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Fatigue behavior of aluminum alloys under biaxial loading

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ABSTRACT

The biaxiality effect, especially the effect of non-singular stress cycling, on the fatigue behavior was studied, employing cruciform specimens of aluminum alloys 1100-H14 and 7075-T651. The specimens, containing a transverse or a 45° inclined center notch, were subjected to in-phase (IP) or 100% out-of-phase (hereinafter referred to as "out-of-phase or OP") loading of stress ratio 0.1 in air. The biaxiality ratio λ ranged from 0 to 1.5, and 3 levels of stress were applied. It was observed that: (1) at a given λ, a lower longitudinal stress induced a longer fatigue life under IP and OP loading, and the fatigue life was longer under IP loading, (2) the fatigue crack path profile was influenced by λ, phase angle (0° or 180°), and initial center notch (transverse or 45° inclined); (3) the fatigue crack path profiles, predicted analytically and determined experimentally, had similar features for the specimens with a transverse center notch under IP loading; and (4) the fatigue crack growth rate was lower and the fatigue life longer for a greater λ under IP loading, whereas it changed little with change in λ under OP loading. These results demonstrate that non-singular stress cycling affects the biaxial fatigue behavior of aluminum alloys 1100-H14 and 7065-T651under IP and OP loading.

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1. Introduction

Metal fatigue has been studied mostly under uniaxial stressing for the fatigue life prediction, design and maintenance of structural components. However, the fatigue-prone portions in structures are subject to substantial levels of biaxial stress. Current methods of fatigue prediction, which generally ignore biaxiality, are often inaccurate. The biaxial stressing arises from geometry, material inhomogeneity, and loading in different directions with different frequencies and/or different phases. The effects of biaxial stressing on fatigue have been investigated theoretically [1,2] and experimentally [3,4] by many researchers, and various conclusions, some contradictory, have been drawn.

Elastic analyses indicate that biaxial stresses would produce only a second-order effect on the fracture properties of ideally elastic materials. Since real materials exhibit plastic behavior near the crack tip and the plastic deformations depend on the entire stress state and history, one cannot assure that loading parallel to the crack will not affect the conditions near the crack tip and alter the fatigue and fracture behavior of the material. There is considerable evidence in the literature to demonstrate that the non-singular stress, parallel to a crack, has an influence on the fatigue crack growth, even though it does not contribute to the stress intensity factor [5]. This has been observed in aluminum alloys [6], steels [4] and polymers [7]. The crack-tip plastic zone size is influenced by the biaxial stress state, and this may be demonstrated to affect the fatigue crack growth. Furthermore, it has been reported that the tensile transverse stress can increase [8–10], reduce [2,6,11], or have little effect [12] on fatigue crack growth rate, and can cause instability of the crack path [13].

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Nomenclature

α	crack angle
λ	biaxiality ratio
σ	longitudinal stress
$\lambda\sigma$	transverse stress
$\sigma_{\theta\theta}$	tangential stress component
r, θ	cylindrical polar coordinates of a point with respect to a crack tip
x, y	Cartesian coordinates of a point with respect to a crack tip
a	a half crack length
K_I	Mode I stress intensity factor
K_{II}	Mode II stress intensity factor
N	fatigue life
R	stress ratio
IP	in-phase
OP	out-of-phase

A study has been conducted to clarify the effect of biaxial stressing, including non-singular stress cycling parallel to the crack plane, on the fatigue crack path, growth and life. The results with aluminum alloys are discussed in this paper.

2. Experimental procedure

2.1. Material and specimen

As the specimen materials, 2 mm thick sheets of aluminum alloys, 1100-H14 and 7075-T651, were selected. Their chemical compositions and mechanical properties are shown in Tables 1 and 2, respectively.

From these sheets, cruciform specimens were machined to have the overall length or width of 393 mm, including the grip areas of the loading arms. A sketch of the specimen is shown in Fig. 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 (or horizontal) notch or a 45° inclined one, 38 mm long and 0.25 mm wide, was made by electro-discharge machining. The transverse notch was made in the 1100-H14 specimen and the 45° inclined one in the 7075-T651 specimen. Subsequently, a precrack was made under cyclic biaxial loading until its length reached 1 mm from each end of the central notch.

2.2. Biaxial fatigue test

The biaxial fatigue test was conducted in a MTS Model 793.10 Multiaxial Purpose Test-Ware with two pairs of servo-hydraulic actuators and two 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. The cyclic biaxial loading, IP or OP, was done at various longitudinal stresses σ and biaxiality ratios λ, stress ratio $R = 0.1$ and loading frequency 15 Hz in air. The growing crack length was measured by means of DC potential drop method. When the crack length reached 140 mm, it was defined that the specimen was failed by fatigue. The fractograph was examined in a scanning electron microscope, JEOL SEM JSM-6460LV, operated at an accelerating voltage of 20 kV.

3. Experimental results

The experimental results are divided into two parts: biaxial fatigue behavior of specimen with a transverse notch and that with a 45° inclined notch under IP and OP loading.

Table 1
Chemical compositions of aluminum alloys 1100 and 7075 (wt.%).

Al-alloys	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other	Al
1100	0.11	0.53	0.0765	0.0039	0.0010	0.0017	0.0027	0.0011	0.15	Balance
7075	−0.50	−0.7	1.2–2.0	−0.30	2.1–2.9	0.18–0.4	5.1–6.1	−0.20	0.15	Balance