The role of existing strength gradient on fatigue crack growth rate of bare and clad 2024 AA

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Abstract

The fatigue growth rate of a crack propagating inside a yield strength gradient in 2024-T3 aluminum alloy was investigated. Heat treatment was implemented to produce a yield strength gradient at the crack front of the specimen. Fatigue crack growth rate tests were measured on reference material and material with a strength variation at the crack tip. In the experimental analysis, the role of clad surface protection on crack growth rate was examined. The results have shown that crack growth rates are increased due to the presence of strength gradient and fatigue crack propagation is influenced by the slope of the gradient at the crack tip.

Keywords: fatigue crack propagation; yield strength gradient; crack path;

1. Introduction

In aluminum alloys local strength variations in the form of gradients exist near weld regions as a result of the dissimilar temperature distributions induced during the welding process. In the presence of a strength gradient the growth rate of a propagating crack can be influenced by the occurring gradual microstructural and hence property changes influencing closure (e.g. plastic zone size, cyclic strain hardening characteristics, etc.) at the crack path [1-6].

In an early work, Reifsnider and Kahl [7] have shown that in the case of heat treatable aluminum alloys of 6xxx and 7xxx series, crack propagation rates depend on the slope of the yield strength gradient ahead the crack tip. It was demonstrated that crack propagation rates are reduced during the transition of a crack from a uniform strength region to an increasing yield strength gradient. At larger crack lengths with continuous increasing strength the phenomenon is reversed and crack propagation rate increases up to the initial levels. The transient effects on fatigue crack growth rate observed as a result of the varying slope of strength gradient reveal the strong dependency of crack propagation behavior on the local material properties at the tip of the crack. For a clearer understanding of the mechanisms involved, it is useful to consider a simple case of an increasing or decreasing gradient on a propagating crack.

In the present work the effect of a single yield strength gradient on fatigue crack propagation in 2024-T3 aluminum alloy was investigated experimentally. A special heat treatment process was utilized to achieve overaging conditions resulting in a controlled yield strength variation at the crack front of the specimen.

Two distinctive slopes of strength gradients were examined: a) increasing strength and b) decreasing strength with advancing crack length. The results were compared with alloy having uniform strength at the crack path. In the experimental analysis, the clad protected and bare 2024 T3 aluminum alloy was considered.

2. Material

Sheet, 2024 aluminum alloy with a thickness of 3.2mm was used in T3 condition, which includes solution heat treatment at 495^{o}C, control stretching and natural aging. The nominal chemical composition of the alloy is Al-4.3Cu1.5Mg-0.6Mn (wt.%). The material was received bare and with clad surface protection with a clad surface thickness of 0.125mm. The material was tested in the longitudinal (L) direction.

3. Heat treatment

A special heat treatment process was utilized to produce specimens with variation of strength (gradual decrease or increase of hardness) at the crack path. The samples were exposed to a temperature gradient between two boundaries ranged from 250 to 200^{o}C for 15hours. The temperature boundaries were selected according to the determined overaging curves (Fig.1). The results of the hardness profile in the material after heat treatment are shown in Fig.2.

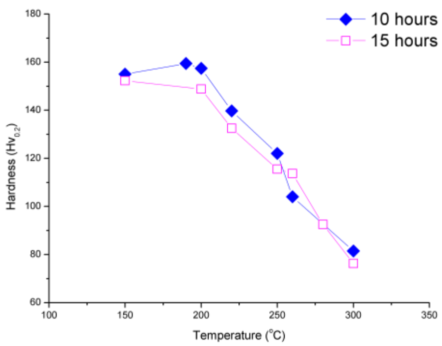


Fig. 1. Overaging curves of 2024 T3 aluminum alloy showing variation of hardness with temperature

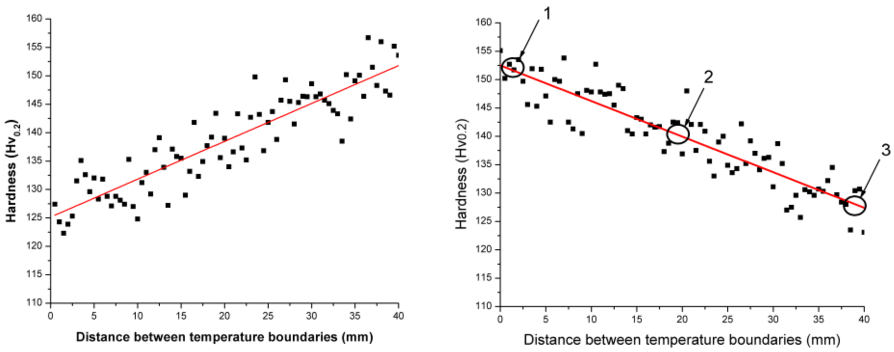


Fig. 2. Hardness profiles of specimens after heat treatment (a) linear hardness increase with distance (b)linear hardness decrease with distance

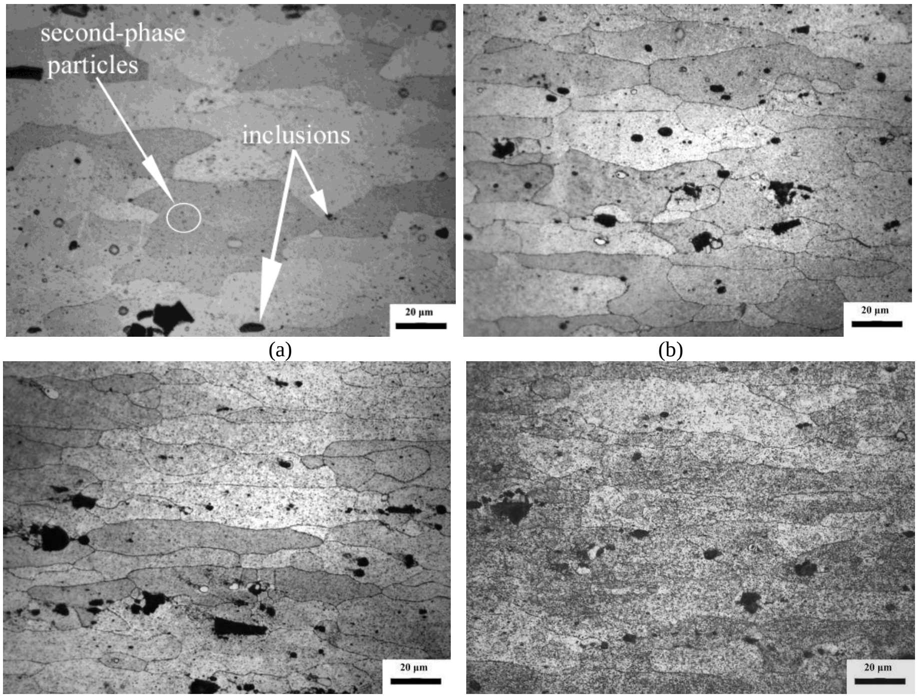
The correlation between hardness and yield strength was obtained empirically, from [8]:

$$\sigma_y = 3*Hv - 90 \quad (1)$$

4. Microstructure

The microstructural variations resulting in the hardness profiles of Fig. 2, at positions 1, 2 and 3 within the gradient as well as the T3 microstructure are shown in Fig. 3. The T3 microstructure consists of three types of inclusions: (i) Al-Cu containing particles (ii) Al-Cu-Fe-Mn containing particles, and (iii) Al-Cu-Fe-Si-Mn containing particles as obtained from the performed scanning electron microscopy/energy dispersive X-ray spectroscopy analysis [8]. The microstructure is characterized by two major second-phase particles: Al_2Cu (θ′phase) and Al_2CuMg (S′ phase) [9].

With regard to the T3 material, in microstructures corresponding to areas (1), (2) and (3), inclusions seem to be unaffected, while coarsening of the metastable phases can be observed inside the grains. With decreasing hardness, coarsening of metastable phases is more pronounced.



(a) (b) (c) (d)

Fig. 3. Microstructure of (a) 2024 material in T3 state; and materials subjected to artificial aging (b) position 1; (c) position 2; (d) position 3 of Fig.2b

5. Fatigue crack growth tests

Fatigue crack growth (FCG) tests were carried out on compact tension C(T) specimens including a single (decreasing or increasing) strength gradient in accordance with ASTM E647-00. The notch was machined parallel to the rolling direction. The tests were performed on a 100kN servo-hydraulic fatigue machine at room temperature with a constant stress ratio of R=0.1. The maximum stress was σ_{max}= 10MPa and the frequency 5Hz. A COD gauge was used to measure crack opening displacement at points A,B

(Fig.4) and conversion to crack length data was made by implementation of the compliance method. Crack growth rates were measured at an intermediate ΔK region ranging from 11 to 25 $MPam^{1/2}$.

The C(T) specimens were appropriately machined so that the axis at the notch tip perpendicular to the notch plane coincides with the boundary of strength gradient (Fig.5). The fatigue crack growth results were compared with respective results of material with uniform yield strength associated with the initial material condition when the crack enters the gradient (e.g. notch tip). Specifically, the specimen with increasing yield strength gradient (Fig. 5b) was compared with a specimen having a uniform yield strength value of 240MPa (heat treated at 250°C for 15hrs) and the specimen with decreasing gradient (Fig.5a) was compared with a specimen having a uniform yield strength value of 375MPa (heat treated at 200°C for 15hrs). The heat treated material at 200°C and 250°C for 15hours, is referred to as A200 and A250 material.

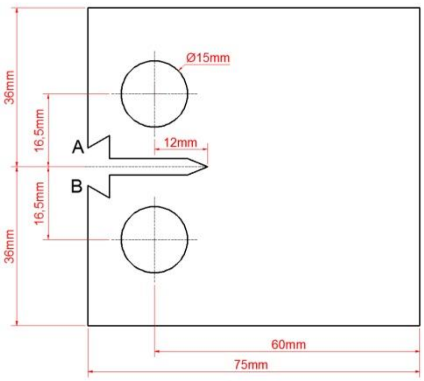


Fig. 4. C(T) specimen configuration according to ASTM E 647-00

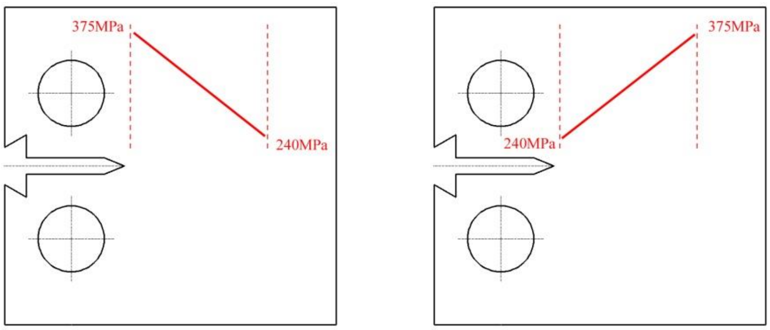


Fig. 5. C(T) specimen with (a) decreasing; and (b) increasing strength gradient boundaries in front of notch tip resulting from heat treatment

In Figs. 6 and 7 the FCG results are compared in bare and clad form. In specimens with increasing yield strength gradient, crack growth rates were higher with regard to the reference condition in the whole ΔK range examined (Fig. 6a and 6b). In the case of clad material crack growth rates are reduced compared to the bare alloy and the effect of gradient is slightly more pronounced.

In specimens with decreasing yield strength gradient, only the case of bare material has been examined. Fatigue crack growth rate is not influenced by the presence of the gradient, when examining overage da/dN behavior including certain scatter of results.

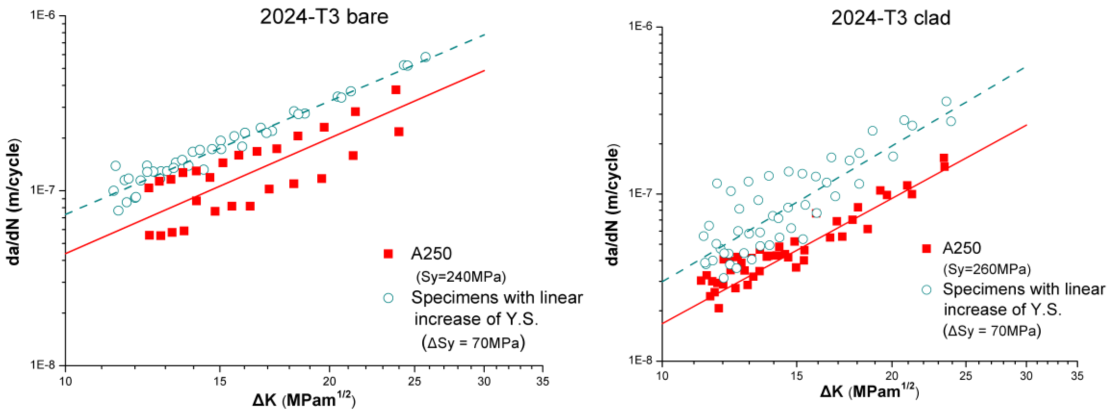


Fig. 6. Fatigue crack growth rates versus stress intensity factor range (da/dN-ΔK) in A250 and material with increasing yield strength with regard to the crack tip (a) bare 2024-T3; (b) clad 2024-T3

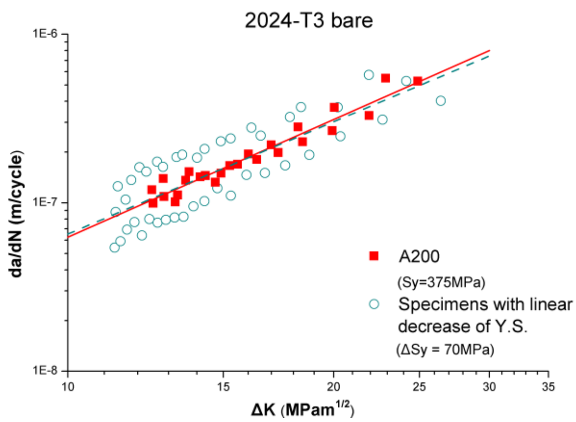


Fig. 7. Fatigue crack growth rates versus stress intensity factor range (da/dN-ΔK) in bare A200 and material with decreasing yield strength with regard to the crack tip

In Fig.8 crack growth rates for materials A200 and A250 with uniform yield strength (375MPa and 240MPa respectively) are compared. The crack growth rates are reduced in the A250 compared to A200 alloy. The effect of increasing overaging temperature on the fatigue crack propagation in 2024 aluminum alloy has been investigated in more detail in [8,10].

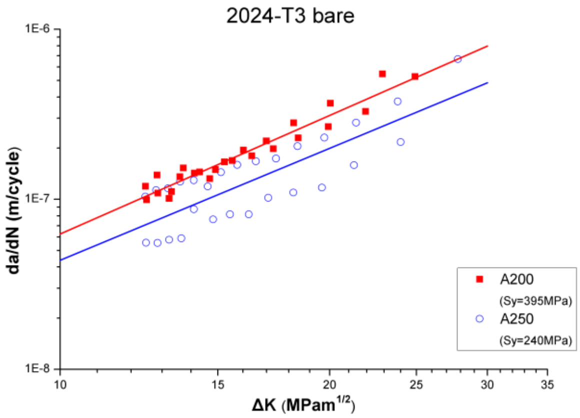


Fig. 8. Fatigue crack growth rates versus stress intensity factor range (da/dN-ΔK) in bare A200 and A250 materials

5.1. Fractography

Fractographic analysis was performed to evaluate specific fracture characteristics during fatigue crack propagation. In the micrographs of Figs 9 and 10 fracture surfaces at specific crack lengths taken with scanning electron microscope are displayed. The crack lengths were 15mm (area A) and 25mm (Area B) corresponding to ΔK value of 11 and 20 $MPam^{1/2}$. In both gradients a semi-cleavage fracture pattern is observed with the cleavage characteristics more pronounced in area A. By comparing areas A and B for the two gradients, the characteristics are similar consisting of dimples as well as cleavage facets.

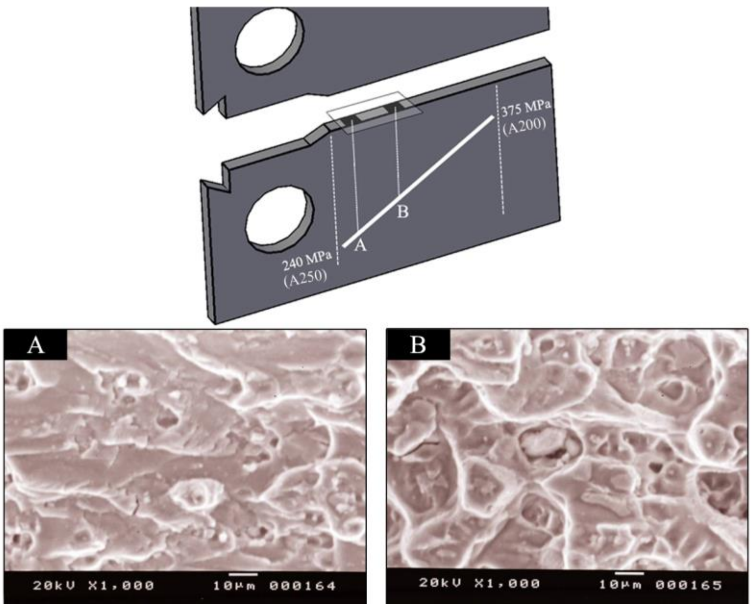


Fig. 9. SEM micrographs of specimen with increasing yield strength profile showing fracture surface characteristics during FCG at range a) ΔK=11 $MPam^{1/2}$ b) ΔK=20 $MPam^{1/2}$

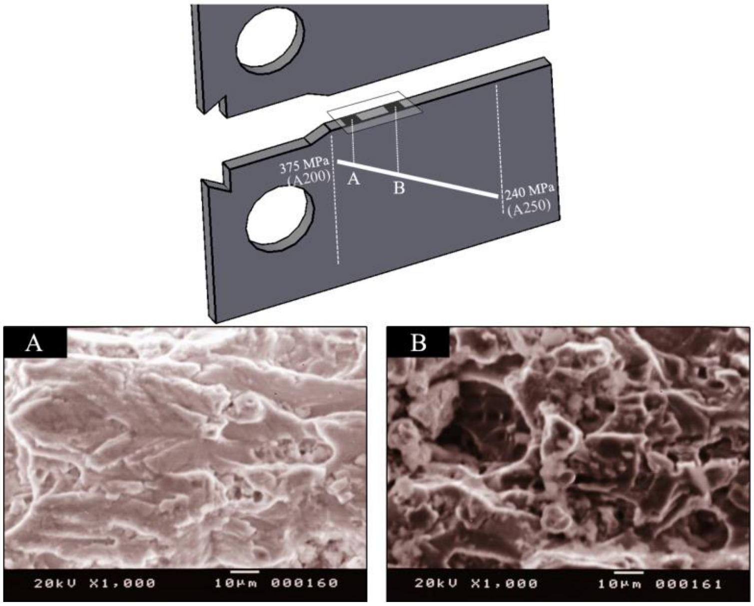


Fig. 10. SEM micrographs of specimen with decreasing yield strength profile showing fracture surface characteristics during FCG at range a) $\Delta K=11\ MPam^{1/2}$ b) $\Delta K=20\ MPam^{1/2}$

6. Discussion

Strength gradients may influence fatigue crack growth rate in 2024-T3 aluminum alloy. The effect is noticeable when strength is increasing from the crack tip. In the decreasing gradient the behavior seems not to be influenced. In [7] the role of gradients has been explained with the interactions of plastic zone size and their effect on crack growth rate. Here, in the case of increasing gradient the shift to higher σ_y may delay generation of significant plastic deformation with the advancing crack. In the case of negative gradient the shift to lower σ_y should enhance plastic deformation at the crack tip, however retardation of crack growth is not observed. In [8], increase of overaging temperature has been associated with increased closure levels during fatigue crack growth. Considering this behavior in the increasing gradient (Fig. 9) the crack initiates in a material with higher resistance to crack growth rate (A250) and propagates towards a direction of material with lower fatigue crack growth resistance (A200) as shown in Fig. 8. In the decreasing gradient, the crack initiates in a material with lower crack growth resistance (A200) and propagates towards a direction of material with higher resistance, which may explain the fact that crack propagation seems not to be affected.

The mechanisms influencing crack growth rate in the cases examined here, are interactive and further investigation is required to assess which effect on fatigue crack growth is more dominant.

7. Conclusions

The effect of yield strength gradient on fatigue crack propagation in 2024-T3 aluminum alloy was investigated experimentally. The results showed that:

- Crack growth rates are dependent on the slope of gradient at the crack tip. An increasing yield strength gradient at the crack path accelerates crack growth rates while a decreasing yield strength gradient does not influence significantly crack propagation behavior.
- Clad surface protection seems to enhance fatigue crack growth resistance with regard to the bare material.

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