IDENTIFICATION OF MECHANISMS RESPONSIBLE FOR DEGRADATION IN THIN-WALL STRESS-RUPTURE PROPERTIES

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Abstract

A series of critical experiments was performed on single crystal CMSX-3 and equiaxed grain Mar-M246 specimens to identify the mechanisms responsible for the degradation in stress-rupture properties of 0.020 in. thick mini-flats machined from airfoils compared with 0.250 in. diameter standard test bars. Both materials exhibited approximately a factor of 3X life degradation at a stress level of 20,000 $lb/in.^2$, when uncoated airfoil mini-flats were tested in air.

To determine the influence of specimen geometry on test results, a series of tests was conducted on CMSX-3 alloy using 0.020 in. thick mini-flats and 0.020 in. wall-thickness cylindrical hollow specimens. Both types of specimens were machined from 5/8 in. diameter bars. The results obtained indicated no noticeable difference in stress-rupture lives, suggesting that, in this material, specimen geometry does not influence the test results.

The next series of tests was conducted using aluminide coated CMSX-3 airfoil mini-flats tested in air and uncoated airfoil mini-flats tested in high purity argon. The stress-rupture lives obtained were equivalent to those obtained on 0.250 in. diameter baseline specimens, suggesting that, in this material, the life degradation observed in airfoil mini-flats is primarily due to environmental effects.

The last series of tests was conducted using aluminide coated equiaxed grain Mar-M246 airfoil mini-flats. No improvement in stress-rupture

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lives was obtained compared with uncoated airfoil mini-flats tested in air, suggesting that the primary life degradation mechanism in this material is related to the behavior of grain boundaries in thin sections.

Introduction

An important consideration in gas turbine airfoil design is the effect of section thickness on creep and stress-rupture properties of the turbine blade and vane alloys. Past experience with equiaxed grain nickel- and cobalt-base superalloys indicates a reduction of a factor of 3 to 5 in stress-rupture properties of thin-wall castings (0.020-0.025 in. section thickness) compared with standard 0.250 in. diameter test bars. A recent study by the authors (1) showed a similar reduction in stress-rupture properties of uncoated single crystal mini-specimens machined from thin-wall hollow airfoil castings and tested in air.

The objective of the present study, therefore, was to ascertain which specific mechanisms were responsible for the observed thin-wall effects in stress-rupture properties of the equiaxed and single crystal castings. A series of critical experiments was conducted with the aim of separating various contributions due to microstructural, environmental and geometric factors. The present study is an extension of the work previously reported by the authors (1).

Background and Experimental Approach

Figure 1 provides a comparison of the stress-rupture properties of 0.020 in. thick single crystal CMSX-3 mini-flat specimens machined from thin-wall hollow airfoils with those of 0.250 in. diameter standard specimens machined from 5/8 in. diameter bars (1). It is seen that at stress levels less than 30,000 lb/in.^{2}, the stress-rupture properties of thin-wall specimens show considerable degradation. At 20,000 lb/in.^{2}, for example, the stress-rupture lives of thin-wall specimens are reduced by a factor of approximately 3. A similar behavior is displayed in Figure 2 by the equiaxed grain Mar-M246 alloy. At a stress level of 20,000 lb/in.^{2}, the stress-rupture lives of 0.020 in. thick mini-flat specimens are reduced, in this case, by a factor of approximately 2.5.

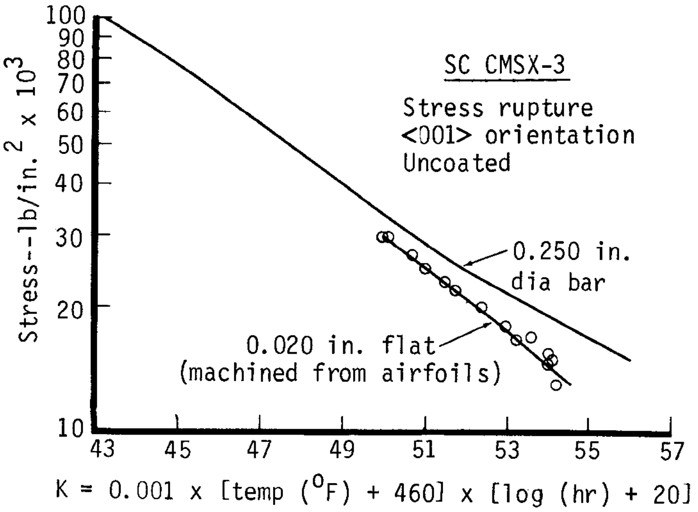


Figure 1: Larson-Miller representation of the stress-rupture properties of 0.020 in. thick mini-flat specimens machined from hollow CMSX-3 airfoils. The solid line represents the data obtained on 0.250 in. diameter bars (1).

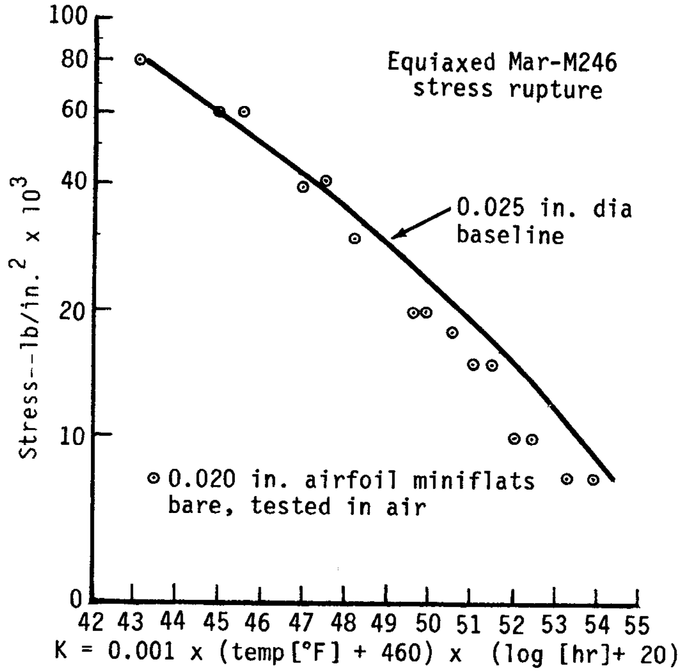


Figure 2: Larson-Miller representation of the stress-rupture properties of 0.020 in. thick mini-flat specimens machined from equiaxed grain Mar-M246 airfoils. The solid line represents the data obtained on 0.250 in. diameter bars.

A number of mechanisms are expected to contribute to the observed thin-wall degradation phenomenon in single crystal and equiaxed grain alloys:

(1) differences in the degree of microsegregation and/or microshrinkage/ microporosity between thin and thick section castings

(2) specimen geometry effects: mini-flat specimens with free edges versus round specimens and/or the possibility of inducing greater bending stresses due to potential misalignment problems with mini-flat specimens

(3) oxidation/alloy depletion during testing

(4) decreased number of grains in the specimen cross-section and the increased incidence of transverse grain boundaries across the specimen thickness (mini-flats for equiaxed grain materials only)

In order to determine the individual contributions associated with the mechanisms listed above, a series of experiments was performed using four different specimen geometries illustrated in Figure 3. These specimens were fabricated as follows:

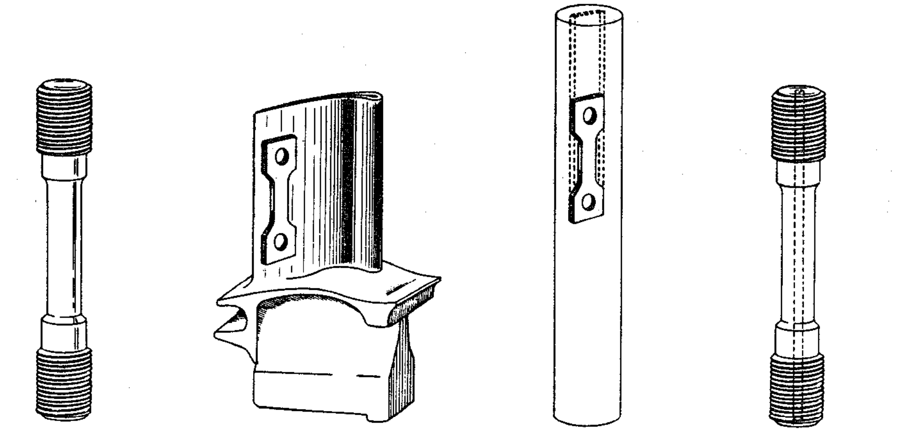
(a) Type A: 0.250 in. diameter test section standard specimens machined from 5/8 in. diameter bars (to establish the baseline behavior)

(b) Type B: 0.020 in. thick mini-flats machined from thin-wall (0.025 in. nominal wall thickness) hollow airfoils

(c) Type C: 0.020 in. thick mini-flats machined from 5/8 in. diameter

(d) Type D: 0.020 in. wall thickness hollow round standard size specimens

Specimen types B and C were selected to identify to what extent solidification related microstructural characteristics (e.g., microsegregation, microshrinkage, microporosity, etc) were responsible for thin-wall effects. Specimen types C and D were used to establish if the test results were influenced by specimen geometry.



0.250 in. diameter

0.020 in. mini-flat

0.020 in. mini-flat

0.020 in. wall thickness

Figure 3: Specimen geometries used to investigate the section thickness effects on stress-rupture properties.

The first series of tests was conducted in air on uncoated specimens Hence, environmental effects, if present, were included in the test results. In another series of experiments, the environmental effects were eliminated while the specimen geometry was held constant. This was accomplished by conducting the following tests:

- coated mini-flat (Type B) specimens tested in air
- uncoated mini-flat (Type B) specimens tested in high purity argon

The test temperature range was 1650 to 2000°F for the CMSX-3 alloy and 1520 to 1950°F for the Mar-M246 alloy. The stresses used were in the range of 13 to 50 ksi for the CMSX-3 and 8 to 80 ksi for the Mar-M246 alloy. The results are presented in terms of stress versus the Larson-Miller parameter K.

Results and Discussion

Figure 4 provides a comparison of the stress-rupture lives of uncoated 0.020 in. thick mini-flats (Type C) with those of uncoated 0.020 in. wall cylindrical specimens (Type D). Both types of specimens in these tests were machined from 5/8 in. diameter bars and tests were conducted in

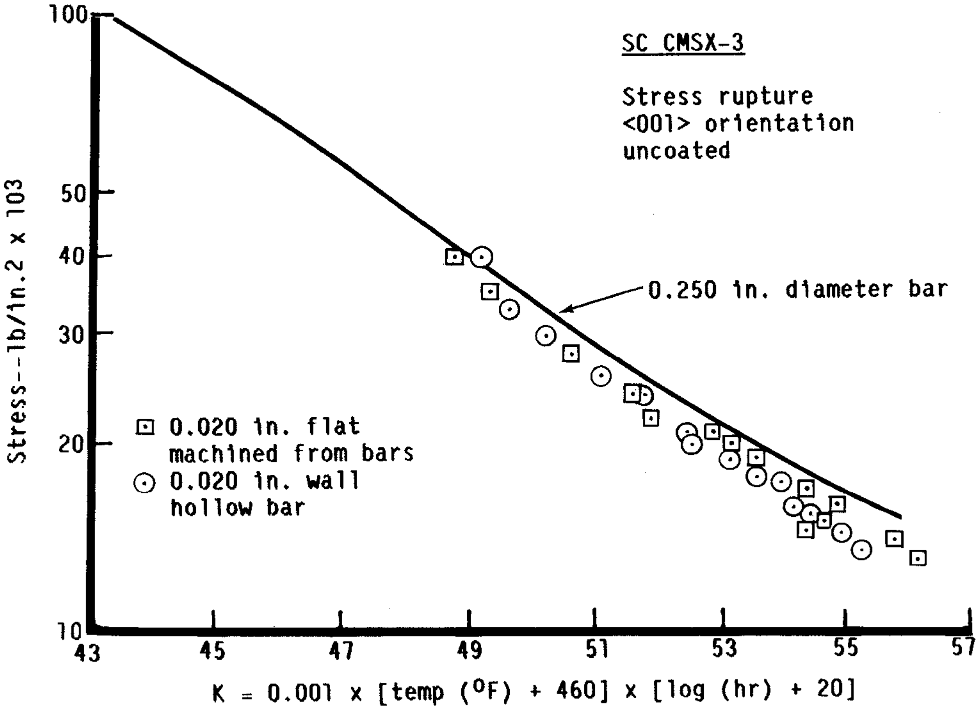


Figure 4: Stress-rupture properties of 0.020 in. thick mini-flat and 0.020 in. wall thickness hollow cylindrical specimens machined from 5/8 in. diameter bars. The solid line represents the data observed in 0.250 in. diameter bars (1).

air. No appreciable difference exists between the behavior of these specimens, implying that the specimen geometry is not responsible for the observed thin-wall degradation in the CMSX-3 alloy.

A comparison of the Type C and D specimen results described above with the results obtained in Type B specimens (i.e., mini-flats machined from airfoils) is presented in Figure 5. It is seen that at stresses below 20 ksi (and at test temperatures above 1875°F), the reduction in stress-rupture lives of Type C and D specimens appears to be less than that observed for the mini-flats machined from airfoils (Type B speci-imens). Implication here is that differences may exist between thin-flats machined from airfoils (Type B) and those machined from 5/8 in. diameter bars (Type C), in terms of either microstructural characteristics or surface characteristics (i.e., as-cast versus ground surface). More will be said about this observation in the following paragraphs.

The next series of tests on CMSX-3 alloy was conducted using aluminide coated mini-flat specimens machined from airfoils (Type B). The results are plotted in Figure 6. The stresses for the coated mini-flat specimens in Figure 6 were calculated assuming the load was carried by the unaffected area only, i.e., the coating thickness was not included in the cross-sectional area. It is seen that when presented in this manner, the results on coated mini-flats become essentially identical to those obtained on 0.250 in. diameter standard specimens. This implies that the observed degradation in stress-rupture lives of the mini-flats machined from airfoils (Type B) is due primarily to environmental effects (Mechanism 3). To further substantiate this observation, a series of tests

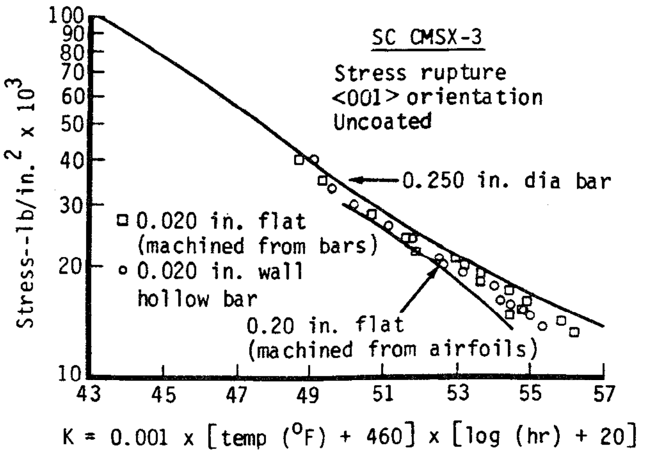


Figure 5: Comparison of stress-rupture properties of 0.020 in. thick CMSX-3 specimens of various geometries. Solid lines represent data obtained on 0.020 in. thick mini-flats machined from airfoils and on 0.250 in. diameter bars (1).

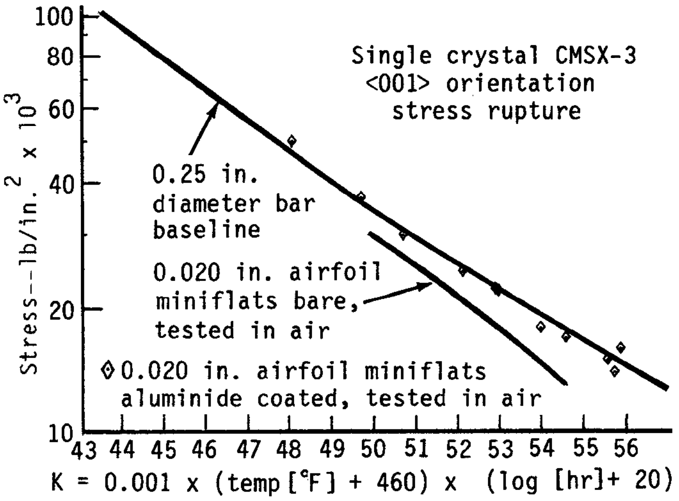


Figure 6: Stress-rupture lives of aluminide coated 0.020 in. thick mini-flats machined from hollow CMSX-3 airfoils. Solid lines represent data obtained on uncoated 0.020 in. thick mini-flats and 0.250 in. diameter bars. All tests are conducted in air.

were, then, conducted in high purity argon using uncoated mini-flat specimens (Type B). The results are presented in Figure 7 along with the data displayed in Figure 6. These results indicate essentially no difference between the stress-rupture lives of the uncoated mini-flats tested in high purity argon and the aluminide coated mini-flats tested in air. Further, the stress-rupture lives of both types of specimens are about the same as those of 0.250 in. diameter baseline specimens. These observations clearly demonstrate that for the CMSX-3 alloy it is the environmental effects (Mechanism 3) that are primarily responsible for the observed degradation in the stress-rupture lives of 0.020 in. mini-flats machined from airfoils. The observation that the degree of degradation in stress-rupture lives of Type B specimens increases with decreasing stress (Figure 1) is also in accord with this mechanism since, almost in all cases, the decrease in stress was accompanied with an increase in test temperature. The higher the test temperature, the greater will be the effect of oxidation on uncoated specimens.

In view of the observations made in the preceding paragraph, the differences between the stress-rupture lives of Type B and Type C specimens (Figure 5), however, appear to be puzzling. As noted previously, the data presented in Figure 5 implies that differences exist between thin-flats machined from airfoils (Type B) and those machined from 5/8 in. diameter bars (Type C) in terms of either microstructural or surface characteristics. The results presented in Figure 6 rule out the possibility that

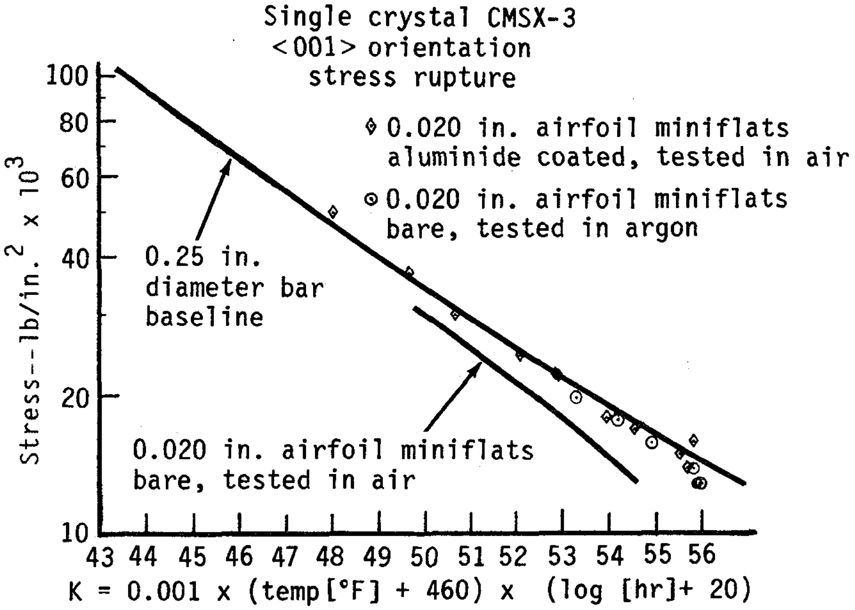


Figure 7: Comparison of the stress-rupture lives of aluminide coated 0.020 in. thick CMSX-3 mini-flats tested in air with those of uncoated mini-flats tested in high purity argon. Solid lines represent data on uncoated 0.020 in. thick mini-flats and 0.250 in. diameter bars tested in air.

microstructural differences (Mechanism 1) may be responsible for the observed behavior. The only other plausible explanation at this time, therefore, appears to be the possible differences in the response of these specimens to environmental degradation due to differences in their surface conditions. Additional work is needed to fully understand this phenomenon.

In tests conducted on equiaxed grain Mar-M246 alloy, however, the observed degradation in stress-rupture lives of thin-wall specimens cannot be attributed to the environmental effects (Mechanism 3). As noted previously in Figure 2, the stress-rupture lives of uncoated mini-flats machined from equiaxed grain Mar-M246 airfoils (Type B specimens) are degraded compared with baseline (Type A) specimens, with the amount of degradation being comparable to that observed for the single crystal CMSX-3 alloy. In contrast to CMSX-3, however, the application of an aluminide coating to the Mar-M246 mini-flats did not result in any improvements in the stress-rupture lives; see Figure 8. These results suggest that in the case of the equiaxed Mar-M246 mini-flats, the primary mechanism responsible for the stress-rupture life degradation is related to the behavior of grain boundaries in thin sections (Mechanism 4). This mechanism apparently overrides the environmental effects in this material within the range of test temperatures employed.

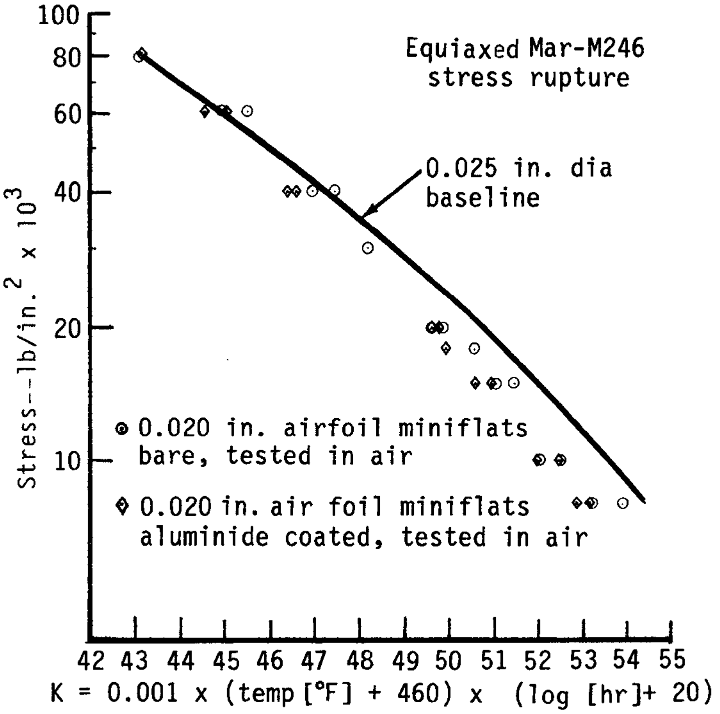


Figure 8: Comparison of the stress-rupture lives of aluminide coated 0.020 in. thick Mar-M246 airfoil mini-flats with those of uncoated mini-flats tested in air. The solid line represents the data obtained on 0.250 in. diameter bars.

Summary and Conclusions

Stress-rupture tests conducted on 0.020 in. thick mini-flat specimens machined from hollow airfoil castings indicated degradation in stress-rupture lives of both CMSX-3 and Mar-M246 alloys at stress levels below 40,000 lb/in.^{2}. The life degradation is approximately 3X at 20,000 lb/in.^{2}.

Tests conducted on CMSX-3 alloy on 0.020 in. thick mini-flats machined from 5/8 in. diameter bars and 0.020 in. wall-thickness cylindrical hollow specimens (also machined from bars) indicated no noticeable difference in stress-rupture lives. This implies that in this material the specimen geometry does not influence the thin-wall stress-rupture test results.

Experiments conducted using aluminide coated CMSX-3 airfoil mini-flats tested in air and uncoated airfoil mini-flats tested in high purity argon, resulted in stress-rupture lives equivalent to those obtained on

0.250 in. diameter baseline specimens. This suggests that the stress-rupture life degradation observed in CMSX-3 airfoil mini-flats is primarily due to environmental effects.

In tests conducted on aluminide coated Mar-M246 airfoil mini-flats, no improvement in stress-rupture lives was obtained compared with uncoated airfoil mini-flats tested in air. This suggests that for the Mar-M246 alloy, the primary mechanism responsible for thin-wall stress-rupture life degradation is related to the behavior of grain boundaries in thin sections.

Acknowledgment

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References

1. M. Doner and J. A. Heckler, "Effects of Section Thickness and Orientation on Creep-Rupture Properties of Two Advanced Single Crystal Alloys", SAE Paper 851785.