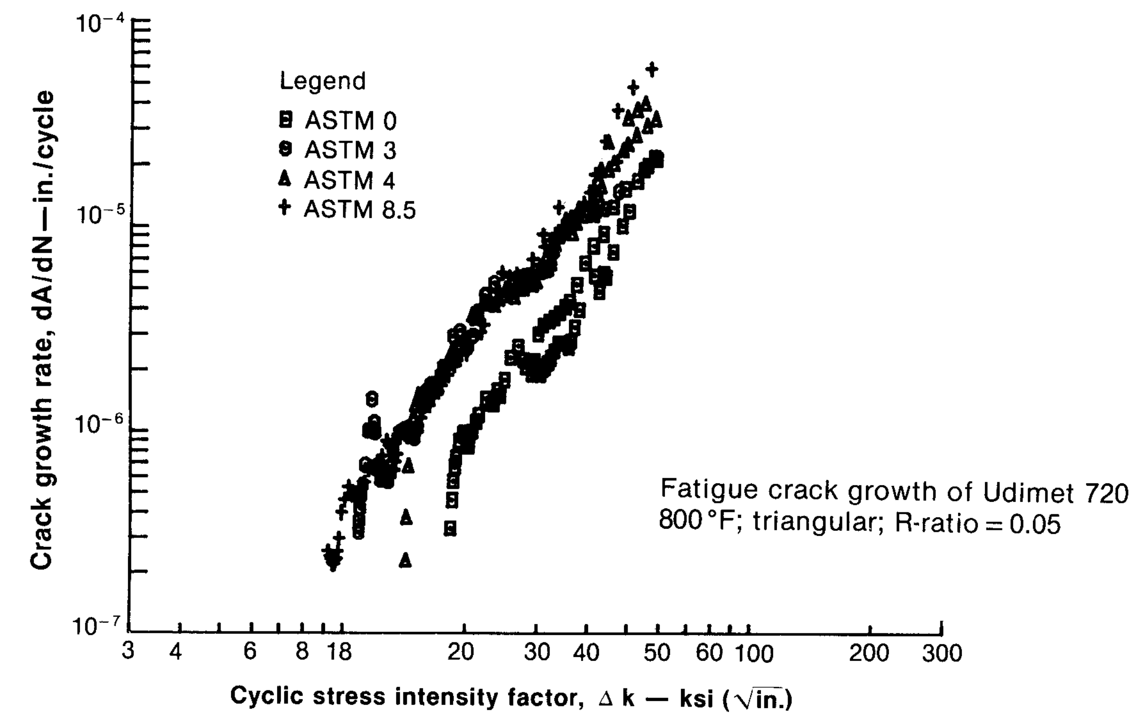

Figure 5. Fatigue crack growth at 800°f. The ASTM 0 grain size has an increased threshold and a reduced growth rate.

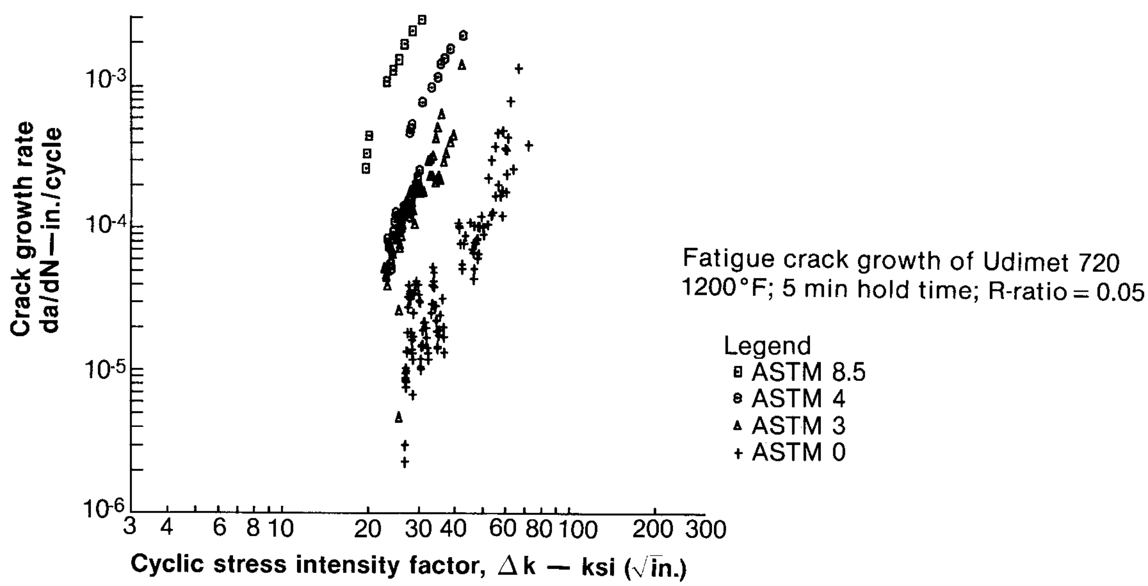

Figure 6. Fatigue crack growth at 1200°f with a 5 minute dwell at the maximum load. Fatigue crack growth rate decreased with increasing grain size.

Table 2
Grain Boundary Phases Observed in UDIMET 720

Grain Size	TiC	$CR_{23}C_6$	$(Cr,Mo,W)_3B_2$	M_xB_y
ASTM 0	X		X	
ASTM 3	X		X	X
ASTM 4.5	X	X	X	X
ASTM 8.5	X	X	X	
DUPLEX	X	X	X	X

The large ASTM 0 grain microstructure gave the best crack growth behavior of the five microstructures studied. At 800°F the large transgranular facets deflected the crack tip which would reduce the effective stress intensity at the crack tip and reduce the crack growth rate. The gamma prime morphology within the grains would have had an

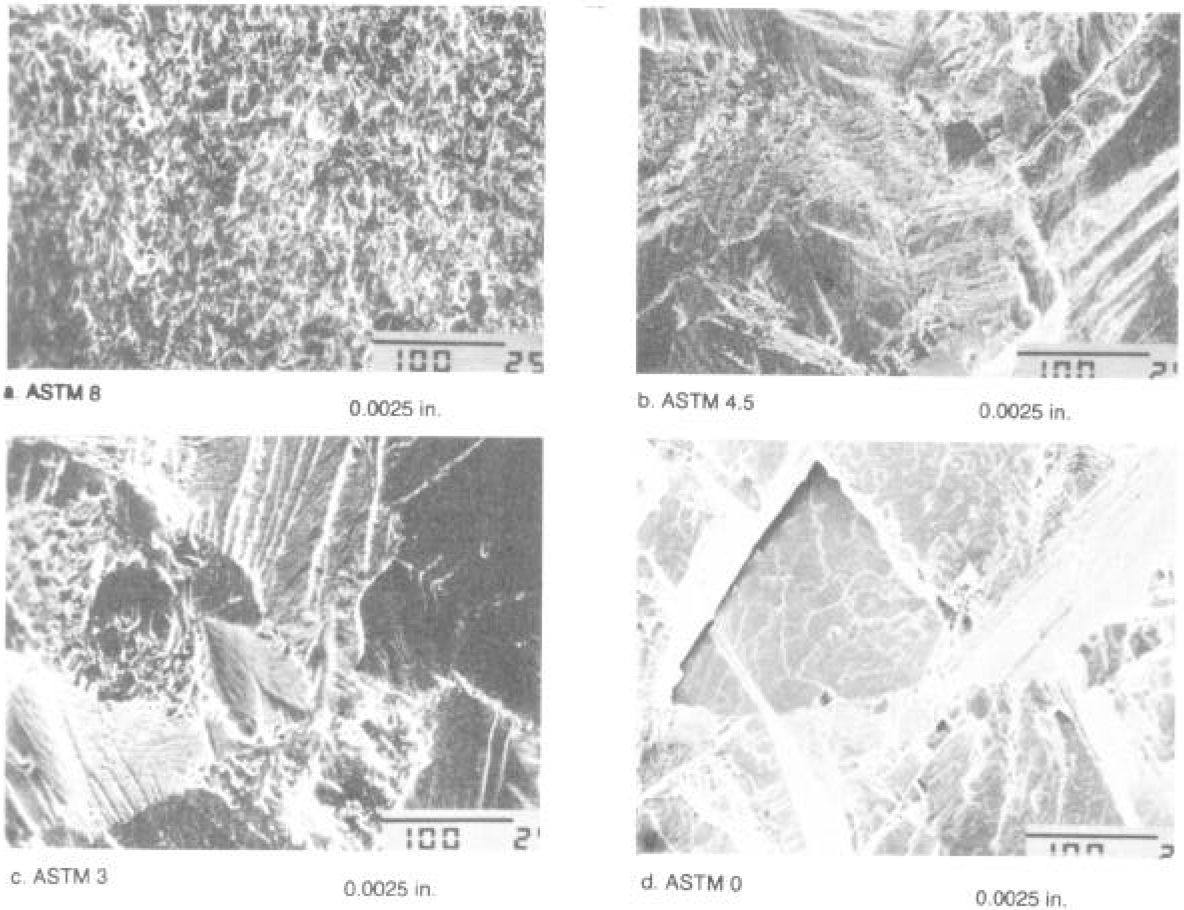

Figure 7. Fractographs of the 800°f FCGR tests. The ASTM 0 grain size has a dramatic increase in fracture roughness.

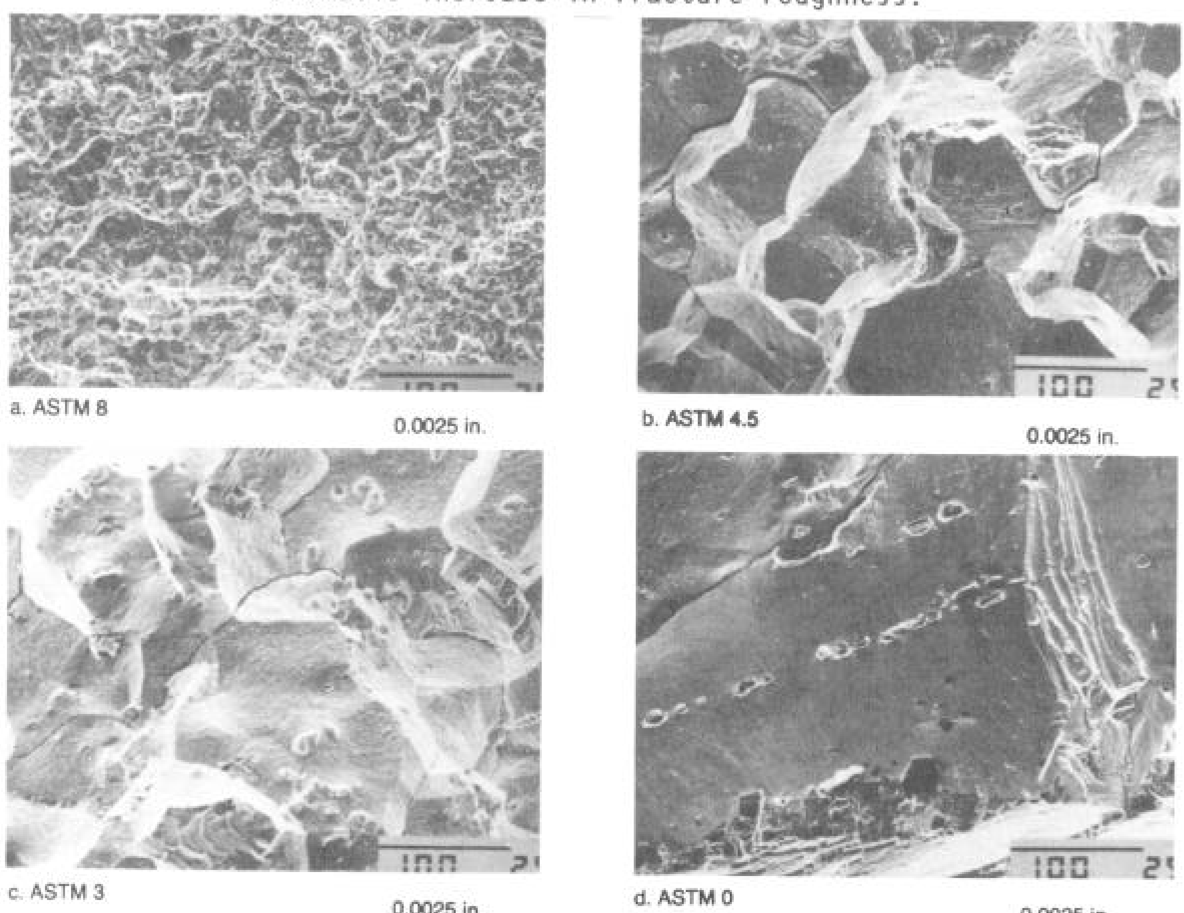

Figure 8. Fractographs of the 1200°f FCGR test specimens. The fracture path was intergranular as expected during time-dependent crack growth.

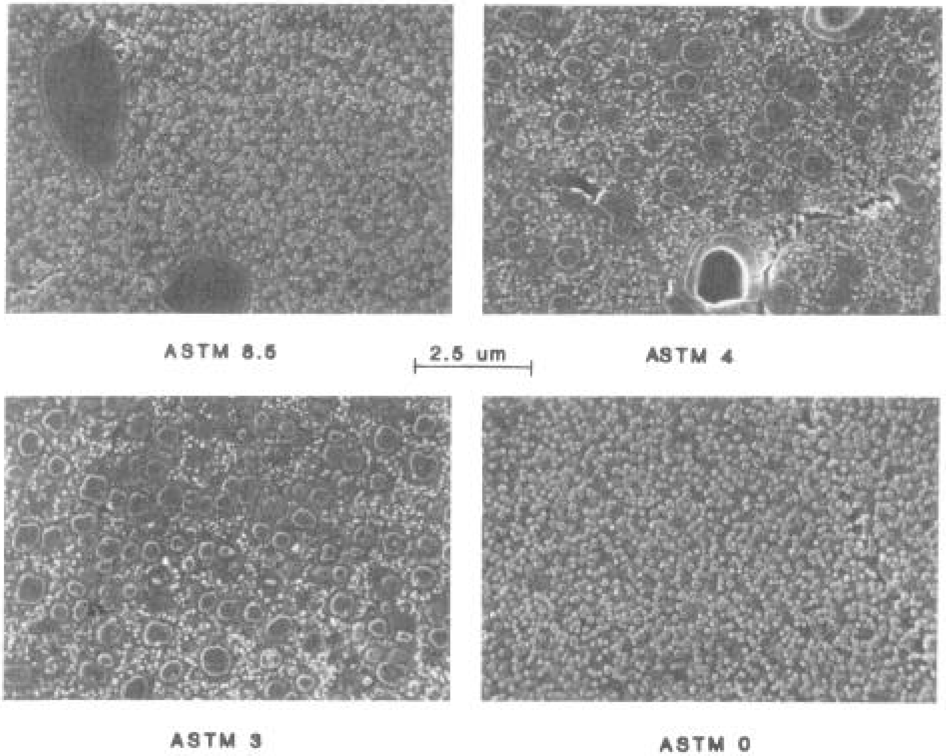

Figure 9. Gamma prime morphology and distribution in four of the microstructures tested. The supersolvus forged structures had a duplex large and small gamma prime distribution which is not optimum for high tensile strength.

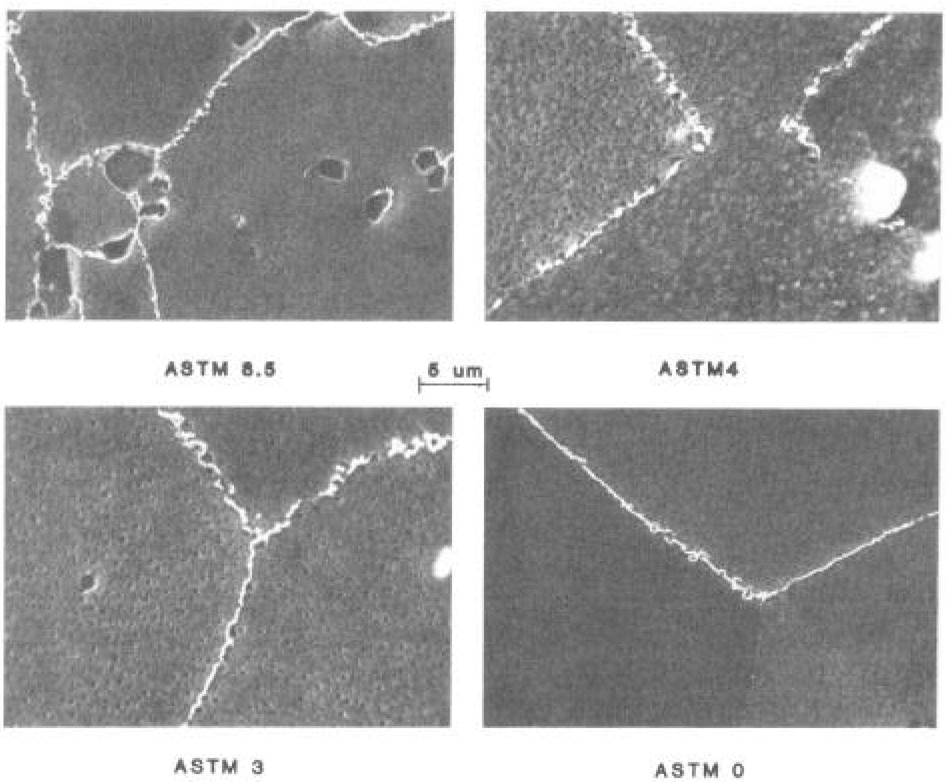

Figure 10. Heavy grain boundary decoration with carbides and borides was observed with all of the structures tested. Continuous grain boundary phases can reduce stress-rupture and low cycle fatigue strength.

effect on the crack growth rate at 800°F. At 1200°F the effect of grain size on the fatigue crack growth rate has been modelled (5). The effect of increasing the grain size from ASTM 8.5 to 0 should have reduced the crack growth rates by more than a factor of 100, and such a decrease was observed. The duplex structure acted more like a small grain size material, however research has shown that duplex structures generally have good time dependent crack growth characteristics. The precipitation of continuous carbide films around the small recrystalized grains may have increased the time dependent crack growth rates observed for the duplex structure.

Conclusion

The development of UDIMET 720 alloy for high temperature damage tolerant applications in advanced turbine disks still requires some additional research. However, the initial work performed indicates that the goal is attainable. Additional work to refine the heat treatments to enhance the low temperature tensile strength along with stabilization heat treatments to alter the precipitation of grain boundary carbides and borides to improve the stress rupture behavior of the microstructures must still be finished. The fatigue crack growth improvements obtained to date already are very significant and offer the potential for developing a 1300°F disk alloy for high strength damage tolerant turbine disk applications. In addition, the low cost of producing this alloy by the conventional VIM/VAR and hot-die forging route significantly reduces the cost of this alloy relative to other competitive high strength alloys which require complex and expensive powder processing to achieve their high strengths.

Acknowledgments

The authors would like to thank Prof. John Radavich for his work on photographing the microstructures produced in this program. The support of Allison Gas Turbine Division of General Motors Corporation and Wyman-Gordon Corporation are also acknowledged along with thanks for their permission to publish this work. Special thanks goes to Mr. Barry Holman and Mr. Paul Korinko for assistance in performing some of the mechanical tests in this program.

References

1. F.E. Sczerzenie and G.E. Maurer, Superalloys 1984 (Warrendale, PA; The Metallurgical Society, 1984), 573-582.

2. D.R. Chang, D.D. Krueger and R.A. Sprague, Superalloys 1984 (Warrendale, PA; The Metallurgical Society, 1984), 245-273.

3. S.J. Choe, S.V. Golwalker, D.J. Duquette and N.S. Stoloff, Superalloys 1984 (Warrendale, PA; The Metallurgical Society, 1984), 309-318.

4. G.A. Whitlow, C.G. Beck, R. Viswanathan and E.A. Crombie, Met. Trans. A, Vol. 15A, January 1984, 23.

5. K.R. Bain, "Effect of Oxygen on Creep Crack Growth in Nickel-Base Superalloys" (Ph.D. thesis, Massachusetts Institute of Technology, 1983), 102-112.

6. S. Floreen, Creep-Fatigue-Environment Interactions, (Warrendale, PA; The Metallurgical Society, 1980), 112-128.

7. R.M. Pelloux and J.S. Huang, Creep-Fatigue-Environment Interactions, (Warrendale, PA; The Metallurgical Society, 1980), 151.