

Fatigue crack growth in an aluminum alloy-fractographic study

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Abstract. A two-fold approach was adopted to understand the fatigue crack growth process in an Aluminum alloy; fatigue crack growth test of samples and analysis of fractured surfaces. Fatigue crack growth tests were conducted on middle tension M(T) samples prepared from an Aluminum alloy cylinder. The tests were conducted under constant amplitude loading at R ratio 0.1. The stress applied was from 20,30 and 40 per cent of the yield stress of the material. The fatigue crack growth data was recorded. After fatigue testing, the samples were subjected to detailed scanning electron microscopic (SEM) analysis. The resulting fracture surfaces were subjected to qualitative and quantitative fractographic examinations. Quantitative fracture analysis included an estimation of crack growth rate (CGR) in different regions. The effect of the microstructural features on fatigue crack growth was examined. It was observed that in stage II (crack growth region), the failure mode changes from intergranular to transgranular as the stress level increases. In the region of intergranular failure the localized brittle failure was observed and fatigue striations are difficult to reveal. However, in the region of transgranular failure the crack path is independent of the microstructural features. In this region, localized ductile failure mode was observed and well defined fatigue striations were present in the wake of fatigue crack. The effect of interaction of growing fatigue crack with microstructural features was not substantial. The final fracture (stage III) was ductile in all the cases.

1. Introduction

Aluminum alloys are of vital importance for many structural applications in automotive, aircraft and nuclear industries. The principal design features of these alloy systems are their high strength with low density along with high corrosion resistance. The 6xxx series aluminum alloys are frequently used due to relatively high strength, good corrosion resistance and high toughness in addition to their good formability and weldability [1].

Thick-walled cylinders are an essential part of many industries e.g. food, petroleum, armament, nuclear and chemical processing. A major use of these cylinders is as storage for gas products. The fluctuating gas pressure inside the cylinders produces the conditions of cyclic loading on the inner wall creating axial and hoop stresses.

In many applications the cylinders are prone to cyclic stresses during their normal operation and large internal pressures produce high tension hoop stresses along the inner surface of the cylinder. The latter may result in the nucleation of the internal surface cracks which propagate due to cyclic action of high-pressure pulses. If the primary crack growth mechanism is slow, the cracks will be detected during routine maintenance by non-destructive testing (NDT) so that corrective measures can be taken



before crack growth moves into a high risk regime. After the crack reaches a critical size, the ultimate failure may be catastrophic and result at pressures which are even lower than the design capacity of the cylinder. For this reason, it is quite necessary to analyze the crack propagation behavior in the cylinders under cyclic hoop stress to ensure their integrity against the fatigue failure. Many researchers have done valuable work to analyze the cylinders under fatigue loading [3-7].

In general, the fatigue process is characterized by three distinct regions [8].

Region I is associated with the growth of cracks with low ΔK 's, and is commonly believed to account for a significant proportion of the fatigue life of a structure.

Region II has received the greatest attention as it is in this region the "Paris" crack growth law [3] can be applied, viz:

$$da/dN = C\Delta K^m$$

where C and m are experimentally obtained constants.

Region III Rapid crack growth occurs in region III and this region is typically thought to account for a small fraction of the total life.

During fatigue process the material undergoes physical changes making imprints of the process on the fracture surfaces. After the material fails, these imprints provide important information about the process going on especially at the crack tip. The study of the fracture surfaces to expose the fatigue behavior of the material on the basis of 'on-site observation' is called the fractographic analysis.

Fractographic techniques using scanning electron microscopes (SEM) are extensively used in analysis of the fracture surfaces. The correct determination of fatigue crack initiation and propagation has obvious and important implications for several steps such as materials selection, component design, manufacturing processes [9].

In present study, a detailed post-fracture fractographic analysis of the fatigue samples was conducted with the help of SEM. The samples under investigation were taken from an extruded aluminum alloy in two orientations and tested under fatigue conditions at different stress levels. The details of the study are given in reference [10]. During the fatigue test, the crack length was measured with the help of travelling microscope. Some tested samples were subjected to detailed fractographic analysis using SEM. The crack growth region was divided into three sub regions and the width of striations were examined in detail in these three regions. The results obtained from the two techniques (experimental and SEM analysis) were compared.

2. Experimental

2.1 Material characterization

The material investigated was AA 6061. The chemical composition and the mechanical properties are reported in reference [10].

2.2 Fatigue crack growth test

Fatigue crack growth tests were performed on middle tension M(T) specimens. Samples were cut from the cylinder in LR orientations, Figure 1. This orientation refers to the standard ASTM E 399 which provides the crack plane orientation code for bar and hollow cylinder. In this orientation the samples were perpendicular to the longitudinal axis of the cylinder 'L' while the notch direction was such that the crack propagation was along the radial direction 'R' as shown in Figure 1. Samples were machined according to the standard ASTM E 647. The machined samples were subjected to mechanical grinding and subsequently fine polishing.

Fatigue crack growth experiments were performed on a servo-hydraulic testing machine. Tests were conducted in the tension-tension mode under constant amplitude loading with R ratio 0.1. A sinusoidal waveform was applied at a loading frequency of 10 Hz. Tests were conducted at stress levels of 20, 30 & 40 per cent of the yield strength of the material. Crack length was measured with the help of a traveling microscope, at a magnification of 100x and the data was recorded against the number of cycles. Tests were conducted in air at a temperature 22°C and approximately 30 per cent relative humidity.

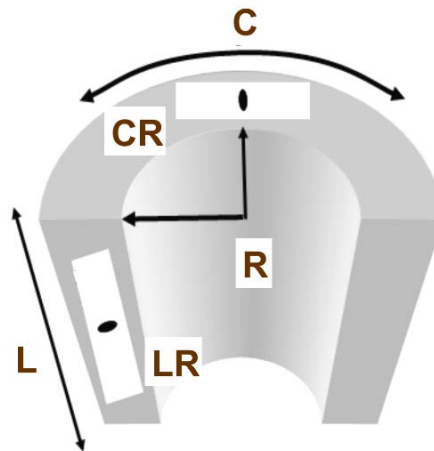


Figure 1. Orientation of the LR and CR samples representing tangential

3. Results and discussion

1.3 Fatigue crack propagation

The material was subjected to experiments to reveal the fatigue crack growth behavior of the cylinder in CR and LR directions. Figure 2 shows the plots for the crack length versus the number of cycles. It was observed that crack growth is faster in CR orientation as compared to LR orientation. This may be attributed to prior working of the material.

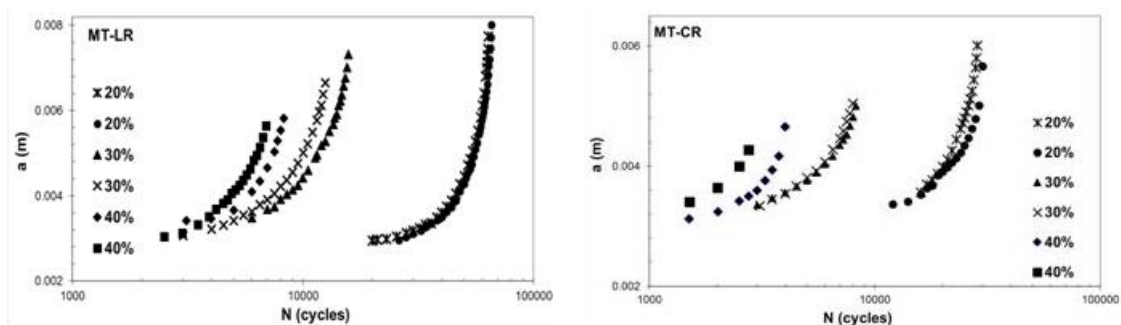


Figure 2. The plots for the crack length versus the number of cycles for CR and LR orientations

1.4 Stereography

The stereo-micrographs of representative fracture surfaces of both directions are shown in figure 3. The stereo-micrographs in both orientations showed typical fatigue crack surfaces, consisting of an initiation region marked as R1, followed by a smooth region representing the crack growth region marked as R2 and finally the rapid fracture region due to overload named as R3. It was noted that crack grows faster in CR orientation as compared to LR orientation. It was also observed that crack grows faster at higher stress level and vice versa in both orientations.

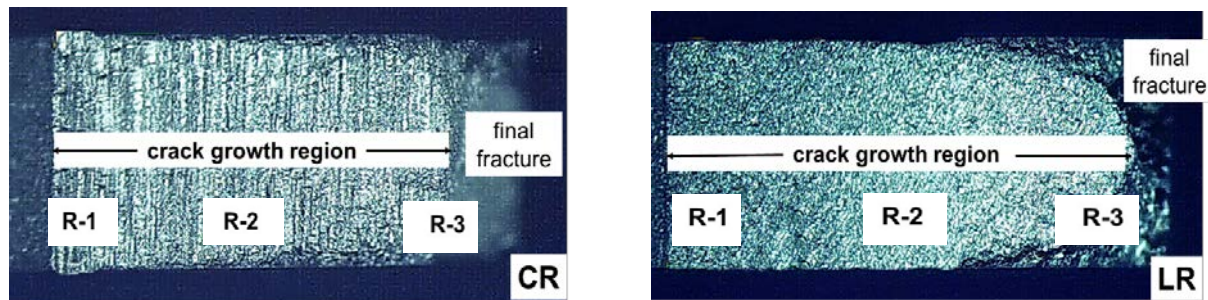


Figure 3. Stereo micrographs of fractured surfaces in both orientations

1.5 SEM analyses

The fracture surfaces of types of samples (CR, LR) were then subjected to quantitative SEM analysis. The lengths of fatigue striations were measured in three regions marked as R1, R2 and R3. Crack growth rate (CGR) was measured through fatigue striation spacing. The CGR was also calculated from already measured crack lengths during testing. This data was then plotted as shown in Figure 4 for both orientations. The Comparison of fatigue test and SEM results shows close agreement at low stress levels and differ significantly at higher stress levels. This difference was more prominent in LR samples than CR samples, being about three fold of fatigue test results. This may be due to the fact that in both orientations the crack front is almost parallel in R1 and R2 regions. However in R3 region of LR samples the crack front is projected out whereas in CR samples it is almost parallel, Figure 3. Thus when crack is measured during test, we are not at the actual crack tip in LR samples. This causes difference in fatigue and SEM data at high stress levels i.e. in region R3.

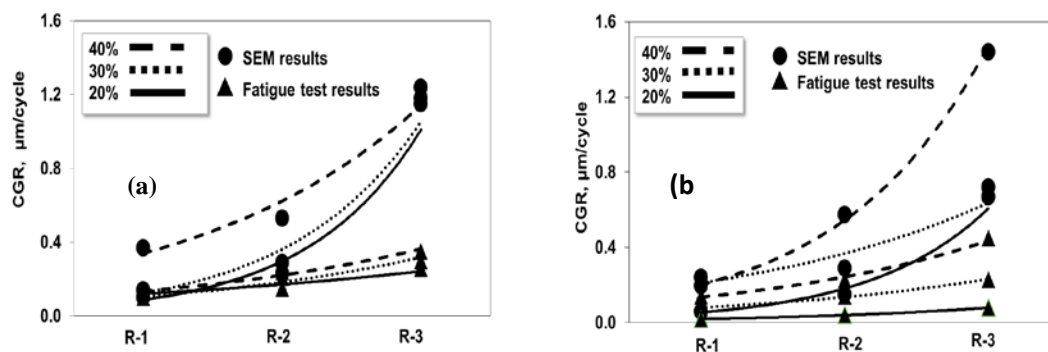


Figure 4. Comparison of fatigue test results and SEM results of CGR in different regions of
a) CR & b) LR samples

During SEM analyses it was also observed that in R2 region (crack growth region), the failure mode changes from intergranular to transgranular as the stress level increases in both LR and CR orientations. In the region of intergranular failure the localized brittle failure was observed and fatigue striations were difficult to reveal as shown in Figure 5. However, in the region of transgranular failure the crack path is independent of the microstructural features. In this region, localized ductile failure mode was observed and well defined fatigue striations were present in the wake of fatigue crack, see Figure 6. The effect of interaction of growing fatigue crack with microstructural features was not substantial. The final fracture (R3) was ductile in all the cases.

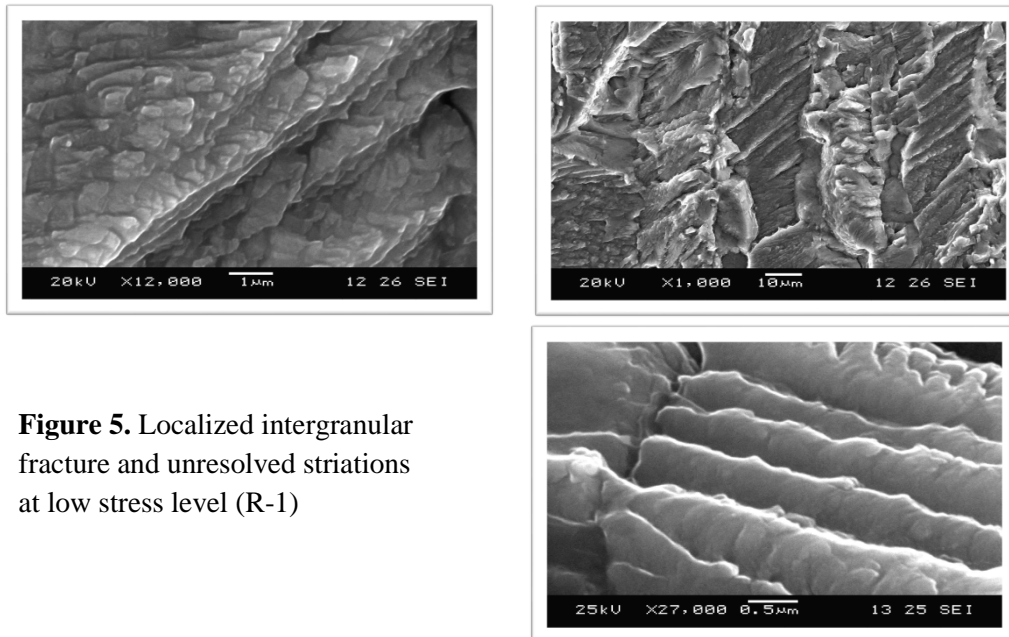


Figure 5. Localized intergranular fracture and unresolved striations at low stress level (R-1)

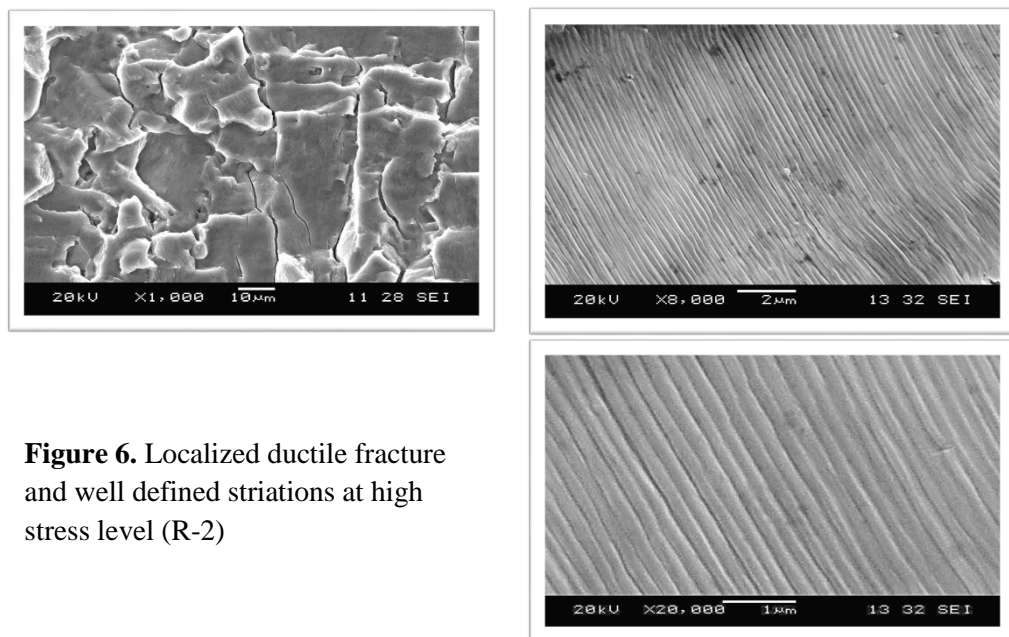


Figure 6. Localized ductile fracture and well defined striations at high stress level (R-2)

4. Conclusion

- I. The fatigue crack grows faster in CR orientation as compared to LR orientation.
- II. The fracture appearance was very different in CR and LR directions owing to prior deformation.
- III. In stage II (crack growth region, R2), the failure mode changes from intergranular to transgranular as the stress level increases
- IV. Fracture surface morphology was changed from brittle to ductile with increasing stress level. The qualitative and quantitative CGR data was in agreement with each other at low stress level i.e. in intergranular region. However appreciable difference was observed at high stress level i.e. in the transgranular region.

5. References

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