Stable Crack Growth Thresholds in an Aluminiumsilicon bronze

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ABSTRACT

Stable crack growth has been studied in an aluminium (7%) silicon (2%) bronze under both sustained static and cyclic loading conditions. The incubation period for the onset of sustained load cracking and the total time to complete failure were both found to be strongly dependent on the initial value of stress intensity, K_i. Also it was found that a reduction of moisture content in the test environments used i.e. air, nitrogen and oxygen resulted in an extended incubation time and total life. An intergranular fracture mode was observed for this sustained load cracking in all the environments tested together with macro-scale branching from the original pre-crack.

Near-threshold fatigue crack growth was also found to be intergranular though macroscopically planar. Comparable threshold stress intensity values were found for the onset of sustained load cracking (K_i at threshold) and for fatigue crack growth (K_{max} at threshold). This indicates that there is a time dependent environmental contribution to the near-threshold fatigue crack growth mechanism.

INTRODUCTION

The sea water corrosion resistance and moderate strength of copper-aluminium alloys are of great value in a number of marine applications e.g. fasteners, flanges and propellers. However, fracture failures have been experienced in fasteners manufactured from an aluminium-silicon bronze (ASB) alloy under both static and cyclic loading in air. In earlier work (Ref. 1), it was shown that under constant sustained load the incubation period prior to the onset of stable crack growth and subsequent time to complete failure were both stress dependent. Also an influence of moisture in the environment on the onset of crack growth was indicated.

In this study, as a part of a wider evaluation, the stable crack growth behaviour under constant sustained load for the ASB alloy has also been considered in different environments.

MATERIALS DETAILS AND EXPERIMENTAL PROCEDURE

The alloy studied is an aluminium-silicon bronze of nominal composition 7% Al, 2% Si, which is widely used in marine environments. The chemical composition, mechanical properties and manufacturing history of the alloy are given in detail elsewhere (Ref 1, 2).

Examination under the microscope of both longitudinal and transverse sections revealed no significant directional variation in the microstructure. The average grain diameter of the alloy was found to be 27 μm.

For the sustained load tests, single notched (SEN) cantilever bend specimens machined logitudinally from extruded bar were used. Prior to the sustained load tests the specimens were fatigue pre-cracked to obtain appropriate a/W ratios typically of about 0.6, at a stress ratio of R = 0.1. The maximum and mean loads were adjusted to obtain a final stress intensity range, ΔK, of approximately 25 MPa $m^{1/2}$.

The sustained load tests were performed in a cantilever bend rig with the load-line displacement monitored using a linear differential transducer (LVDT). The tests were conducted in different environments including room temperature air, dried oxygen-free nitrogen and dried oxygen. For the latter two environments a perspex chamber was placed around the specimen and the gases supplied from cylinders. In order to minimise or eliminate the moisture content the gases were passed through a train of driers containing silica gel crystals whilst the air was expelled from the chamber using a vacuum pump.

On completion of the tests one half section of each specimen was prepared to give a longitudinal section of the notch, for optical microscopy and a second for direct examination of the fracture surface using a Jeol JSM 35 scanning electron microscope (SEM).

RESULTS

Stable crack growth under sustained load was studied at various initial stress intensity factor (K_i) levels using fatigue pre-cracked bend specimens in different environments. Examination of several specimens at the early stages of cracking showed that the LVDT was sufficiently sensitive in indicating crack advance under the application of sustained load.

The results obtained in room temperature air, on the basis of LVDT deflection versus time, are presented in Figure 1. The results show that an incubation period exists before crack growth, which depends on the load. The higher the load, controlling the initial value of K_i, the shorter is the incubation period and the subsequent time to failure. The stable crack growth is presented only qualitatively since considerable difficulty was encountered in trying to quantify the crack propagation rate due to the crack bifurcating, as shown in Figure 2.

A plot of K_i, versus the incubation period for the onset of stable crack growth is shown in Figure 3. In this figure the data corrected for crack branching and crack tip blunting is included. It has been shown (Ref. 3) that if two cracks are propagating instead of one then the applied K is reduced by a factor of $\sqrt{2}$. Further to allow for crack tip blunting a

correction procedure proposed by Austen et al (Ref. 4) was applied given by the relationship:

$$K \propto \delta/\rho^{1/2} \qquad \text{...... (1)}$$

where δ is the crack opening displacement (COD) for critical crack propagation and ρ is the crack tip radius.

Also in Figure 3 a comparison is made between the results of sustained load cracking and near-threshold fatigue crack growth (Ref. 2), i.e. K_i against incubation time and K_{max} at the fatigue crack growth threshold. A possible 'threshold' (K_i) for sustained loading of 6 MPa $m^{1/2}$ is indicated whereas K_{max} at the fatigue threshold was found for stress ratios of 0.1 and 0.5 to be about 5 MPa $m^{1/2}$.

The incubation period was found to not only depend on the load but also on the environmental condition. change of environment from laboratory air to dried oxygen-free nitrogen and dried oxygen atmosphere had the effect of increasing the incubation period and the subsequent time to failure. Failure 4 summarises the results, showing the variation of deflection (indicated by LVDT signal) versus time for duplicate tests carried out at the same K_i value of 46 MPa $m^{1/2}$. The results obtained in both dried oxygen-free nitrogen and dried oxygen environments are fairly consistent as regards both the incubation period and the subsequent growth of the crack. The longest incubation period was found in dried oxygen.

At all the K_i values studied, the sustained load cracks grew along two macro-branches (Figure 2). At the surfaces of the specimens no sustained load cracking was observed initially whereas in the centre of the specimens the extension was found to be several millimetres long. The crack occurred in a thumbnail fashion which made surface optical measurement of the crack impossible. If the load was applied over a long period of time, the cracks eventually broke out completely through the thickness of the specimens. The cracks appeared to start from one corner of the blunted fatigue crack tip, to be of nearly equal length and the direction of each branch was approximately 70 degrees from the uncracked ligament.
Examination under a light microscope of the sub-critical crack growth at the tip revealed a predominantly intergranular mode for the sustained load cracking, which seems to suggest a low energy type of fracture along the grain boundaries.

SEM fractographic examination of sections taken from specimens exposed to the different environments showed in all cases that the fatigue precracking was transgranular (Figure 5(a)), the sustained load cracking was almost entirely intergranular (Figure 5(b)), whilst the final overload fracture was by transgranular micro-void coalescence (Figure 5(c)).

DISCUSSION

The onset of stable crack growth in this alloy under sustained load has been confirmed to be strongly dependent on stress level. Furthermore a strong influence of moisture in the air is indicated since the incubation period in air is significantly shorter than in either dried oxygen-free nitrogen or dried oxygen.

The bifurcation of the sustained load cracking at about ± 70° to the uncracked ligament is probably related to the crack tip plasticity generated in the fatigue pre-cracking. It has been shown by both Levy et al (Ref. 5) and Tuba (Ref. 6) for Mode I cracks that the maximum extent of the crack tip plastic zone is at this 70° angle. Also the equations of linear elastic fracture mechanics (LEFM) (Ref. 7) indicate that the maximum value of shear stress in the planes through the crack tip occur at 70°. In the present study, the macroscopic direction of sustained load cracking can be associated with the maximum shear stress/strain planes through the pre-crack tip and the direction of maximum extent of its plastic zone.

Balladon et al (Ref. 7) have shown that the occurrence of macro-crack branching in steels is related to the cyclic plastic zone size generated at the crack tip during fatigue pre-cracking. Crack propagation by stress corrosion cracking (SCC) was found to be relatively planar when the final value of K_{max} in the fatigue pre-cracking was maintained below or equal to the initial stress intensity value during the stress corrosion test i.e. $K_{max} < K_i$. Macro-crack branching was found not to occur when a high temperature anneal was carried out after pre-cracking.

In the present study, the test specimens were fatigue pre-cracked at ΔK = 25 MPa $m^{1/2}$. Figure 1 shows that the K_i value for sustained load testing ranged from 14 to 46 MPa $m^{1/2}$, but in all cases macro-branching occurred even at the highest K_i value of 46 MPa $m^{1/2}$ when $K_i \gg K_{max}$. No annealing heat treatment was carried out after per-cracking therefore the influence of this factor could not be determined.

In the dried oxygen-free nitrogen and dried oxygen environments, whilst the incubation period was found to be considerably longer than for tests in air, intergranular cracking eventually occurred. This suggests that traces of moisture probably remained in these nominally 'dried' atmospheres sufficient for a conjoint stress/corrosion intergranular cracking mechanism to operate.

Existing LEFM concepts provide a means of quantitative evaluation of SCC behaviour provided that the crack conforms to the geometry required for K to be applicable. However, in the present study, the occurrence of macro-branching (Figure 2) and crack growth in an intergranular manner (Figure 5(b)) involving micro-crack branching and crack tip blunting presented difficulties in the estimation of K. Despite these problems, an attempt has been made to quantify the crack growth behaviour in terms of initial stress intensity value K_i, versus incubation time (Figure 4). By correcting for macro-branching (Ref. 3) and crack tip blunting (Ref. 4), the threshold value for sustained load cracking in air (K_{iscc} in air?) is in good agreement with the value at the FCG threshold for R = 0.1 and 0.5 (Ref. 2). In fact the FCG threshold K_{max} is slightly lower than the K_{iscc} value under sustained load, indicating a stronger synergistic effect of stress and environment under cyclic versus static loading conditions.

Fractographic examination of the fracture surfaces showed that whilst the fatigue pre-cracking was mainly transgranular the sustained load cracking was predominantly intergranular. This latter cracking was very similar to that found near the fatigue threshold crack tips for both R = 0.1 and 0.5, though the cracking there was macroscopically normal to the applied tensile stress. For sustained load cracking at relatively high $K_i > 26$ MPa $m^{1/2}$, numerous slip lines (Figure 5(d)), were present on

the intergranular facets indicative of high local strain. Such features were not strongly present for sustained load specimens tested at the lower K_i values or for the near-threshold FCG intergranular cracking.

A plastic collapse limit load analysis was carried out for both the pre-cracking in 3-point bend (to ASTM E813-81) and for the sustained load cantilever bending using a procedure proposed by Ewing and Swingler (Ref. 9). The pre-cracking maximum load was found never to have exceeded 40% of the limit load. However, for the sustained load tests where $K_i > 26$ MPa $m^{1/2}$, the limit load was indicated to be approached i.e. at K_i = 26 MPa $m^{1/2}$ the bending moment reached 63% of its limiting value, whilst at K_i = 46 MPa $m^{1/2}$ a 98% level was reached. These values were found using the most pessimistic value for the flow stress as defined in (Ref. 9). This suggests that the presence of slip lines on the intergranular facets, at higher K_i values, is associated with the approach to the limit load, and plastic collapse.

CONCLUSIONS

1. The incubation period for the onset of stable cracking and time to failure under sustained load are strongly stress dependent in room temperature air.

2. The extended incubation period in both oxygen-free nitrogen and dried oxygen as compared to room temperature air indicates an influence of atmospheric moisture on the crack growth mechanism.

3. Sustained load cracking is found to macro-branch at 70° angles from the uncracked ligament and advance in an entirely intergranular manner.

4. At relatively high initial K_i values > 26 MPa $m^{1/2}$, involving loads approaching the plastic collapse limit load, slip lines are present on the intergranular facets, a feature not observed for sustained load tests at lower stress intensity levels.

5. The intergranular cracking mode found at stress intensity levels close to ΔK_{th} is similar to that observed for the alloy under constant sustained load at a comparable K_{max} value. A time-dependent environmental contribution to the near-threshold fatigue crack growth mechanism is indicated.

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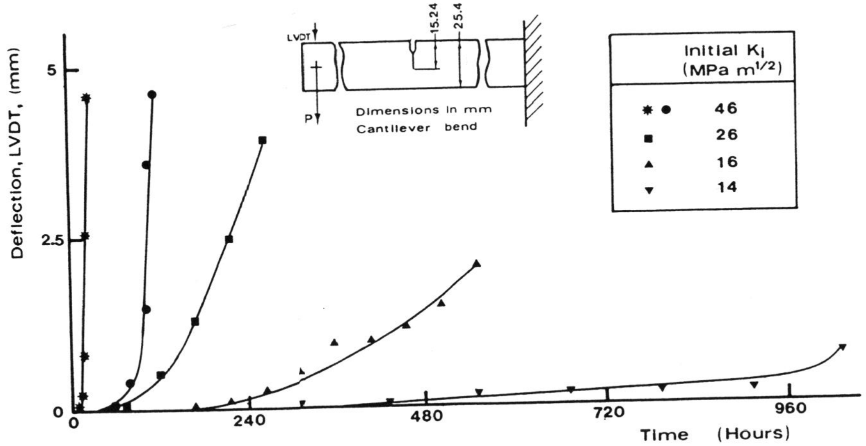

Figure 1. sustained load cracking (as indicated by LVDT signal) with time in room temperature air for different initial loading conditions.

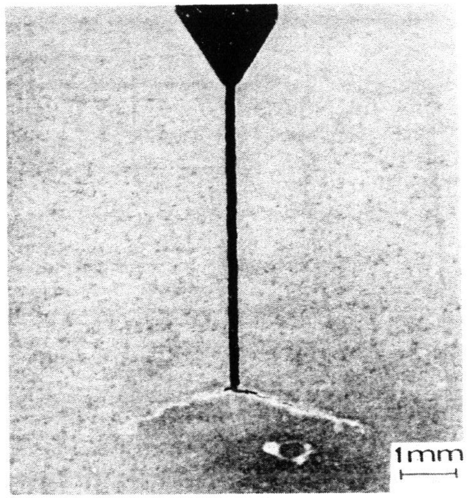

Figure 2. Sustained load crack branching shown at mid-thickness. Alcoholic ferric chloride etched.

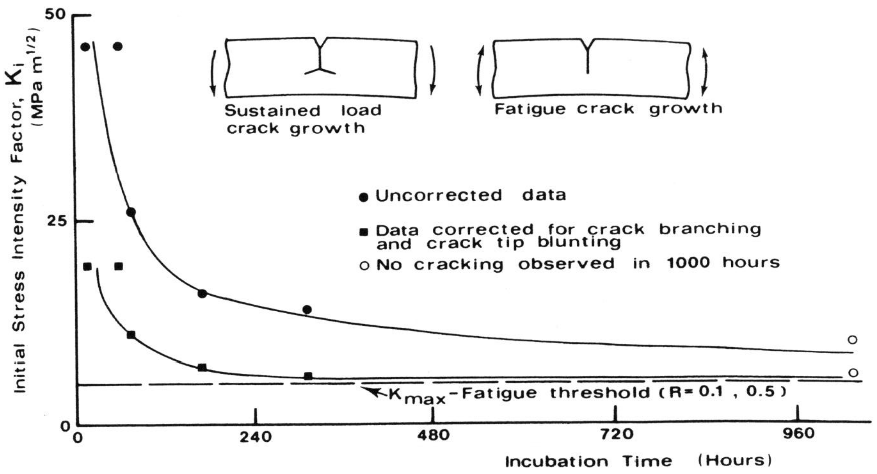

Figure 3. Initial K_I as a function of incubation period for sustained load tests at onset of stable crack growth - room temperature air.

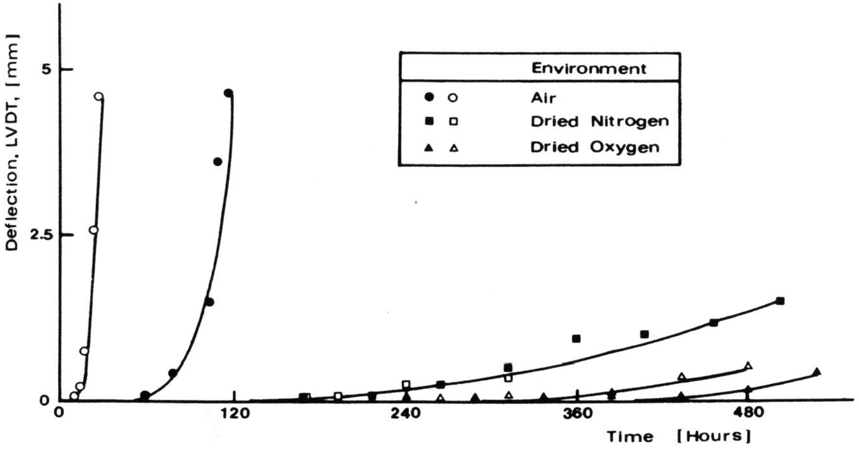

Figure 4. Variation of LVDT signal against time for tests in different environments at same initial K_i of 46 MPa $m^{1/2}$.

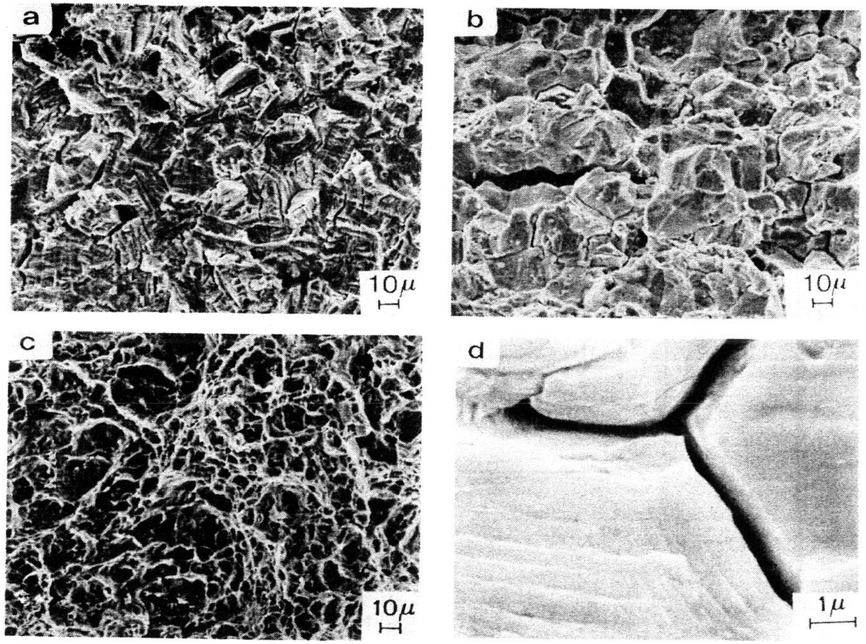

Figure 5. SEM fractographs showing: (a) transgranular fatigue cracking. (b) intergranular sustained load cracking. (c) final fracture by micro-void coalescence, and (d) grain surfaces covered with slip lines, K_i = 46 MPa $m^{1/2}$.