Fatigue Crack Propagation in a Cobalt Base Aligned Eutectic

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Fatigue crack propagation rates were determined for directionally solidified Co-10Ni-10Cr-14Ta-1.0C (CoTaC) at room temperature in laboratory air. Single edge crack specimens, 0.25 cm thick, tested in tension-tension at a stress ratio of less than 0.1 produced a relationship between crack growth rates, \( \frac{da}{dN} \), and stress intensity range, \( \Delta K \), as follows:

\[
\frac{da}{dN} = 8 \times 10^{-14} \Delta K^{4/5} \quad (m \text{ and MN/m}^{3/2})
\]

A stress ratio of \( R = 0.5 \) increased \( \frac{da}{dN} \) by a factor of six. A prestrain sufficient to break fibers into 5 to 10 \( \mu \text{m} \) long segments had no effect upon subsequent crack growth rate. Compact tension specimens, tested with the stress axis normal to the fiber axis, exhibited more rapid cracking for equivalent \( \Delta K \) and a steeper slope, obeying the relationship

\[
\frac{da}{dN} = 1.2 \times 10^{-15} \Delta K^{6.5}
\]

Fractographic examination showed Stage I cracking for \( \Delta K \) less than 10 MN/m\(^{3/2} \), mixed Stage I and Stage II cracking for 10 MN/m\(^{3/2} \) < \( \Delta K \) < 20 MN/m\(^{3/2} \) and only Stage II cracking for larger \( \Delta K \). The extent of fiber failure was measured and found to be proportional to \( K_{\text{max}} \). The plastic zone size was shown to be three times greater at the surface than at the interior.

The concepts of fracture mechanics have recently been applied to the fatigue behavior of directionally solidified eutectic alloys. Mills and Hertzberg studied the lamellar eutectic Ni-Ni\(_3\)Nb (Cb) (\( \gamma - \delta \)) and observed fatigue crack propagation (FCP) rates similar to those of high strength steels. An improvement in FCP resistance was obtained by heat treating to precipitate Ni\(_3\)Nb in the \( \gamma \) matrix. Yuen and Leverant measured FCP rates at elevated temperatures for Ni\(_3\)/Ni\(_3\)Al-Ni\(_3\)Nb (\( \gamma'/\gamma - \delta \)) and a cobalt based eutectic alloy, 73C, containing Cr\(_2\)C\(_7\) fibers. The precipitation of the \( \gamma' \) precipitate in \( \gamma'/\gamma - \delta \) slightly lowered FCP resistance. The cobalt alloy had much lower FCP resistance. The absence of a solidification rate effect was explained by the large plastic zone size at the crack tip relative to the interlamellar or interfiber spacing.

Failure of the Ni\(_3\)Nb lamellae ahead of the crack tip was reported for the nickel based materials. The fibers of the cobalt alloy did not fail ahead of the tip even though the calculated plastic zone size was greater than the interfiber spacing.

In the present study, FCP rates were measured for a directionally solidified CoNiCr alloy containing 10 vol pct TaC fibers (CoTaC). FCP rates also were measured for the same alloy with segmented fibers, without fibers, and with fibers perpendicular to the stress axis. Additionally, plastic zone sizes (PZS) were measured using broken fibers as markers to define the zone boundaries.

**EXPERIMENTAL PROCEDURE**

Vacuum-cast ingots of nominal composition Co-10Ni-10Cr-14Ta-1.0C were remelted in flowing argon in alumina crucibles and directionally solidified in a Bridgman-type induction furnace at 0.64 cm/h. The resultant structure is shown in Fig. 1. Specimen blanks were removed by electrodischarge machining (EDM), ground to final shape, mechanically polished.
to 0.06 μm alumina grit, and etched lightly to better reveal the fibers in replicas. Yield stress and ultimate tensile stress are, respectively, 725 and 965 MN/m² with 30 pct elongation. Two specimen types were used. Single edge crack (SEC) specimens with gage section widths of 1.27 cm were used for all tests other than the transverse tests, which used compact tension (CT) specimens of width 2.0 cm and h/w = 0.486. The use of two types was dictated by the small size of the ingots. All specimens were 0.25 cm thick. Notches were introduced by EDM.

The SEC specimens were loaded by clamped pins which were free to roll on flats to prevent the transmission of bending moments. The CT specimens were loaded by a simple clevis and pin arrangement. Tests were conducted on closed-loop servohydraulic fatigue machines. Crack lengths on both surfaces of each specimen were measured from plastic replicas. Crack profiles were determined by "marking" the crack front several times during a test by momentarily reducing the applied stress range. The profiles, which were approximated as circular arcs, were interpolated for other crack lengths and a computer program was used to integrate ΔK, the stress intensity factor range, over the profile of the crack front. This resulted in an effective ΔK and an effective crack length. This procedure was deemed necessary because of the small width of the specimens and the large geometric correction factor for SEC specimens. It was also used for the CT specimens. Data presented in graphs are for all measurements taken unless noted "edited" in which case the minimum crack advance is 0.02 cm between points.

Plastic zone sizes were determined by measuring the extent of fiber failure below the fracture surface, Fig. 2. The mode of deformation at the crack tip for ΔK > 20 MN/m² is in the form of two narrow regions of gross slip and fiber damage extending ahead of the crack tip at an angle of approximately 45 deg to the direction of crack propagation. This mode is readily observed on the specimen surface (see Fig. 6). The plastic zone "radius" reported here is the distance between the most distant broken fiber and the associated crack tip. The error in measurement entails two factors. First, only a few fiber failures are found at the distances measured, possibly due to unusual weakness or stress in these particular fibers. Second, broken fiber ends possibly mate after the stress that broke them is relieved, rendering the fiber breaks difficult to detect. These two factors work in opposition, but to an uncertain extent.

RESULTS

The data for the SEC tests conducted at a stress ratio, R, of approximately zero appear in Fig. 3. These include specimens tested at different gross section stresses and one specimen that was prestrained 6 pct. This prestrain was sufficient to break the fibers into 5 to 10 μm long segments. These data form a scatter band with a width represented by a factor of two in da/dN at intermediate ΔK. A threshold stress intensity range, below which crack propagation does not occur, is suggested at about 7 MN/m². The critical stress intensity for unstable propagation is approximately 64 MN/m². Crack propagation rates between 5 × 10⁻⁹ and 2 × 10⁻⁶ m/cycle follow the relation

\[
\frac{da}{dN} = 8 \times 10^{-14} \Delta K^{4.6} \quad (m \text{ and } MN/m^{3/2}).
\]

![Fig. 2—Longitudinal section below fracture surface showing fiber breakage indicating plastic zone (high ΔK). Fiber breaks extend far below region of photograph, magnification 475 times.](image1)

![Fig. 3—Fatigue crack propagation rates da/dN for SEC specimens vs stress intensity factor range ΔK.](image2)