ON THE FATIGUE CRACK PROPAGATION BEHAVIOR OF SUPERALLOYS AT INTERMEDIATE TEMPERATURES

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Summary

Fatigue crack propagation (FCP) rates at 650°C and 0.33 Hz have been measured for several forms of Rene 95 and IN-100 with varying grain sizes and strengths. FCP rates have also been measured for selected forms of Rene 95 in vacuum at 0.33 Hz and in air using cycles with a 120 sec tensile dwell. These data and earlier data on various forms of Astroloy are discussed with respect to the effects of grain size, strength, composition, environment, and creep on the rate and mode of cyclic crack propagation at 650°C. Large grain size showed the most beneficial effect of the metallurgical variables studied. In tests at 0.33 Hz, increasing grain size promoted a transgranular FCP mode rather than the more rapid intergranular mode which occurred in the fine-grained alloys. Even for the 120 sec dwell cycle, which produced intergranular FCP in all grain sizes, increasing grain size reduced the FCP rate. Where the transgranular FCP mode was observed, FCP rates decreased both with increasing strength and grain size, independent of alloy composition. However, strength had little effect on the rate of the intergranular FCP mode. Tests showed that the intergranular FCP mode is controlled by environmental attack and does not occur in vacuum. The rate of the intergranular FCP mode was the same in the fine-grained forms of all three alloys, however this was taken to mean there were compensating differences among the three particular alloys studied, rather than no effect of composition in general on the intergranular FCP mode. The importance of large grain size in the rim area of future gas turbine engine disks designed to allow higher rim temperatures is stressed.

Introduction

Understanding the FCP resistance of superalloys is of current interest because of desires to adopt a "retirement for cause" methodology for gas turbine engine disks based on a safe crack extension life from a given size flaw, and also to develop improved alloys. Previous studies have shown that the advanced, high-strength, fine-grained superalloys have relatively poor resistance to FCP at turbine disk rim temperatures, and that it is further degraded by low frequencies or tensile dwells (1-4). However, neither strength, grain size, composition, nor powder metallurgy or conventional processing alone correlated exactly with FCP resistance. Differences in the cyclic deformation characteristics of the alloys were observed (5,6), but again these characteristics alone did not seem to explain FCP behavior.

More recently it was found in a systematic study of Astroloy, that fine grain size, but not high strength in itself, lead to poor crack propagation behavior at 650°C and 0.33 Hz (6). Fine grain size was shown to promote a transition from a transgranular to an intergranular mode of FCP, which was apparently environmentally controlled, since it did not occur in vacuum. In the fine-grained forms of Astroloy, where FCP was intergranular, the rate was not affected by alloy strength. However, in the large grained form studied, increasing strength decreased rather than increased FCP rates.

In the present work, two additional superalloys used in gas turbine engine disks, Rene 95 and IN-100, have been tested in several forms at 0.33 Hz in air and compared together with the previous data on Astroloy to gain a more comprehensive picture of the effects of grain size, strength, and alloy composition on FCP behavior. In addition, selected forms of Rene 95 were tested at 0.33 Hz in vacuum, and in air using a cycle with a 120 sec tensile dwell to evaluate the effects of environment and creep.

Materials

The three alloys discussed in this paper are all nickel-base superalloys strengthened by the ordered intermetallic γ' precipitate. Astroloy, Rene 95, and IN-100, with 43, 50, and 60 v/o of the γ'-phase, contain 12, 13, and 15 a/o total of Al, Ti, and Nb, respectively. All three alloys contain as the principal carbide an MC. Rene 95 and Astroloy also contain some $M_{23}C_6$ and M_3B_2. The compositions of the various forms of the alloys tested are shown in Table I.

The processing methods and heat treatments for each alloy and the resulting grain sizes and strengths are summarized in Table II. Only 4 of the 9 forms of Astroloy studied previously (6) will be discussed here, those representing the extremes of behavior.

Table I. Chemical compositions in weight percent.

ELEMENT	P&E ASTROLOY	HIP ASTROLOY	CAP&R RENE 95	HIP RENE 95	C&W RENE 95	PM IN-100	VADER IN-100
Al	4.1	4.0	3.9	3.7	3.7	5.0	5.0
Ti	3.5	3.5	2.3	2.0	2.2	4.5	4.3
Nb	-	-	3.7	3.6	3.4	-	-
Cr	15.0	15.1	13.5	13.0	13.8	12.0	12.4
Mo	5.0	5.2	3.6	3.3	3.5	3.1	3.1
W	-	-	4.0	4.3	4.2	-	-
V	-	-	-	-	-	0.8	0.8
Co	17.1	17.0	8.0	8.2	8.0	18.4	18.3
Ni	Bal	Bal	Bal	Bal	Bal	Bal	Bal
C	0.027	0.023	0.062	0.047	0.150	0.09	0.09
B	0.028	0.024	0.02	0.02	0.04	0.019	0.019
Zr	0.01	0.01	0.022	0.025	0.040	0.063	0.060

Table II. Processing history, grain size, and 650^{o}C monotonic tensil

MATERIAL	PROCESSING	SOLUTION	AGE	GRAIN SIZE (μm)	YIELD STRENGTH (MPa)
P&E ASTROLOY	Powder hot pressed and subsequently extruded using an 8:1 reduction ratio @ 1065C	1110C/2Hr/OQ	845C/4Hr/AC 650C/24Hr/AC	5	1165
		1110C/2Hr/OQ	980C/120Hr/AC 650C/24Hr/AC	5	860
HIP ASTROLOY	Powder consolidated by hot isostatic pressing for 3 hours @ 1190C and 105 MPa	1160C/2Hr/OQ	845C/4Hr/AC 650C/24Hr/AC	50	1105
		1120C/2Hr/OQ	980C/120Hr/AC 650C/24Hr/AC	50	690
CAP&R RENE 95	Powder consolidated by Universal Cyclops' CAP* process and hot rolled to 67% reduction @ 1120C	1080C/1Hr/AC	760C/8Hr/AC	3	1260
		1080C/1Hr/AC	955C/24Hr/AC	3	980
HIP RENE 95	Powder consolidated by hot isostatic pressing for 3 hours @ 1120C and 105 MPa	1120C/1Hr/AC	760C/8Hr/AC	10	1100
C&W RENE 95	Cast product which was subsequently cross rolled via a proprietary schedule	1220C/1Hr/AC 1120C/1Hr/AC	760C/8Hr/AC	150	930
		1220C/1Hr/AC 1120C/1Hr/AC	1040C/24Hr/AC	150	680
PM IN-100	Powder consolidated by Pratt & Whitney's Gatorizing* process	1120C/2Hr/OQ	870C/0.7Hr/AC 650C/24Hr/AC 760C/4Hr/AC	4	1110
VADER IN-100	A cast version of IN 100 produced by Special Metals' VADER* process which was subsequently HIPed for 3 hours @ 1160C and 105 MPa	1120C/2Hr/AC	870C/0.7Hr/AC 650C/24Hr/AC 760C/4Hr/AC	500	880

*Registered trademarks of respective companies

Test Procedure

FCP tests were conducted using a modified compact tension specimen which has been previously described (6). Crack growth rates, da/dn, were correlated with the stress intensity factor range, ΔK. The specimens were precracked at room temperature according to quidelines set forth in ASTM E647-78T and subsequently tested at 650°C under load control using a 0.33 Hz triangular waveform and an R-ratio (minimum load/maximum load) of 0.05. Crack length was monitored continuously with a DC potential drop system (6).

All forms of the alloys were tested in air at 0.33 Hz and selected forms of Rene 95 were also tested in a vacuum of 5×10^{-6} torr or less at 0.33 Hz. Additionally, selected forms of Rene 95 were tested in air in creep--fatigue cycles with a 120 sec dwell at maximum load. The waveform used was identical to that of the 0.33 Hz tests except for the 120 sec dwell. For each test type of each material, the da/dn vs. ΔK curves shown are composed of data from at least 2 individual tests.

Results and Discussion

Fatigue Crack Propagation.- The forms of Rene 95 and IN-100 studied showed the same effects of grain size and strength on FCP behavior in air at 650°C and 0.33 Hz as shown previously for Astroloy (6). The behavior of all three alloys is summarized in Figure 1.

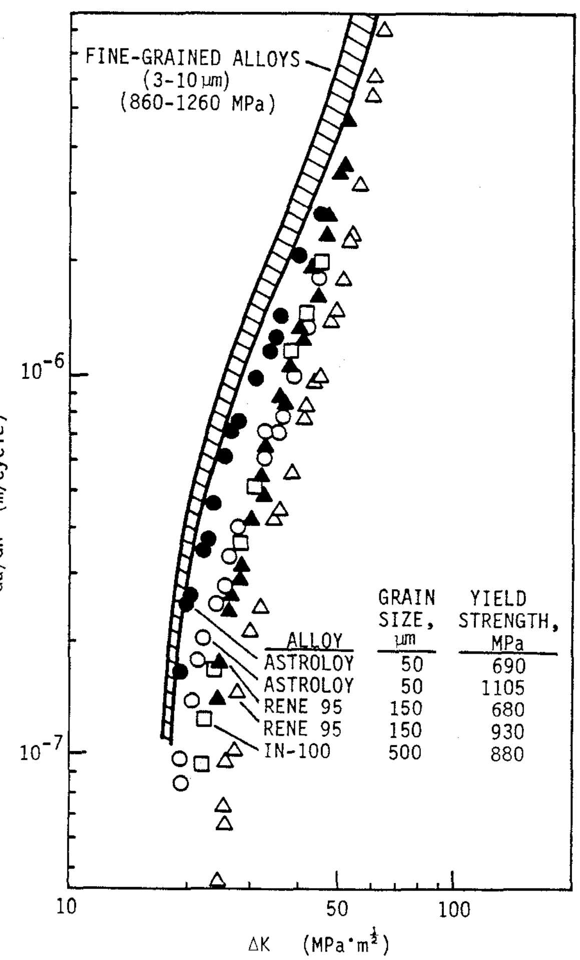

Figure 1. Crack growth data for all alloy forms at 650°C and 0.33 Hz in air.

All the fine-grained alloys exhibited intergranular FCP, and over the range that they were varied neither strength nor grain size appeared to greatly affect the rate of FCP. The band shown includes the FCP rates of all the fine-grained alloys. Grain sizes vary from 3 to 10 μm, and yield strengths vary from 860 to 1260 MPa. Although not shown, the change in FCP rate with strength for any one alloy was even smaller. The inference that alloy composition also does not greatly affect resistance to this intergranular mode of FCP seems surprising and may only be the result of competing effects. However, discussion of this subject will be reserved for later.

The large grained forms of the three alloys all exhibited a transgranular mode of FCP and lower rates than the fine grained forms, as shown in Figure 1. In Astroloy the transition from transgranular to intergranular FCP occurred at a grain size of less than 20 μm (6). It was further shown that when the transgranular mode of FCP was operating, both increasing grain size and increasing strength increased FCP resistance in Astroloy. A relationship of the following form was found to collapse the data in the Paris regime:

$$da/dn = A(\sigma_y^{-1} d^{-\frac{1}{2}})\Delta K^n,$$

where σ_y and d are the alloy yield strength and average grain diameter, respectively. Fatigue crack propagation rates for the various forms of Rene 95 and IN-100 studied here show about the same exponential dependence of da/dn on ΔK. Thus, when (da/dn) for the various materials at a given ΔK is plotted against $(\sigma_y^{-1} d^{-\frac{1}{2}})$ as in Figure 2, the FCP rate is normalized for grain size and strength.

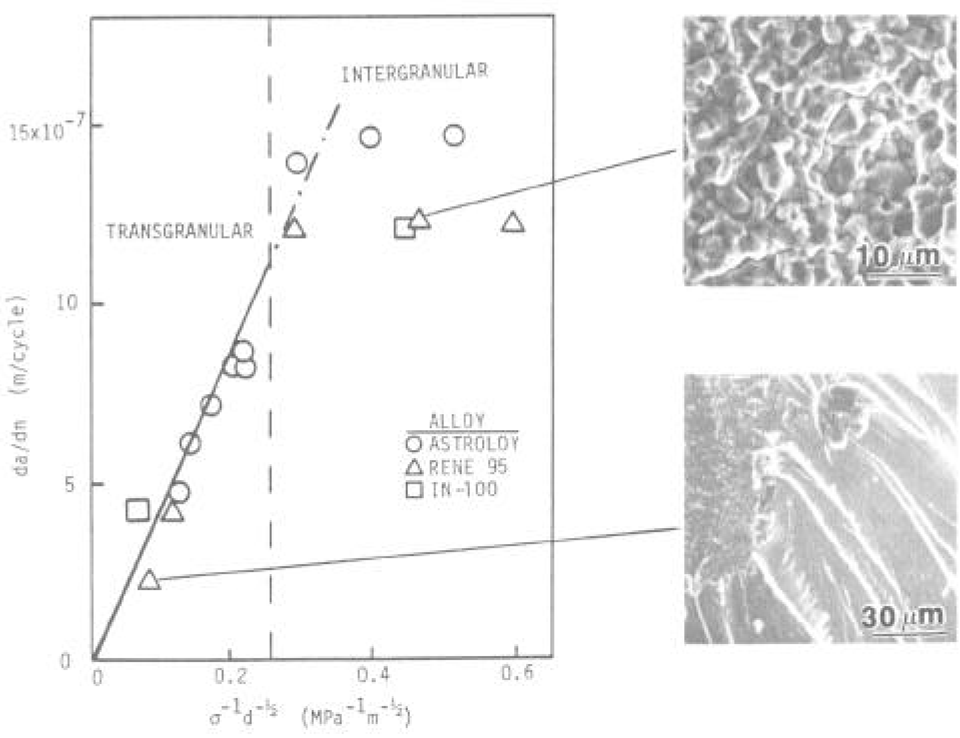

Figure 2. Normalized crack growth rates of all alloy forms shown in Figure 1 and reference 6. ΔK=30 MPa$\sqrt{m}$.

It may be seen that where the transgranular FCP mode operates the data fit the above correlation very well, independent of alloy composition except in as it affects strength. The form of this correlation can be related to several models of ductile FCP. The inverse dependence of FCP rate on yield strength appears in many models, see the review of Yokobori (7). In addition, several models based on the incremental fatigue failure of the material immediately ahead of the crack show an inverse dependence of FCP rate on size of the zone within which this process is occurring (8-11). In the present case, the grain size might be interpreted as restricting the size of the process zone. It may also be seen in Figure 2, that the data for the fine-grained materials do not fit the above correlation. It breaks down because of the previously shown independence of the rate of the intergranular FCP mode on strength.

Several studies have been made of the effect of microstructure on the FCP behavior of superalloys (12-16). Among these studies test conditions, alloys, and microstructures differ considerably, still there does appear to be a reasonable consensus that increasing grain size is good for FCP resistance (12-15). Support for the claim that increasing strength also improves FCP resistance is only indirect, however. Several studies have concluded that a fine γ' dispersion is beneficial for FCP resistance because it leads to a coarse, planar deformation mode, but not because it usually also leads to high strength (13,14,16). These studies show there is reason to believe that other material characteristics, such as slip planarity or work hardening rate, may affect the rate of the transgranular FCP mode. Still, the relationship above based on grain size and simple monotonic yield strength, which is easily quantified, does to a first order correlate FCP rates for this consistent set of tests on several materials with widely varying microstructures. Also, as previously stated, the inverse dependence of FCP rate on yield strength and grain size can be related to several models based on the mechanics of materials.

The intergranular mode of FCP, on the other hand, is environmentally controlled. Fatigue tests conducted here on Rene 95 and previously on Astroloy (6) show that the intergranular mode of FCP in the fine-grained forms does not occur in vacuum. Figure 3 shows the FCP rates of fine- and large-grained Rene 95 tested in air and vacuum at 650°C and 0.33 Hz. Fine-grained Rene 95, like fine-grained Astroloy showed a threefold improvement in FCP rate in vacuum, and a corresponding change from the intergranular mode observed in air to a transgranular mode. The large-grained form of Rene 95 exhibited transgranular FCP both in air and vacuum and the rate decreased only slightly in vacuum. Based on these results and the absence of any evidence of creep damage on the fracture surfaces, it appears likely that the intergranular mode of FCP in the fine-grained alloys is largely caused by environmental damage at the grain boundaries. Oxygen is the likely species. Others support this conclusion (17).

Since it is unlikely that the rate of oxygen penetration is directly related to the strength of the material, it is not surprising that the FCP rate for a given fine-grained alloy does not appear to be significantly influenced by varying strength. However, differences between alloys might be expected, since the rate of oxygen diffusion through or oxidation of the grain boundary should depend on composition. It seems quite possible that differences in the concentrations of several elements among the alloys studied here have compensating effects. For example, though Cr concentration decreases from Astroloy to Rene 95 to IN-100, Al concentration increases. A detailed analysis of compositional effects is not possible without an experiment specifically designed for the purpose.

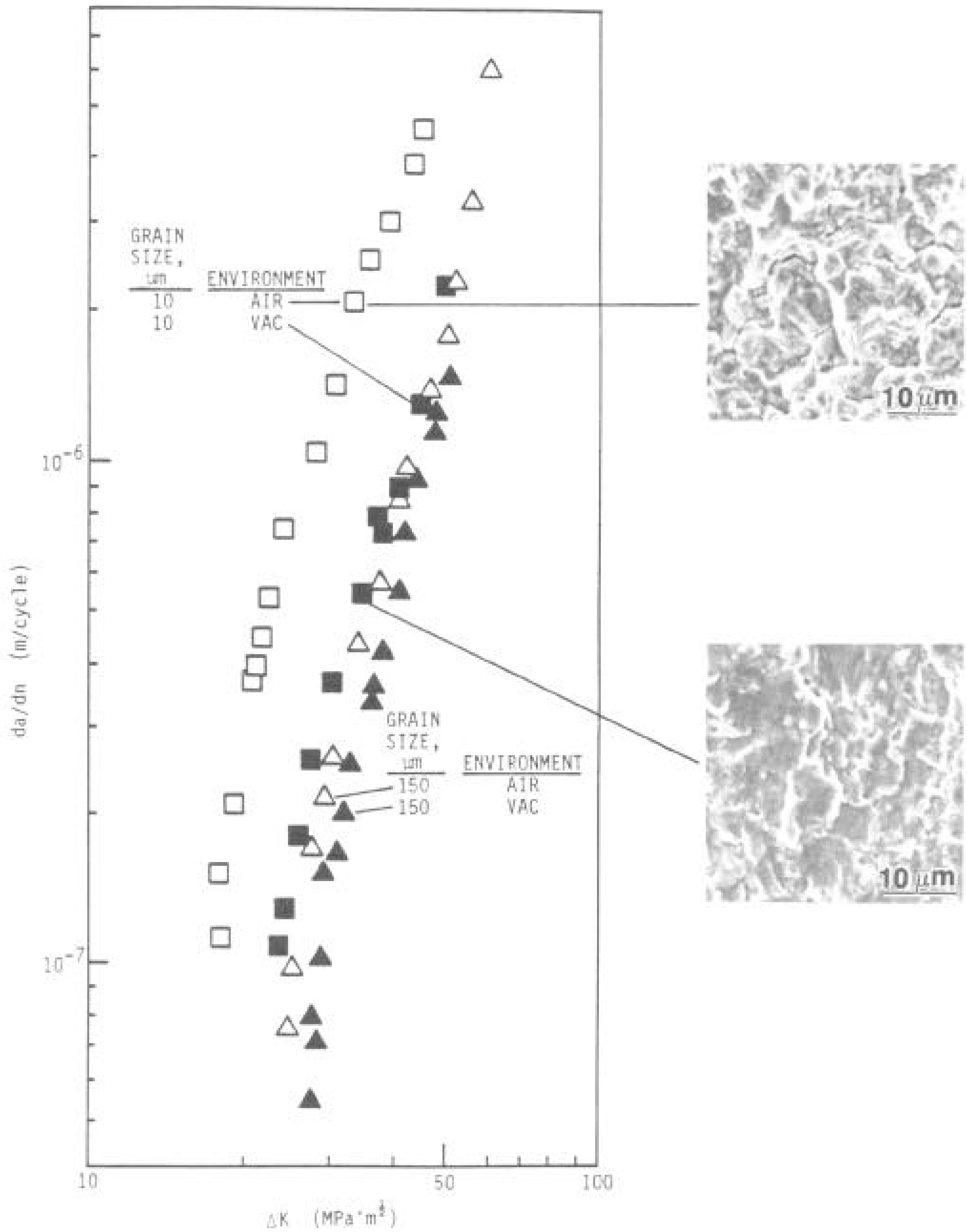

Figure 3. Comparison of air and vacuum crack growth rates at 650°C and 0.33 Hz. All data are for Rene 95 aged at 760°C.

Creep-Fatigue Crack Propagation.- In previous studies of several superalloys (1-4), it was observed that crack propagation in a cycle employing a 900 sec tensile dwell was intergranular in even the largest grained alloys. Still, increasing grain size did appear to reduce the FCP rate. Figure 4 shows the results obtained here on a single alloy, Rene 95, with various grain sizes and strengths for a creep-fatigue cycle at 650°C employing a 120 sec dwell at the maximum load in the cycle. In this test, failure was intergranular in all forms of the alloy, including that with the largest grain size. However, increasing grain size was still the dominant factor in reducing the rate of propagation, as it was for the 0.33 Hz tests. The effect of changes in strength, if any, are mixed. The forms of Rene 95 with 10 and 150 μm grain sizes show small but opposite effects of increasing strength. It is felt that these effects are more likely caused by changes

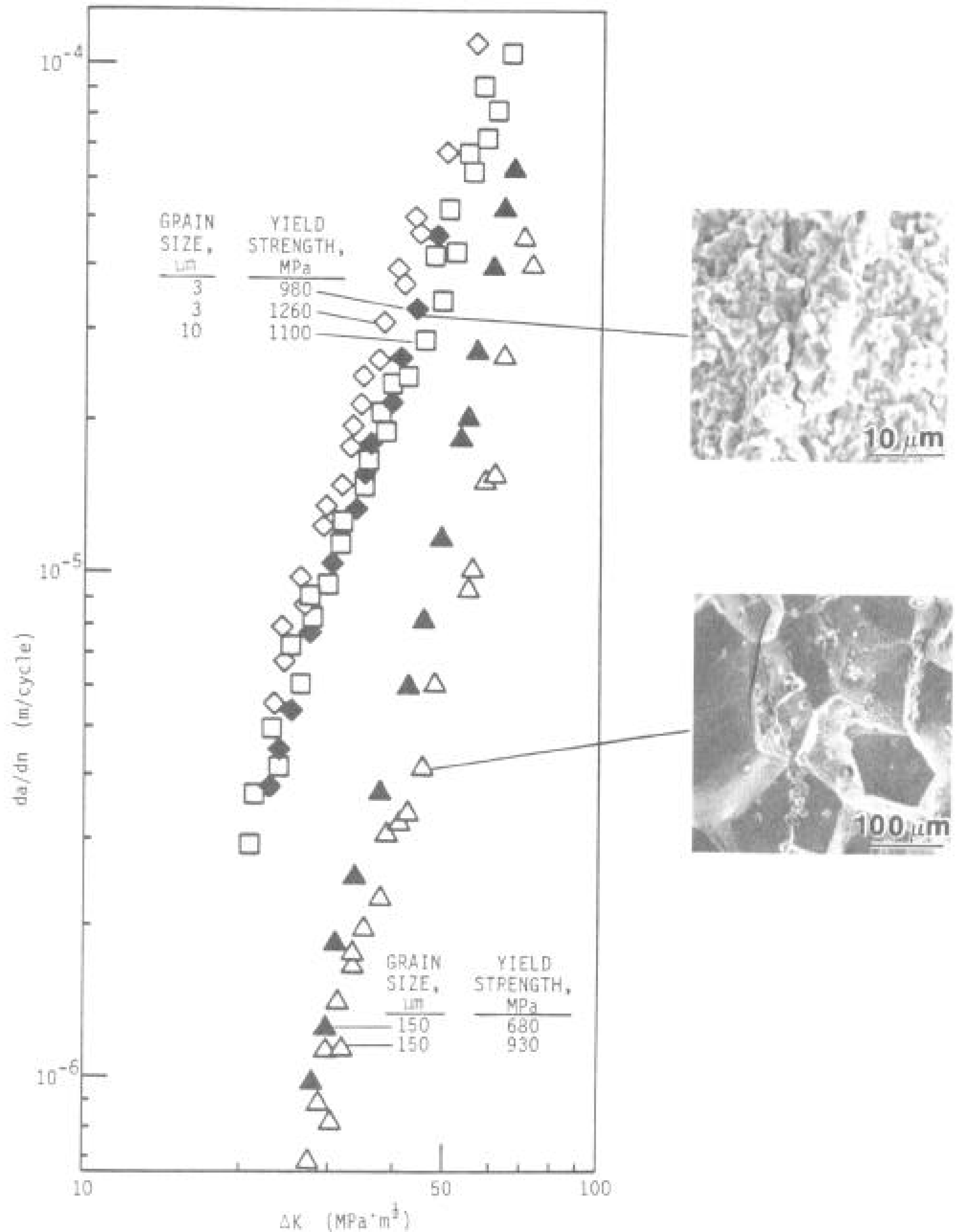

Figure 4. Creep-fatigue crack propagation data for Rene 95. Tests were run in air at 650°C using a 120 sec dwell at maximum load.

observed in grain boundary morphology produced by the different aging treatments.

A detailed comparison shows that for the creep-fatigue cycle, the crack growth rates of the fine-grained forms are even higher relative to those of the large-grained forms than they were for the fatigue cycle. This might be explained by either increased environmental damage or creep damage introduced by the 120 sec dwell, and it is likely that both occur in some degree. However, in a study of commercially-aged HIP Rene 95, others have concluded that at 650°C environmental damage predominates in creep-fatigue crack propagation (17).

One possible mechanism for the effect of decreasing grain size in promoting grain boundary failure is that the increased grain boundary volume effectively dilutes the composition in those elements which segregate to the grain boundaries such as B and Zr. Recent work has suggested that B in particular is effective in reducing the susceptability of Ni to environmental embrittlement at high temperatures (18). This mechanism has been suggested to explain the effect of decreasing grain size on creep crack growth rates in nickel-based superalloys (19). However, Floreen and Davidson found no effect of varying B and Zr concentrations on creep or fatigue crack propagation rates in a Ni-Fe-base superalloy (20). The present work on Rene 95 shows that the large-grained form, which presumably has the highest grain boundary B concentration, does indeed have the lowest crack propagation rate even for the 120 sec dwell tests, where it exhibits intergranular crack propagation just as the fine-grained forms. However, between the two fine-grained forms, the difference between 3 and 10 μm grain size has little effect on crack growth rate either in the 0.33 Hz or 120 sec dwell cycle tests. Clearly, a critical experiment is needed to test the B dilution model.

Concluding Remarks

This work emphasizes the benefit of large grain size on the fatigue and creep-fatigue crack growth resistance of superalloys in the temperature range which aircraft gas turbine engine disk rims operate. For the superalloys studied in tests at 0.33 Hz, grain sizes of about 20 μm or larger precluded the more rapid mode of environmentally controlled intergranular FCP which occurred for finer grain sizes. Also for a cycle somewhat more closely representing that in a turbine disk having a 120 sec tensile dwell, larger grain size was still very beneficial, though failure was intergranular for all grain sizes. For the larger grained materials in tests with frequencies sufficiently high that transgranular FCP occurred, FCP rates decreased with increasing yield strength. However, for the intergranular mode of FCP which is more likely to occur in a real service cycle, strength had little effect.

The desires to maximize resistance both to FCP and to creep in the hot rim of a turbine disk require a large grain size, and further justify continued development of disks with different microstructures and/or compositions in the rim and bore (21-22). The desire for fine grain size to maximize tensile strength and fatigue crack initiation resistance in the bore need not compromise the microstructure in the rim. Further, the environmental nature of the intergranular mode of FCP, which is likely to be inescapable at rim temperatures of advanced disks, should be borne in mind in developing alloys for disk rim applications. It is felt that the effects of grain boundary chemistry must be further investigated, and that the lack of any large effect of composition on the rate of the intergranular FCP mode among the alloys studied here was probably the result of competing effects.

Acknowledgements

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