THE INFLUENCE OF ORIENTATION ON THE FATIGUE OF DIRECTIONALLY SOLIDIFIED SUPERALLOYS

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A comprehensive program was undertaken to understand the dependence of fatigue in DS superalloys on material orientation including load controlled high cycle, strain controlled low cycle, and thermal fatigue testing. Load controlled tests were insensitive to orientation; while in strain control, life was reduced dramatically as material orientation deviated from the solidification direction. The elastic modulus variation dominated the strain controlled response through its control of stress level. Orientation dependence of life was quantitatively predictable from a master fatigue curve based on maximum tensile stress and modulus. At high temperatures, transverse and equiaxed material lives fell below those predicted on the basis of modulus alone due to the introduction of intergranular modes of failure. Fatigue life was shown to be governed by crack growth from pre-existing or environmentally introduced defects.

INTRODUCTION

Directionally solidified (DS) nickel base superalloys were introduced to improve performance of jet engine turbine airfoils. The DS process imparts improved creep-rupture (1) and thermal fatigue (2) resistance in the solidification direction due to preferred crystallographic texture and grain boundary orientation, Figure 1. Although the solidification direction is the prime load bearing direction in turbine airfoils, the actual stress states are in general quite complex as a result of thermal stresses and geometric constraints. This complexity inevitably leads to the generation of stress in directions other than the solidification direction. For satisfactory airfoil performance, the

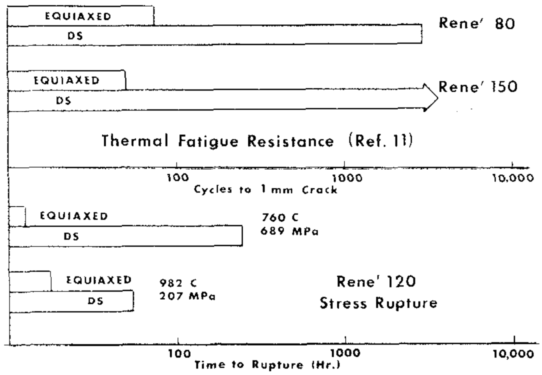


Figure 1 Comparative Thermal Fatigue and Stress Rupture Lives of Equiaxed and DS Superalloys

material capability in these off-axis orientations must be determined, since DS alloys are highly anisotropic. In addition, definition of the orientation dependence of properties is necessary in establishing reasonable grain orientation acceptance limits for hardware. While the study of anisotropy in DS alloys encompasses a wide range of mechanical properties, this paper is concerned with characterizing the orientation dependence of fatigue and determining the significant factors controlling this dependence for the purpose of formulating adequate material acceptance and design life criteria. This study encompassed load controlled (high cycle), strain controlled, and thermal fatigue of DS materials oriented parallel (0°), transverse (90°), and at intermediate angles to the solidification direction. The tests were conducted at various temperatures and cyclic conditions.

Specimens of two superalloys, Rene' 120 (9 Cr, 10 Co, 3.8 Ta, 2 Mo, 7 W, 4.3 Al, 4 Ti, .2 C, .015 B, .07 Zr, Bal. Ni by wt.) and Rene' 150 (5 Cr, 10 Co, 6 Ta, 1 Mo, 5 W, 5.5 Al, 2.2 V, 1.5 Hf, .06 C, .015 B, Bal. Ni by wt.) were machined from DS ingots at the desired angle to the growth direction. Specimens of Rene' 120 were heat treated at: 1220C/2 hr., 108C/4 hr., 925C/8 hr. and 760C/16 hr. Rene' 150 heat treatment was: 1200C/1/2 hr, 1080C/4 hr, and 900C/16 hr. Standard test specimens and techniques were used. After testing the specimens were examined fractographically and grain orientations checked against the nominal DS orientations.

RESULTS AND DISCUSSION

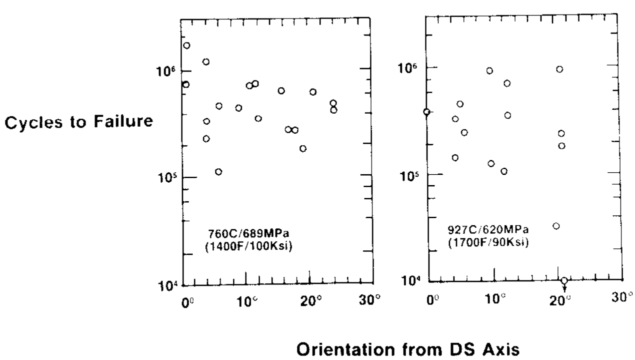
Load Controlled (High Cycle) Fatigue

A series of tests was conducted on Rene' 150 specimens at one stress range for load orientations of 0°, 10° and 20° to the DS axis. As shown in Figure 2, for orientations between 0° and 20°, essentially no dependence of fatigue life on orientation was detected. This is in agreement with observations on load controlled low cycle fatigue of DS MarM200 + Hf (3).

Strain Controlled (Low Cycle) Fatigue

The variation of fatigue life of DS Rene' 120 with orientation at 650°C, A = ∞, 20 cpm continuous strain cycling conditions is shown in Figure 3. For comparison, data on equiaxed Rene' 125, an alloy of similar composition (4) are also shown. In contrast to the load controlled behavior, there is a strong dependence of life on orientation. Testing conducted at 650°C showed an identical trend. The strain controlled life decreased rapidly as the orientation deviated from 0°, reaching a minimum at about 45° orientation, and then increasing again at 90°. The equiaxed Rene' 125

Fig. 2 Orientation Dependence of Load Controlled (High Cycle) Fatigue of DS Rene' 150



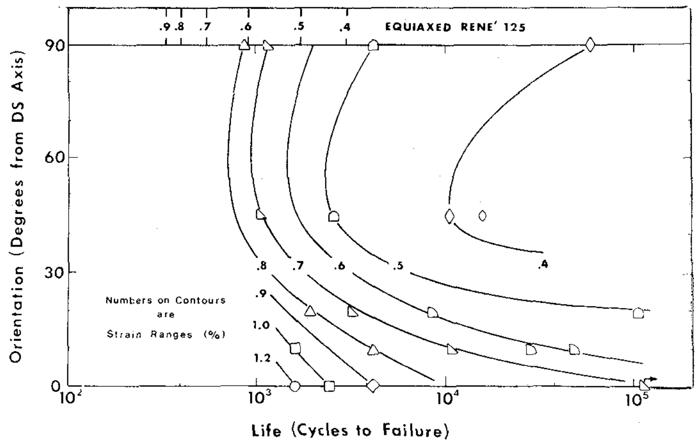
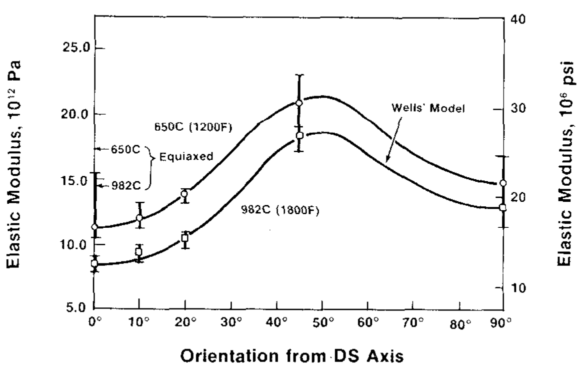


Figure 3 Orientation Dependence of Strain Controlled (Low Cycle) Fatigue in DS Rene' 120 at 982°C (1800°F), $A_\varepsilon = \infty$, 20 cpm.

data fell below the 90° DS orientation at both 650°C and 982°C, indicating that the transverse direction of the DS material was somewhat superior to the equiaxed material, despite the presence of grain boundaries in both cases. Elastic moduli were measured from the strain controlled LCF hysteresis loops. An orientation dependence inverse to the fatigue life was noted, with a minimum in modulus at 0°, and a maximum near 45° as shown in Figure 4. This behavior is in excellent agreement with a model presented previously (5) for transversely isotropic materials, such as DS alloys.

Fig. 4 Orientation Dependence of Elastic Modulus in DS Rene' 120



This variation in elastic modulus with orientation will have a strong effect on the stress levels developed in a strain controlled test. This is illustrated in Figure 5, where schematic hysteresis loops are shown for high and low modulus orientation. This figure assumes that cyclic plastic strain range is relatively small compared to the total strain range so that the elastic properties dominate behavior. It also assumes that the cyclic flow stresses are relatively orientation independent. Both of these conditions were very well satisfied in this study. The plastic strain range was only half of the total at about 100 cycles life (the so-called "transition fatigue life") in these high strength alloys and decreased rapidly at longer lifetimes. At 650°C only a few tests had any measurable cyclic plastic strain.

This variation of stress level with orientation in strain controlled testing coupled with the observed life variation leads us to suggest that maximum tensile stress is the dominant influence in controlling fatigue life in these materials. Indeed, when the maximum tensile stress rather than the total strain range is plotted against life as in Figure 6, most of the data for the various orientations collapses on to one master curve at each temperature. The only exception to this was noted at 982°C, where the 90° (transverse) data fell significantly below the 0° to 45° data band. The reasons for this will be discussed below.

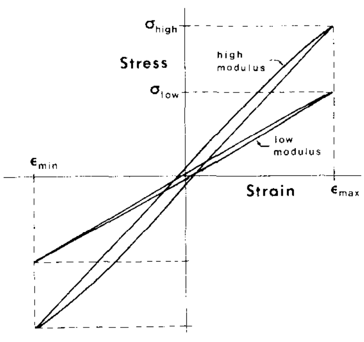
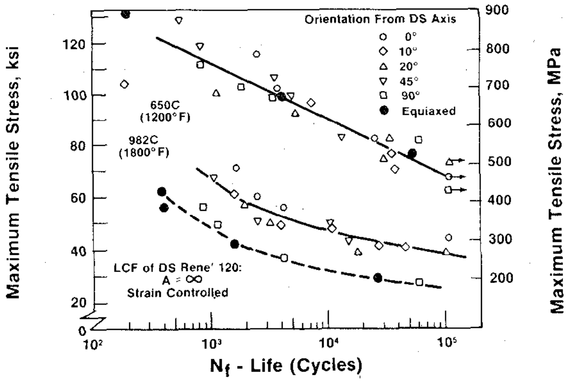


Figure 5 Schematic Hysteresis Loops Showing Effect of Modulus on Maximum Stress

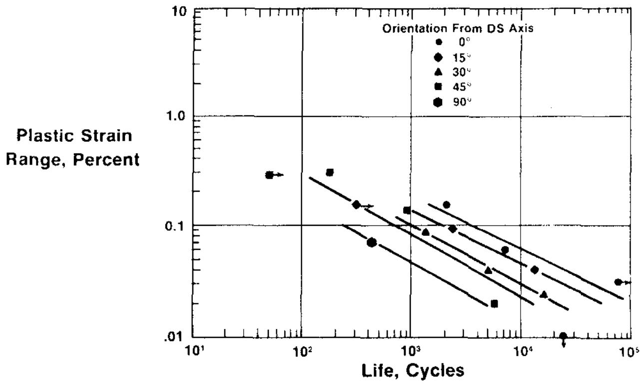
Fig.6 Dependence of Strain Controlled LCF Life on Maximum Cyclic Tensile Stress for Various Orientations in DS Rene' 120



Note that the fatigue data for equiaxed Rene' 125 also conform to the master curve at 650°C, and follows the 90° (transverse) data to 982°C. This implies that the inherent (load controlled) fatigue behavior of equiaxed and DS material is basically the same, and the differences in life observed in strain controlled testing are due to stress level differences arising out of the modulus differences.

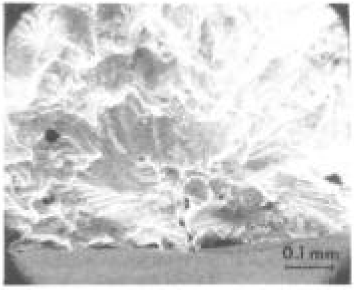
The use of maximum tensile stress as the life controlling parameter in strain controlled fatigue is unusual and warrants comparison to the more usual plastic strain range Coffin-Manson representation. As mentioned previously, at 650°C little cyclic plasticity could be observed in the hysteresis loops, so that the comparison will be limited to 982°C. In DS Rene' 120 a plot of plastic strain range vs. life resulted in a single straight line for all the orientations on a log-log plot. Thus the conventional Coffin-Manson behavior was observed. Unlike Rene' 120, however, the fatigue life of DS Rene' 150 did not correlate uniquely with plastic strain range for all the orientations examined at 982°C. Instead, the results layered out in a consistent order of descending life from 0° to 90° orientation, Figure 7. Maximum tensile stress for this alloy still provided an excellent correlation of all the data, in the manner of Figure 6. The reason for this difference in behavior from Rene' 120 is unclear. In any event, the result indicated is that stress level is more important than plastic strain range in this regime.

Fig.7 Dependence of Strain Controlled LCF on Plastic Strain Range in DS Rene' 150 at 982C (1800F), 20 cpm

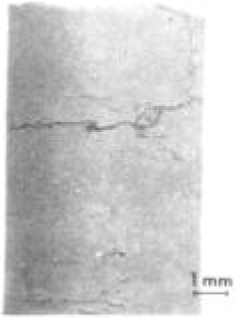


The use of stress as a life prediction parameter gained support from the fractographic analysis of these specimens. Most of the fractures at 650°C initiated from defects such as porosity (Figure 8a). If crack initiation occurred early in life at such defects as has been shown to be the case in other superalloys (6), then life would be propagation controlled, and tensile stress levels would be important in driving the crack growth. At 982°C fractures tended to initiate from surface cracks that originated under the obvious influence of oxidation as described by McMahon and Coffin (7). For orientations between 0° and 45°, these cracks were transgranular, beginning at localized oxidation spikes in interdendritic regions of the incompletely homogenized cast structure, Figure 8b. At 90° orientation, the cracking was entirely intergranular, Figure 8c. This is similar to the behavior reported for equiaxed nickel base alloys (7), except a subsequent transition to transgranular cracking was generally not observed here. The intergranular modes have been observed to begin early in life, so that environmentally assisted crack growth should dominate life. The inferior lives of the 90° and equiaxed structures shown in Figure 6 undoubtedly reflect the more rapid intergranular crack propagation process that occurs at elevated temperatures.

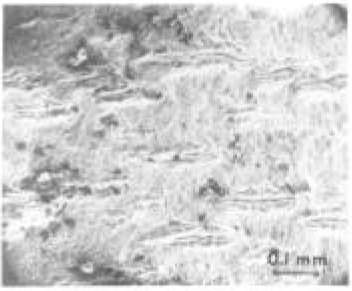
The ability of maximum tensile stress to account for orientation dependence of low cycle fatigue extended beyond rapid continuous cycling behavior. Tests conducted under more complex conditions, such as with hold times or with combined thermal and mechanical cycling, also showed an orienttation dependence that varied inversely as the specimen modulus, according to the maximum stress developed. Thermal fatigue tests on tapered wedges in a fluidized bed system after the manner of Woodford and Mowbray (8) illustrated the characteristic orientation dependence expected on the basis of modulus variation, Figure 9. This behavior is in agreement with thermal mechanical fatigue crack growth measurements on DS Mar-M200 (9) and with the observations reported by Bizon et. al. on Mar M247 (10) in that cracking variation was due to crystallographic (modulus) orientation and not grain boundary failure modes. Strain hold time tests on DS Rene' 150 oriented at 0°, 15° and 45° to the DS axis also were normalized to one curve similar to Figure 6 when modulus variation was taken into account.



a) 650C: Porosity



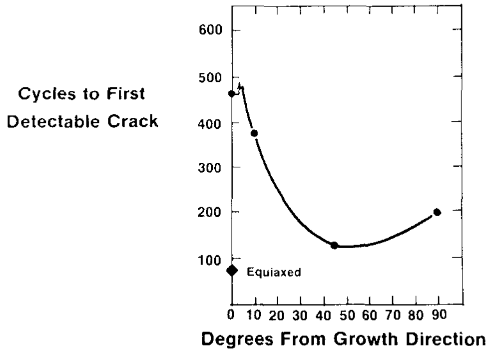
c) 982C: (90° Orientation) Grain Boundaries



b) 982C (0° Orientation) Surface Oxidation

Figure 8. Crack Initiation Modes in DS Rene' 120

Fig. 9 Thermal Fatigue Crack Initiation of DS Rene' 120 As a Function Of Specimen Orientation. Fluidized Bed Test, R.T. to 975C (1787F)



SUMMARY AND CONCLUSIONS

1. In high strength nickel-base DS alloys the orientation dependence of fatigue life varied with the maximum tensile stress developed for a given fatigue cycle type. The dominance of maximum stress appears to hold for a wide range of cyclic lives above approximately 200 cycles and a variety of cyclic conditions ranging from rapid continuous cycling to slow cycles with hold times to strictly thermal fatigue.

2. The results of this investigation thus suggest a simple and rational method of assessing fatigue life in off-axis directions of DS materials. Up to intermediate temperatures, a maximum stress-life curve for any desired cycle type can be constructed from specimens of one orientation only. Fatigue life dependence on orientation can then be determined from elastic modulus and the maximum stress-life curve. At very high temperatures, however, two orientations are required to accomodate the difference between transgranular and intergranular modes.

3. It is clear from this investigation that the improvement in strain controlled fatigue life in DS superalloys is due primarily to modulus reduction in the principal stress directions. This is particularly true at intermediate temperatures (e.g. 650°C) where DS and equiaxed forms showed similar dependence of life on maximum tensile stress. At higher

temperatures, (e.g. 982°C) there is an additional benefit of DS in orientations less than 45° due to suppression of grain boundary cracking.

4. The strong dependence of life on tensile stress makes it reasonable to conclude that the fatigue life in these alloys is controlled by crack propagation. This conclusion is supported by the fractographic observations of relatively early, defect-related initiation, either at porosity at low temperatures or at oxidized crack nuclei at high temperatures. This points directions for a quantitative life prediction methodology based on crack growth concepts.

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