Biaxial Fatigue of Aluminum Alloy 1100

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ABSTRACT. *Biaxiality effect on fatigue was studied employing cruciform specimens of aluminum alloy 1100-H14. The specimen, containing a transverse center notch, was subjected to in-phase (IP) or out-of-phase (OP) loading of stress ratio 0.1 in air. The biaxiality ratio λ ranged from 0.5 to 1.5, and 3 different stress levels were applied. It was observed that: 1) the fatigue strength was greater with greater λ under both IP and OP loadings; 2) the fatigue strength was greater and the fatigue life was longer under IP loading at a given λ; 3) the fatigue life was longer for a lower longitudinal stress at a given λ under both IP and OP loadings; 4) the fatigue crack path was straight for λ ≤ 1 but it turned away diagonally from its initial direction for λ > 1 under IP loading. but the fatigue crack path was straight for λ = 0.5 ~ 1.5 under OP loading, and; 5) the fatigue crack growth rate was smaller and the fatigue life was longer for a greater λ under IP loading. However, the fatigue crack growth rate was slightly greater and the fatigue life was slightly shorter for a greater λ under OP loading. At a given λ, the fatigue crack growth rate was lower and the fatigue life was longer under IP loading than under OP loading.*

INTRODUCTION

Metal fatigue has been studied mostly under uniaxial loading for the fatigue life prediction, design and maintenance of structural components. However, the load biaxiality effect on the fatigue should be taken into account, because many components are under biaxial or multiaxial loading. The biaxial loading arises from geometry, material inhomogeneity, and loading in different directions with different frequencies and/or different phases. The biaxial fatigue is controlled by 3 parameters: load biaxiality, crack angle, and stress intensity factor range. Depending on the first two parameters, cracks may grow in Mode I, Mode II, or mixed-mode [1]. One basic problem of biaxial fatigue is the role of a stress parallel to the crack. Some linear elastic analyses indicate that a stress parallel to the crack has no effect on the stress distribution at the crack tip, does not contribute to the stress intensity factor, and so no influence on the crack growth under biaxial loading [2,3]. On the other hand, there are conflicting reports of the load biaxiality influence on the crack tip plastic zone size and crack opening displacement [4-8]. The corresponding effect on crack growth, however, is uncertain. The fatigue crack growth rate may be increased [9,10], reduced [11,12] or unchanged [13], and the crack path direction may be unstabilized [14].

This study was initiated to clarify the biaxiality effect on the fatigue behavior of an aluminum alloy 1100-H14, and fatigue tests were conducted under biaxial loadings of different biaxiality ratios, stress ranges and phases.

EXPERIMENTS

As the specimen material, 2.3 mm thick sheets of aluminum alloy 1100-H14 were used. The chemical composition (%) was (Si+Fe) 0.1100, Fe 0.5300, Cu 0.0765, Mn 0.0039, Mg 0.0010, Cr 0.0017, Zn 0.0027, Ti 0.0111, other 0.15 and Al balance. The mechanical properties were tensile ultimate strength 132 MPa, tensile yield strength 129 MPa, elongation in 50 mm 9.00%, and Rockwell superficial hardness 15T 54. The electrical conductivity was 60% IACS. From these sheets, cruciform specimens were machined to have an overall length or width of 393 mm, including the grip areas of the loading arms, Figure 1. The vertical arms were in the longitudinal (or rolling) direction and the horizontal ones in the transverse direction of the sheet. Each arm was 127 mm wide and 133 mm long. At the specimen center, a transverse notch, 38 mm long and 0.25 mm wide, was made by electro-discharge machining.

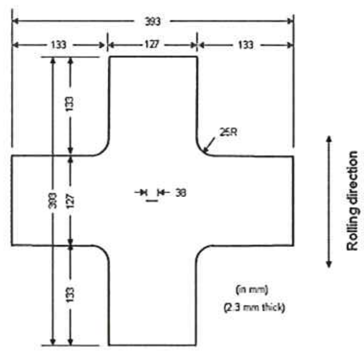


Figure 1. Sketch of cruciform specimen

The biaxial fatigue test was conducted in a MTS Model 793.10 Multiaxial Purpose Test-Ware with 2 pairs of servo-hydraulic actuators and 2 pairs of load cells, arranged perpendicular to each other on a horizontal plane in a rigid frame. It was capable of static and cyclic biaxial loading in vertical and horizontal directions, separately or simultaneously. Tensile or compressive loads could be applied to each pair of the arms, developing a biaxial stress field in the working section. Prior to a biaxial fatigue test, a pre-crack was developed under cyclic biaxial loading until its length reached 1 mm from each end of the center notch. The biaxial fatigue loading was done at longitudinal stresses, σ_y = 35.7, 42.9 and 51.5 MPa, and λ = 0.5, 1 and 1.5 at ambient temperature. The loading was IP or 180° OP at frequency of 15 Hz. The growing crack length was measured, employing DC potential drop technique. When the crack length reached 140 mm, it was defined that the specimen was failed by fatigue. The fractograph was examined with a scanning electron microscope, JEOL SEM JSM-6460LV, operated at an accelerating voltage of 20 kV.

EXPERIMENTAL RESULTS

Fatigue strength

Under IP loading, a greater λ and/or a lower longitudinal stress σ_y induced a longer fatigue life and a greater fatigue strength, Figures 2 and 3. The fatigue crack path was horizontal and straight for $\lambda \leq 1$, and began to curve and proceeded to the radius between the loading arms with increasing λ from 1 to 1.5.

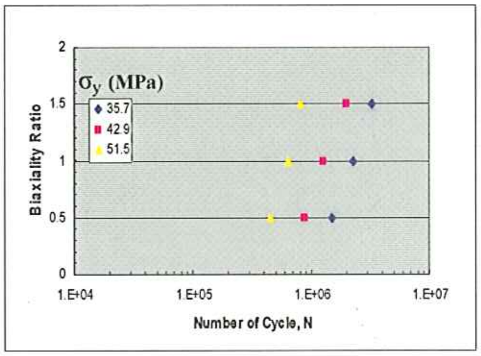


Figure 2. Variation of fatigue life with biaxiality ratio under in-phase cyclic loading.

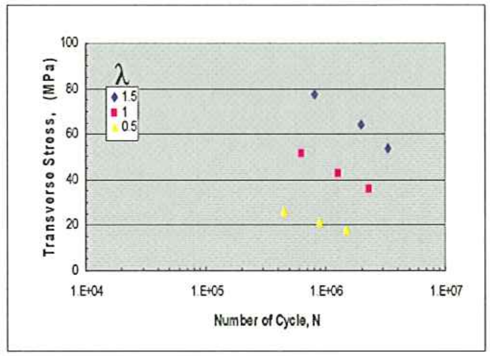


Figure 3. Variation of fatigue life with transverse stress under in-phase cyclic loading.

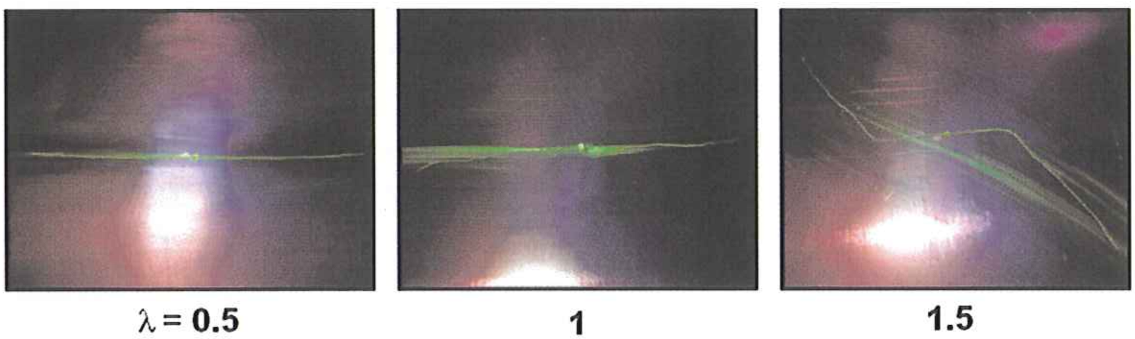


Figure 4. Fatigue crack paths at different biaxiality rations, 0.5, 1, and 1.5.

Under OP loading, a greater λ and/or a lower σ_y resulted in a similar or slightly shorter fatigue life and a greater fatigue strength, Figures 5 and 6. The fatigue crack path was horizontal and straight for λ = 0.5, 1, and 1.5. The fatigue strength was smaller under OP loading than under IP loading, and the difference was smaller for a smaller λ and a smaller transverse stress σ_x, Figure 7.

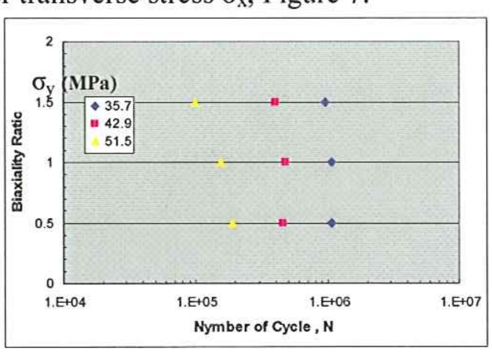


Figure 5. Variation of fatigue life with biaxiality ratio under out-of-phase cyclic loading.

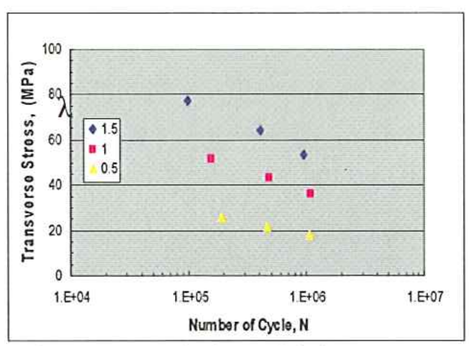


Figure 6. Variation of fatigue life with transverse stress under out-of-phase cyclic loading.

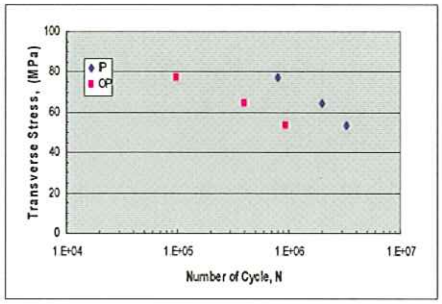


Figure 7. Comparison of transverse stress vs. fatigue life at biaxiality ratio 1.5 under in-phase and out-of-phase loadings.

Fatigue crack growth

The variations of fatigue crack length with number of loading cycle under IP and OP loadings are shown for λ = 0.5, 1, and 1.5 in Figures 8 and 9, respectively. The fatigue crack growth was faster and the fatigue life was shorter for a smaller λ under IP loading, Figure 8. On the other hand, the fatigue crack growth was slightly slower and the fatigue life was slightly longer for a smaller λ under OP, Figure 9. It was also observable that the fatigue crack growth was faster and the fatigue life was shorter under OP loading than under IP loading for a given λ, Figure 10. The difference was greater at a greater λ.

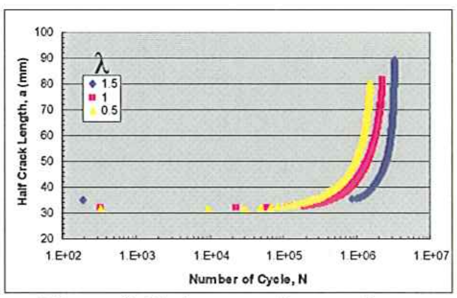


Figure 8. Fatigue crack growth at biaxiality ratios 0.5, 1, and 1.5 under in-phase cyclic loading.

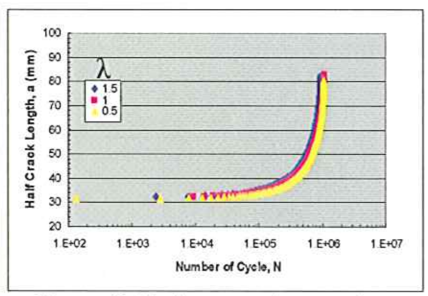


Figure 9. Fatigue crack growth at biaxiality ratios 0.5, 1, and 1.5 under out-of-phase cyclic loading.

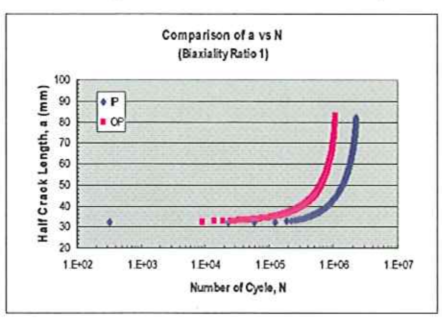
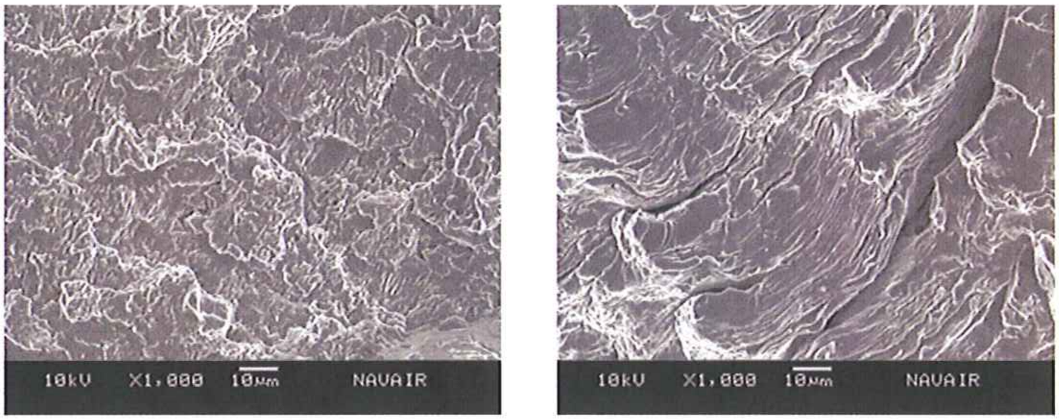


Figure 10. Comparison of fatigue crack growths at biaxiality ratio 1 under in-phase and out-of-phase cyclic loadings.

Fatigue fractograph

The straight and curved portions of the fatigue crack path showed similar fractographic features: clearly defined ductile striations with secondary cracks formed at the roots of many striations on fatigue patches, Figure 11. The noticeable difference was the greater striation spacing and wider fatigue patch in the curved portion, Figure 11.



Straight Path **Curved Path**

Figure 11. SEM fractographs of straight and curved fatigue crack paths.

DISCUSSION

Fatigue strength

Under the both IP and OP loadings, the fatigue strength was smaller with smaller λ, Figures 2, 3, 5, and 6. Furthermore, the fatigue strength was smaller under OP loading than under IP loading. The difference is smaller for a smaller λ and smaller σ_x, Figure 7.

Finney [15] found the fatigue strength decreasing with the stress state changing from uniaxial to biaxial and increasing phase angle between the longitudinal and transverse stresses at any given λ.

Fatigue crack path

It was observed that the fatigue crack grew straight in the tests with $\lambda \leq 1$ or $\sigma_x \leq \sigma_y$. However, when $\lambda \geq 1$ or $\sigma_x > \sigma_y$ the crack turned away from its initial plane and curved towards the radius between the loading arms.

In the study with cruciform specimens of 2024-T351 and 7075-T351 aluminum alloys, Liu [16] observed the fatigue crack growing straight in the tests with $\sigma_x \leq \sigma_y$ but turning away from its initial plane and ending up crack growth in a direction perpendicular to σ_x. Similar features of fatigue crack growth were also reported by Kibler [8] in their study with Plexiglas specimens. When the biaxiality ratio was greater than 1, Truchon [17] observed a fatigue crack taking an S-shaped path. Leevers [18] conducted a study on the fatigue behavior of centre-cracked PMMA plates under biaxial loading. He found that: (a) under uniaxial stress, the crack followed the specimen center-line normal to the applied load; (b) as the transverse stress was increased, there was an increasing tendency for the crack path to deviate from this line; (c) for $\lambda > 1$, the path curved away from the original direction towards that normal to the maximum load.

Fatigue fractograph

The observed fractographic features were fatigue striations with secondary cracks for both of the straight and curved portions of the fatigue crack path. The noticeable difference was greater striation spacing and wider fatigue patch for the curved portion. This is attributable to the greater crack growth rate da/dN at the later stage of fatigue crack growth, corresponding to the curved path.

Tanaka [19] studied the fatigue crack propagation in biaxial stress fields and the related fractographic features in a 0.04% carbon steel. He observed a relatively smooth fractograph with secondary cracks and brittle-like facets for $\lambda > 0$.

Fatigue crack growth

In this study, it was observed that the fatigue crack growth was slower and the fatigue life was longer for a greater λ under IP loading, Figure 4. On the other hand, the fatigue crack growth is slightly slower and the fatigue life is slightly longer for a smaller λ under OP loading, Figure 5.

Under biaxial loading, the relationship of the fatigue crack growth rate da/dN with the tensile load biaxiality can be expressed by the following equations [20].

$$da/dN = [C(\Delta K_I)^m] / [(1-R)K_c - \Delta K_I] \quad (1)$$

where ΔK_I is the stress intensity range, C and m the empirical constants, R the stress ratio, and K_c the plane stress fracture toughness. The form proposed by Hartman [21] is

$$da/dN = [C(\Delta K_I - \Delta K_0)^m] / [(1-R)K_c - \Delta K_I] \quad (2)$$

where ΔK_0 is the threshold intensity range for fatigue crack growth. The K_c for a sheet of finite width, containing a horizontally oriented center-crack, is

$$K_c(\lambda) = \sigma_c(\lambda).(\pi a)^{1/2}.f(a/W) \quad (3)$$

where λ is the biaxiality ratio, σ_c the fracture stress, a the half crack length, and f(a/W) the correction factor for the specimen width W. Reportedly, σ_c increases approximately linearly with the λ increasing in the range $-1 < \lambda < 2.5$ [20]. Consequently, K_c increases with increasing λ, and the da/dN decreases with increasing K_c or increasing λ.

Previous reports, some conflicting, show that da/dN may be reduced, increased, or unchanged with increasing λ.

Adams' study [5] indicates that the crack-tip plastic zone size is a critical factor influencing da/dN, an increasing λ leads to a reduced crack-tip plastic zone size, and a higher λ can induce a reduced da/dN. Hopper [12] observed a reduction in da/dN as λ increased from -1.0 to 1.0 in the fatigue test of an aluminum alloy, RR58. Kibler [8] found a decrease in the slope of the data when plotted as da/dN vs. ΔK with increase in λ from 0 to 0.33 for 6061-T4 and T6 aluminum alloys. Leevers [22] reported a reduction of da/dN by a factor of 2 to 3 as λ increased from 0 to 2 in PMMA. For all of the above test results, the biaxial loads were IP. In their study with a weldable structural steel sheet WT60, Kitagawa [23] observed decrease in da/dN with increase in load parallel to a crack under IP loading. However, the da/dN increased if the biaxial load was increasingly OP. Hoshide [24] observed the da/dN decreasing with increasing λ from 0 to 1 in a low-carbon steel (JIS SM41C).

Christensen [25] noticed the da/dN greater under biaxial loading of $\lambda > 0$ than under uniaxial loading ($\lambda = 0$) with an identical vertical stress. In the investigation of the biaxiality effect on the fatigue crack growth in 2024-T351 aluminum alloy, Joshi [9] observed an increase in da/dN with an increase in λ under reversed bending.

Leevers [22] reported that variation in λ from 0 to 2 have little effect on the da/dN in PVC. Trunchon [17] studied the influence of biaxiality on the fatigue crack growth in a C-Mn steel. He observed that the λ has no influence on the da/dN. Liu [16] observed negligible effect on the da/dN in 7075-T7351 & 2024-T351 aluminum alloys as λ was varied from -1.5 to 1.75. Pook [26] found little lateral load effect on the da/dN in Ni alloy plates as λ was varied from 0 to 2.0.

SUMMARY AND CONCLUSION

Under in-phase loading: (1) a greater biaxiality ratio induces a longer fatigue life and a greater fatigue strength and; (2) the fatigue crack path is transverse and straight for the biaxiality ratio less than 1 but it curves towards the radius between loading arms for the biaxiality ratio greater than 1.

Under out-of-phase loading: (1) a greater biaxiality ratio induces a similar or slightly shorter fatigue life and a greater fatigue strength and; (2) the fatigue crack path is transverse and straight for the biaxiality ratios, ranging from 0.5 to 1.5.

The fatigue crack growth is faster and the fatigue life is shorter under out-of-phase loading than under in-phase loading.

The fatigue strength is smaller under out-of-phase loading than under in-phase loading.

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