FATIGUE CRACK PROPAGATION RATE TESTING OF SINGLE CRYSTAL

SUPERALLOYS NASAIR 100 AND CMSX-2 AT 982°C

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Summary

Single crystal superalloys NASAIR 100 and CMSX-2 were tested under conditions of fatigue crack propagation (FCP) in air at 982°C. The misorientation of NASAIR 100 was varied between 2-25.5°, and the FCP rate (equivalent to the Paris Law exponent n) was found to decrease as the misorientation increased. Recrystallized surface grains were also produced on NASAIR 100 specimens; and although the FCP rate increased, observations of bench marks on the fracture surface suggested that the single crystal interior primarily controlled the FCP rate, but then increased as the intergranular cracking was encountered. The alloy CMSX-2 was found to have a FCP rate similar to that of NASAIR 100. FCP data on single crystal alloys in general are discussed, utilizing SEM and optical metallography to support the experimental findings.

Introduction

Fatigue crack propagation (FCP) rate tests at 982°C were conducted on two single crystal superalloys, namely NASAIR 100 and CMSX-2 (1). NASAIR 100 was developed under the NASA "Materials for Advanced Turbine Engine (MATE)" Program (2), while CMSX-2 was developed under private sponsorship (3). The composition of these materials is given in Table I.

Table I

Nominal Compositions of Ni Base Single Crystal Superalloys (Wt.Pct.)

	<u>Cr</u>	<u>Co</u>	<u>W</u>	<u>Mo</u>	<u>Al</u>	<u>Ti</u>	<u>Ta</u>	<u>Hf</u>	<u>Zr</u>	<u>C</u>	<u>B</u>
NASAIR 100	9	-	10.5	1	5.8	1.2	3.3	<.1	<.01	.003	.002
CMSX-2 (4)	8	4.6	7.9	.6	5.6	.9	5.8	<.1	<.01	.005	-

The FCP rate testing was conducted to examine how crystallographic misorientation influences the FCP rate of NASAIR 100, how recrystallized surface grains influence the FCP rate of NASAIR 100, and the difference in FCP rate between NASAIR 100 and CMSX-2. Variations in misorientation can be quite large in single crystal castings depending upon the casting process, while recrystallized surface grains occur with some regularity depending again upon the casting process and, to some extent, geometry. Also of particular interest was the threshold cracking stress intensity. For example, only limited data was available at the program inception, and this was on Mar M200 single crystals tested at room temperature (5). The data showed that there was no threshold cracking stress intensity, even at a stress intensity range as low as 1 MPa (m)^{1/2}. This implied that an existing crack in the material would propagate at even the lowest stresses which, if true, would essentially limit the use of this class of materials to non-fatigue applications. Fortunately, this is not the case for the subject materials at 982°C, as will be shown.

To provide as complete a characterization of NASAIR 100 and CMSX-2 without diverging significantly from the subject matter, some tensile and stress rupture data obtained at or near the 982°C test temperature of this investigation, is being presented. Tensile and stress rupture testing, typically of specimens with an axis less than 15 degrees from the {001} crystallographic axis, was conducted on appropriately heat-treated material elsewhere (2,3) and is shown in Table II.

Table II

Tensile and Stress Rupture Properties of Single Crystal Materials

	<u>Temp.</u> <u>(°C)</u>	<u>UTS</u> <u>(MPa)</u>	<u>.2% YS</u> <u>(MPa)</u>	<u>Elongation</u> <u>(%)</u>	<u>R of A</u> <u>(%)</u>	<u>E</u> <u>(GPa)</u>
NASAIR 100	982	836	698	17.5	23	83.4*
CMSX-2	870	1019	860	19.8	-	-
CMSX-2	1050	483	415	24.5	-	-

	<u>Temp.</u> <u>(°C)</u>	<u>Stress</u> <u>(MPa)</u>	<u>Rupture Life</u> <u>(Hours)</u>	<u>Elongation</u> <u>(%)</u>	<u>R of A</u> <u>(%)</u>	<u>Time to 1%</u> <u>Creep (Hours)</u>
NASAIR 100	982	159	1404	12.8	20.7	30
NASAIR 100	982	241	126	25.9	36.7	-
CMSX-2	982	207	302	-	-	-

After the applicable homogenization and age heat treatment, the macrostructures of NASAIR 100 and CMSX-2 are shown in Figure 1 and 2, respectively. The gamma-prime size for both alloys was approximately 0.2 microns.

Figure 1. Macrostructure of NASAIR 100.

Figure 2. Macrostructure of CMSX-2.

Fatigue Crack Propagation Rate Testing Procedure

Test Specimens

Test specimens were cast to size as shown in Figure 3 (except for the 1.3 x .36 mm crack starter slot, which was electro-discharge machined (EDM) after heat treatment). This configuration is considered a center cracked panel (CCP) specimen.

Figure 3. Cast to size CCP specimen. Dimensions in mm.

Typically, the specimens were heat treated and nondestructively inspected (X-ray, fluorescent penetrant, etched to reveal grain boundaries, and crystallographic orientation determined by Laue X-ray back reflection) prior to any machining. In the case of specimens requiring recrystallized surface grains, the center of the reduced section was shot peened (both sides) under various conditions prior to the homogenization heat treatment.

Fatigue Precracking and FCP Test Procedures

The guidelines of Clark and Hudak (6) were used in this study to conduct the precracking and FCP test and analysis. Thus, following their general guidelines, fatigue precracking was conducted in room temperature air at 30 Hz, between nominal stresses of 30-240 MPa, with a mean stress of 135 MPa, which resulted in an average precrack length (including crack starter slot) of 2.6 mm after an average of about 80,000 cycles. Utilizing the appropriate formulae for calculating stress intensity,

$$K = Y (Pa^{1/2})/(BW), \text{ and}$$

$$Y = 1.77 + 2.27(2a/W) - .510(2a/W)^2 + 2.7(2a/W)^3, \text{ where}$$

W = Specimen width (nominally 12.7 mm)

B = Specimen thickness (nominally 1 mm)

2a = Total crack length including crack starter slot

P = Load,

the maximum average precrack stress intensity was determined to be 41 MPa (m)^{1/2}. The 982°C FCP rate tests were conducted in air at 3 Hz between nominal stresses of 23-230 MPa (R = .1), with a mean stress of 126 MPa. The advancing crack was measured by removing the specimen from the furnace and examining it under a microscope, which provided an accuracy of ±0.025 mm. This procedure was repeated several times, and each time a new stress intensity range, ΔK (K_{MAX}-K_{MIN}), was calculated for the ordinate portion of the conventional FCP plots. The crack growth per cycle, da/dN, plotted as the abscissa on the FCP plot, was determined by the secant method, which "simply involves calculating the slope of the straight line connecting two adjacent points on the a versus N curve (6)."

FCP Test Results and Discussion

The familiar Paris Law (7) was used to describe the steady state (Stage II regime) FCP observed for the subject tests and is given by the equation:

$$da/dN = C(\Delta K)^n, \text{ where}$$

$$da/dN = \text{half crack growth (a) per cycle (N),}$$

$$\Delta K = \text{stress intensity range, (K}_{MAX} - K_{MIN}), \text{ and}$$

$$C, n = \text{material constants.}$$

The constants C and n are related to the material for given values of temperature, frequency and load ratio (8), although there is not complete agreement on the effect of load ratio (5). The Paris Law was generally obeyed between a stress intensity range of 11-27 MPa(m)^{1/2}, and between crack growth rates of 10⁻⁵ to 10⁻³ mm/cycle. Values of C and n for the materials in this study and elsewhere are given in Table III. The calculation of C and n always involved at least four specimens. Each of the test categories will be discussed in turn; however, a general discussion of the FCP of single crystal alloys is now in order.

FCP in Single Crystal Superalloys

In general, the fatigue cracking behavior of the subject materials was

brittle in nature - river patterns dominated the fracture surface, and there was no evidence of dimples or striations on the fracture surfaces; however, oxidation may have masked these latter features. In addition, shear lips were practically non-existent, even where fast fracture occurred. At room temperature, the cracking mode appeared macroscopically to be crystallographic in nature. The cracking occurred primarily on the octahedral {111} planes; however, evidence for cracking on (001) planes was also evident. An example of a specimen containing both cracking modes is shown by the SEM fractograph in Figure 4. There is sufficient evidence in the literature to support these observations (10-14) so the crystallographic nature of cracking will therefore not be dwelt upon. To appreciate the general crystallographic cracking nature of fcc metals, the reader is directed elsewhere (15). At the 982°C test temperature, which is

Table III

Paris Law Constants for Single Crystal Alloys

Alloy	Ref.	C*	n	Temp. (°C)	Freq. (Hz)	Load Ratio	Notes ⁺
NASAIR 100	-	2.77×10^{-15}	6.85	982	3	.1	2-4.5°
NASAIR 100	-	1.24×10^{-12}	4.62	982	3	.1	8-12.5°
NASAIR 100	-	8.69×10^{-12}	3.63	982	3	.1	20.5-25.5°
NASAIR 100	-	3.93×10^{-19}	10.32	982	3	.1	surface grain
CMSX-2	-	3.54×10^{-14}	5.64	982	3	.1	---
MAR M002	9	1.02×10^{-13}	4.44	600	1	.1	---
MAR M002	9	1.06×10^{-11}	2.78	RT	10	.1	---
MAR M200	5	3.03×10^{-21}	3.35	RT	20K	-	---
MAR M200	5	3.99×10^{-18}	3.25	RT	20K	-	---
U-700	5	1.02×10^{-19}	3.6	RT	-	-	---

* Units of $(\text{m/cycle})/(\text{MPa}(\text{m})^{\frac{1}{2}})^n$

+ Degrees refer to misorientation of specimen from [001] axis

Figure 4. Starting from the EDM'd notch, left, fatigue precracking initiates on (001) planes, then changes to {111} planes.

the temperature of interest, the cracking changes to a non-crystallographic mode, conforming to the plane(s) perpendicular to the fatigue load. In other related work (13), a Ni-Al-Mo-Ta alloy subjected to charpy impact tests still showed primarily crystallographic cracking at 980°C (but noncrystallographic cracking at 1090°C), suggesting a crack velocity dependence on the cracking mode (or the obvious compositional differences) as well.

FCP Versus Misorientation, NASAIR 100

Misorientation of the single crystal CCP specimens was varied according to a slight, moderate, and severe category, referring to the ranges of 2-4.5°, 8-12.5°, and 20.5-25.5°, respectively. Over this range, it was found that as the misorientation increases, the FCP rate decreases. This is reflected by the Paris Law exponent n in Table III and is shown in Figure 5.

Figure 5. FCP rates plotted for slight, moderate, and severe misorientations of single crystal NASAIR 100.

The decrease in FCP rate is presumably due to the increasingly complex path that the crack follows as the misorientation increases. At low misorientations, for example, the crack will propagate with little secondary cracking (an indication of relative ease) parallel to the planes containing the secondary dendrite branches. As the misorientation increases, the crack must penetrate the dendrite at oblique angles, generating secondary cracking, as shown in Figure 6.

The threshold stress intensity range varied little, from about 8.8 MPa (m)^{1/2} for the slightly misoriented specimens to 11 MPa (m)^{1/2} for the severely misoriented specimens. Thus, the existence of the threshold value represents a limit, below which fatigue cracks should not grow. This data is also supported by more recent findings in Mar M002 at 600°C (9), which demonstrated similar Paris Law exponents (see Table III) and a threshold stress intensity range to those found in this study.

Figure 6. Fatigue crack at 982°C showing interaction with residual dendrites.

FCP With Recrystallized Surface Grains on Single Crystal NASAIR 100

Specimens with a 3-5° misorientation were selected, upon which the surface grains were produced, in order to minimize the contribution of FCP due to misorientation alone. The recrystallized surface grains penetrated the surface of the specimens up to a depth of approximately .2 mm. An SEM fractograph showing an intergranular cracking mode between the surface grains and single crystal interior is shown in Figure 7.

Figure 7. Intergranular cracking between the surface grains and single crystal interior is shown for NASAIR 100.

The presence of the surface grains did cause the FCP rate to increase over that of the slight misorientation category, as the Paris Law exponent $n = 10.32$ would suggest. This is presumably due to the mixed mode of fracture. For example, in Figure 7, beach marks are shown marking the stop and start of a test, illustrating that the direction of FCP was from the single crystal center of the specimen towards the surface grains. Thus, the FCP rate was controlled primarily by the single crystal interior; but as the crack approached the surface grains, the FCP rate increased.

FCP of CMSX-2 Versus NASAIR 100

The specimens of CMSX-2 had a misorientation of less than 15° . The FCP data is plotted in Figure 8, showing the relationship to the combined slight and moderate misorientation categories of NASAIR 100. As the data suggests, the Paris Law exponent, $n = 5.64$, is intermediate to that of the two NASAIR 100 categories, as is the threshold stress intensity range.

Figure 8. FCP of CMSX-2 compared to slight and moderate categories of NASAIR 100.

Conclusions

FCP testing of NASAIR 100 at 982°C demonstrated that a limit below which crack propagation should not occur does exist, according to the principles of linear elastic fracture mechanics. This has since been confirmed with another alloy in more recent work (9).

As the misorientation of the NASAIR 100 increased, the FCP rates decreased. These rates, characterized by n , obeyed the Paris Law for steady state FCP.

When the advancing fatigue crack in NASAIR 100 was subjected to surface grains, the FCP rate did increase. Observations of beach marks on the specimen fracture surface suggests that the FCP rate was primarily controlled by the single crystal interior, but then increased as the intergranular cracking was encountered.

Finally, the FCP rate of CMSX-2 was similar to NASAIR 100.

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