International Journal of Fatigue 109 (2018) 103–113

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Fatigue crack propagation under biaxial fatigue loading with single overloads

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ARTICLE INFO

Keywords:
Biaxial fatigue
Crack propagation
Overloads
Fractography
Crack retardation

ABSTRACT

The crack propagation behavior and the governing crack growth micromechanisms in aluminum alloy under in-plane biaxial fatigue loading with single overloads, of different magnitudes and occurring at different fatigue crack lengths, is investigated. The microscale fracture mechanisms governing crack growth behavior under these conditions are identified through detailed fractography. Crack growth retardation behavior observed due to the occurrence of single overloads is correlated with overload magnitude, instantaneous fatigue crack length, crack-tip plasticity and fracture surface morphology. The results obtained provide insight into the relationship between macroscale crack growth behavior to microstructural mechanisms, which is essential to understanding the fatigue behavior of metallic materials under variable amplitude biaxial loading scenarios.

1. Introduction

Aerospace components are exposed to a wide variety of multiaxial fatigue loading conditions during their service life; therefore fundamental understanding of fatigue damage accumulation and progression under such loading conditions is essential to predicting their useful life [1–6]. Specifically, variable amplitude (VA) loading is one of the most complex loading scenarios experienced by these components and understanding the phenomena which govern the crack growth mechanisms activated under a series of random amplitude loads is a challenging task [7–9]. Although a multitude of studies have been reported on the fatigue behavior of metallic materials under uniaxial loads [10,11], there is very limited understanding of the crack growth behavior under complex multiaxial loading. Uniaxial VA fatigue behavior of aluminum alloys has been studied in depth over the past decades using load spectra such as TWIST and FALSTAF in addition to spectra with single or periodic overloads and underloads [12–21]. However, the crack growth behavior under biaxial VA loading conditions remains largely unexplored.

Lee et al. [22] studied the constant and VA uniaxial fatigue behavior of Al 7075-T651 alloy in vacuum, air and saline environments, using a tension–tension and a tension–compression type load spectrum. Their results showed increased fatigue life (slower crack growth) in the case of tension–tension type spectrum due to the occurrence of overloads; unequal striation spacing was observed as a manifestation of the varying crack growth rate. Schijve et al. [23] reported a fatigue study on Al alloy D16 where VA tests included experiments with single overloads, periodic overloads and underloads and the flight-simulation load history FALSTAFF. An overload ratio of 2 was used in the single overload tests, and delayed crack retardation was reported. The slight delay in crack retardation after overload was attributed to residual stresses and plasticity induced crack closure in the wake of the crack-tip that reduce the effective ΔK. Fractography results correlating striation spacing with macroscopic crack growth rates were also presented and their direct dependence on the load history was established. In another study, Schijve [24] studied the uniaxial VA fatigue crack growth behavior of Al 2023-T3 and Al 7075-T6 by using load spectra with periodic overload cycles superimposed on constant amplitude (CA) cycles. Quantitative fractography and macroscopic crack growth measurements showed that the retardation effects became more prominent with increase in overload ratio and with increase in the number of overloads within an overload block. Overload blocks also acted as marker loads and facilitated microscopic crack growth measurements. In case of high overloads, total crack arrest was observed after the crack-tip propagated about 500 μm into the overload plastic zone [24,25]. Of the many proposed mechanisms for crack retardation, residual compressive stresses and plasticity induced crack closure provide a primary basis for justifying the load-interaction effects. Therefore, many existing models for predicting crack growth rates are based on the crack closure concept [15,26–28]. However, direct experimental evidence for the dominant

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https://doi.org/10.1016/j.ijfatigue.2017.12.018
Received 31 July 2017; Received in revised form 22 December 2017; Accepted 26 December 2017
Available online 03 January 2018
0142-1123/

Nomenclature

P_{max}	maximum load
P_{min}	minimum load
R	load ratio (P_{min}/P_{max})
BR	biaxiality ratio (P_y/P_x)
P_{OL}	overload
R_{OL}	overload ratio (P_{OL}/P_{max})
a	crack length
a_{OL}	crack length at overload
N_{OL}	fatigue cycles at overload
K	Mode-I stress intensity factor
ΔK_i	stress intensity factor range at i^{th} loading cycle
$\left(\frac{da}{dN}\right)_{CA}$	crack growth rate under constant amplitude loading immediately before overload
$\left(\frac{da}{dN}\right)_{OL}$	crack growth rate immediately after overload
$r_{p,CA}$	plastic zone diameter at crack-tip due to cyclic loading
$r_{p,OL}$	plastic zone diameter at crack-tip due to monotonic overload
R_d	size of the transient zone where crack retardation is observed

role of plasticity induced crack closure is limited.

A biaxial fatigue study was conducted by Shanyavskiy [29]; cruciform specimens of Al-based alloys were subjected to CA and VA loading, including sequences of various overloads. The study showed that semi-elliptical fatigue cracks grew faster and striation spacing became larger with increasing biaxiality ratio. Analysis of crack growth rate before and after overload, for various biaxiality and stress ratios, revealed tensile mode-I fractures inside the specimen after an overload and shear lip formation at the specimen surface. Delayed crack retardation was reported, caused by shear stress on the shear lip surface. Significant adverse effect of tensile stress biaxiality on crack growth rate under periodic overloads in a fighter aircraft load spectrum was shown by Liu and Dittmer [30]. This increase in crack growth rate was attributed to the tensile transverse load that reduces the plastic zone size at the crack-tip. Sunder and Ilchenko [1] studied the biaxial fatigue crack growth behavior in cruciform test coupons using CA loading (both in-phase and out-of-phase) and a modified TWIST load spectrum superimposed with biaxial quasistatic load simulating internal cabin pressure. They found that the crack growth rates were sensitive to load biaxiality under CA as well as spectrum loading. The fracture features were also found to be highly dependent on the load history. However, the crack growth behavior was not directly correlated with the microscale fracture features and the mechanisms governing crack propagation under the complex loading conditions were not discussed in detail.

In this research, experimental investigations have been conducted to gain comprehensive insight into the nature of crack propagation under the influence of random amplitude biaxial fatigue loading by studying the effect of individual overloads of different magnitudes. The primary goal is to characterize the in-plane biaxial fatigue crack propagation behavior and investigate the underlying microscale mechanisms in Al-7075T651 test specimens subjected to single overloads of different magnitudes occurring at different fatigue crack lengths. Detailed quantitative fractography studies were conducted and the results provide insight into the active micromechanisms that govern crack growth behavior in the event of an abrupt change in biaxial cyclic load. The effects of different overload magnitudes on fatigue crack growth were analyzed and correlated with instantaneous crack length, crack-tip plasticity and the fracture surface morphology. The following section presents details of the experimental investigation.

2. Materials and methods

2.1. Biaxial fatigue test setup

Experiments were conducted using the MTS planar biaxial/torsion load frame with a dynamic load capacity of 100kN in both horizontal and vertical directions, shown in Fig. 1. The testframe is equipped with six independent controllers; this allows testing under a wide range of biaxial loading conditions, including in-phase, out-of-phase, proportional and non-proportional loading. Specimen design is critical to accurate estimation of fatigue life. The cruciform specimen, shown in Fig. 2, was designed such that the central web area had uniform stress distribution for initial yielding. The specimens were machined from 6.35 mm rolled Al 7075-T651 sheets with the thickness of web area at 1.8 mm. A hole of diameter 6.35 mm was cut at the center of the web area and a notch of length 1.5 mm and width 0.36 mm was made at an angle of 45° (Fig. 2) to facilitate crack initiation and orient the crack propagation direction along the 45° plane with respect to the loading axes under pure mode-I fatigue loading. The presence of the notch at 45° angle facilitates the calculation of mode-I stress intensity factor (SIF) at the crack tip when the crack initiates and propagates under the applied in-phase biaxial fatigue loading with BR = 1. In the absence of this notch, the cracks could initiate at any arbitrary orientation from the periphery of the center hole and the resulting test data would not provide meaningful information. Mall et al. [31] and Neerukatti et al. [32] used similar notch designs at the center hole of cruciform specimens for their studies on the effect of out-of-phase loading that causes mode mixity at the crack tip. A high-resolution camera was positioned on the rear side of the specimen to capture the crack initiation and growth. The camera was programmed using LabVIEW to take images at user-defined time intervals and image processing software ImageJ was used to measure the fatigue crack lengths at different fatigue cycles. This allowed calculation of the cycles for crack initiation, propagation and final failure and the crack growth rate at each crack increment.

2.2. Load spectrums with single overloads

To study the effects of a single overload on biaxial fatigue crack propagation, fatigue load spectrums were generated with single overload excursions in an otherwise CA loading with P_{max} = 15kN, R = 0.1 and a frequency of 10 Hz. For the tests with single overloads, overload ratios ($R_{OL} = P_{OL}/P_{max}$) of 1.75, 2 and 2.25 were used in order to investigate the effect of overload magnitude on fatigue crack growth behavior at different crack lengths (a_{OL}) as detailed in Table 1.

2.3. Quantitative fractography

Following the fatigue tests, quantitative fractography was

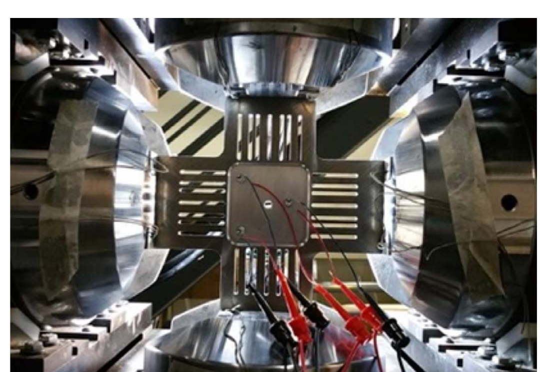

Fig. 1. Cruciform specimen in biaxial test frame.