Estimation of Fatigue Crack Orientation using Critical Plane Parameters: An Experimental Investigation

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ABSTRACT. *Critical plane parameters evaluate fatigue damage on selected planes. These planes are expected to be aligned with the physical cracking planes. This paper examines the predictions of both fatigue life and crack initiation plane using two critical plane parameters: Fatemi-Socie (FS) and Smith-Watson-Topper (SWT). Tubular specimens were machined from AZ31B magnesium extruded sections. Cyclic tests were performed under multiaxial proportional and nonproportional loading conditions. Fatigue crack length and angle were measured using optical microscope. This investigation shows that even though fatigue life can be well predicted the critical plane assumption is not consistent with the observed cracking plane.*

INTRODUCTION

Fatigue damage parameters are classified based on the definition of the parameter that quantifies fatigue damage. This can be stress, strain or energy. In a critical plane approach, parameters are evaluated at specific planes; hence, both fatigue life and crack orientation can be predicted.

Smith-Watson-Topper (SWT) model [1, 2] is among the well-known critical plane models. It assumes the critical plane as the plane of maximum normal strain. The mathematical form of the SWT parameter is

$$\frac{\Delta\varepsilon_1}{2}\sigma_{n,max} = C_1 \quad (1)$$

where $\sigma_{n,max}$ and $\Delta\varepsilon_1$ are the maximum normal stress and maximum normal strain range at the critical plane and C_1 is a constant.

Fatemi and Socie (FS) [3] proposed a damage parameter that assumes the critical plane as the maximum shear strain plane. The mathematical form of the FS parameter is

$$\frac{\Delta\gamma_{max}}{2}\left(1 + k\frac{\sigma_{n,max}}{S_y}\right) = C_2 \tag{2}$$

where $\Delta\gamma_{max}$ is the maximum shear stress range at the critical plane, k is a material constant, S_y is the yield strength, C_2 is a constant. $\sigma_{n,max}$ is the maximum normal stress at the critical plane.

The aforementioned criteria have been widely used to analyze uniaxial and multiaxial loading conditions as well as isotropic and anisotropic materials [4-12]. However, it was found that while critical plane criteria can provide a reasonable prediction of fatigue life, their predictions of the physical fatigue cracking plane are not in agreement with the experimental observations [7, 13, 14].

This paper examines the predictions of both fatigue life and crack initiation plane using two critical plane parameters: the Fatemi-Socie (FS) and the Smith-Watson-Topper (SWT). Tubular specimens were machined from AZ31B extruded sections. Cyclic tests were performed under multiaxial proportional and nonproportional loading conditions. Fatigue crack length and angle were measured using optical microscope.

Experiment

Two loading modes were considered in this experiment: axial and torsional. Strain-controlled cyclic tests were performed on tubular specimens machined from large AZ31B magnesium extrusion sections. Three phase angles were considered in multiaxial tests: 0, 45 and 90º. All tests were stop at 50% load, force or torque, drop. Detailed information about the experimental setup and material characteristics can be found in [4, 13].

After stopping the test, microscopic study was conducted as follows. First, crack initiation and propagation sites were identified. Then, crack measurement was performed using an optical microscope equipped with length measuring scale. To measure the crack surface angle, the projected crack height, *h*, and crack width, *w*, were measured as shown in Fig. 1. Finally, the crack surface angle was calculated as the inverse tangent of the ratio of the height to the width.

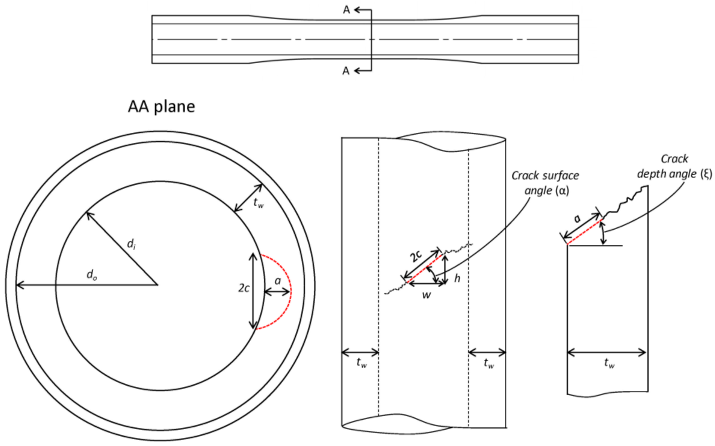

Figure 1. Schematics illustrating crack size and crack orientation measurements.

Results

In most cases, semi-elliptical cracks were observed as shown in Fig. 2. Therefore, the major, 2*c*, and the minor, *a*, radii were measured. The average radii were found to be 2*c* = 2.02±1.4 mm and *a* = 0.68±0.3 mm. It was also observed that AZ31B extrusions show Case A type cracking behavior; Case A type cracks tend to be shallow and have small aspect ratios. It should be noted here that some specimens developed multiple cracks, however, only the largest crack was reported. It should also be noted that specimens that failed along the longitudinal direction were found to develop long cracks that exceed 5 mm. Therefore, if only specimens with surface crack size less than 3 mm were considered the average crack sizes were found to be 2*c* = 1.36±0.55 mm and *a* = 0.73±0.276 mm.

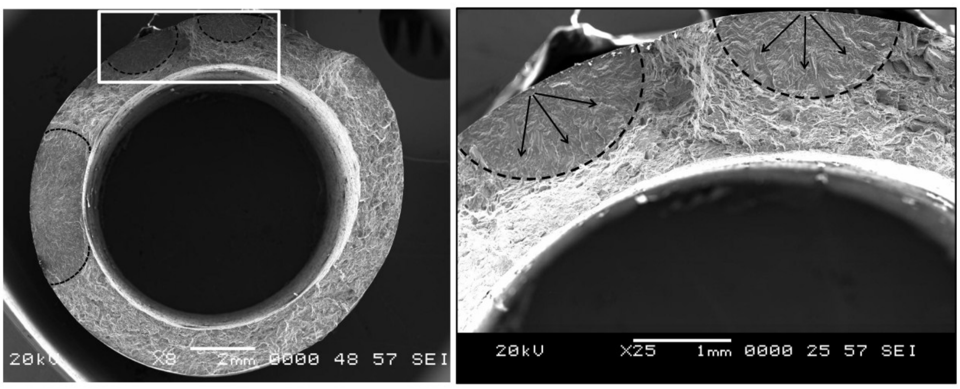

Figure 2. Scanning electron microscopy (SEM) images showing crack initiation and propagation sites for specimen tested under cyclic axial loading with strain amplitude of 0.3%.

Fatigue life predictions from the SWT and the FS parameters are shown in Figs. 3a and b. In addition, Figs. 3c and d show the predictions of fatigue lives but by pre-defining the critical plane as the observed plane from the experiment. The points marked with arrows at N = 10^6 cycles indicate either infinite or unrealistic lives. Generally, it can be seen that both parameters are capable of predicting multiaxial fatigue lives under different phase angles, especially the FS model. However, their predictions of multiaxial fatigue lives based on the observed cracking planes are overestimated. Comparisons between the observed cracking planes and the FS and the SWT planes are depicted in Fig. 4. This figure shows that SWT plane underestimates the cracking angle while FS plane overestimates it.

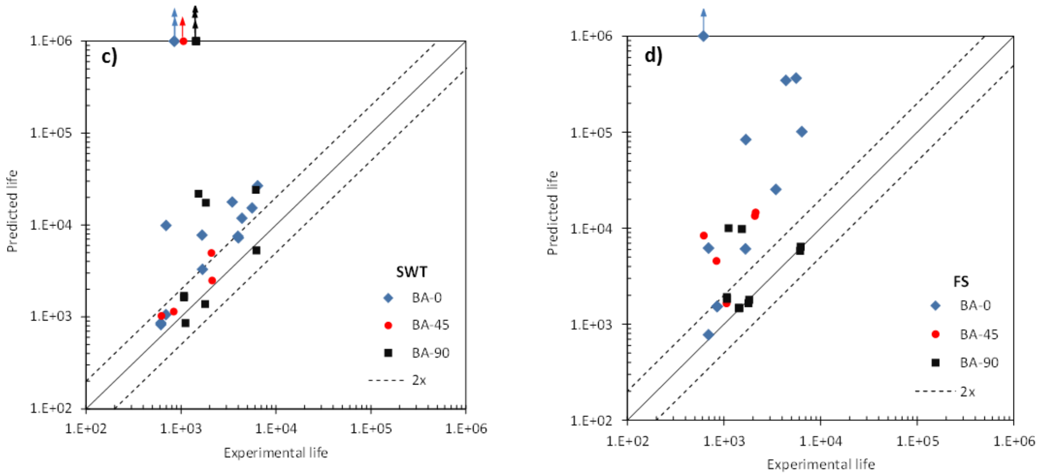

Figure 3. Comparison between fatigue life prediction using SWT and FS parameters. a) and b) Based on critical plane assumption. c) and d) By pre-defining the critical plane as the observed cracking plane.

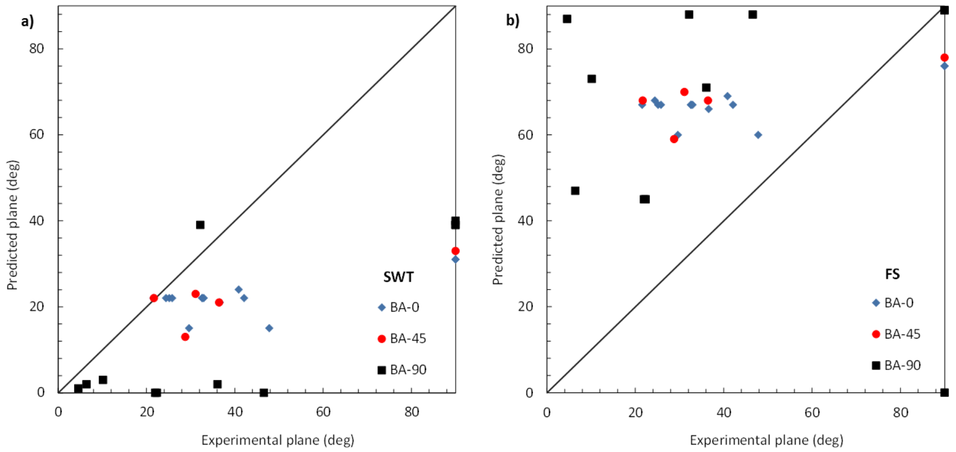

Figure 4. Comparison between observed and predicted crack planes. a) SWT and b) FS.

Discussion

The examined critical plane parameters evaluate fatigue damage on the planes of maximum normal or shear strains. The search for the critical plane is performed using stress and strain transformation relations for plane stress state. The stabilized hysteresis for normal and shear modes were transformed at different plane angles, namely, from 0 to 180° with increment of 1°. This process generates 180 hysteresis loops for each mode. Then, the values of maximum strain, normal or shear, with their corresponding angles were found. Finally, the maximum normal stress was found at the same plane and the fatigue damage is evaluated. The result in Fig. 3d can be explained by examining the transformed hysteresis at the plane of the observed crack. In Fig. 5, three shear hysteresis loops for a multiaxial proportional test are shown. The original hysteresis represents the shear stress-strain response obtained from the experiment. This is the hysteresis at 0° plane angle. The largest loop represents the transformed hysteresis at plane of maximum shear strain. i.e., the FS plane. On the other hand, the third loop is the hysteresis obtained by defining the plane angle as the observed crack angle. As seen from Fig. 5, the shear strain value at this plane is very small. As the shear strain approaches zero the damage value does resulting in infinite or unrealistic life predications.

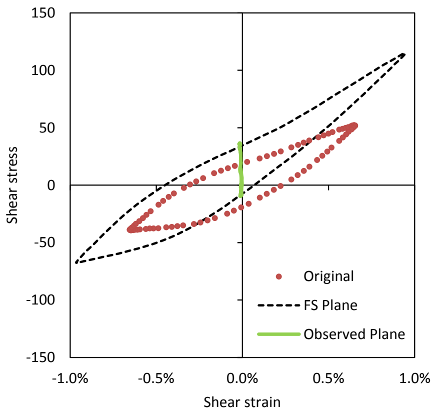

Figure 5. Plane stress transformation of shear mode hysteresis obtained from proportional test.

If the lives marked with arrows in Figs. 3c and d are ignored, it can be generally seen that the predictions of the SWT models are less overestimated compared to those of the FS model. An interesting observation can be made by examining the relation between the phase angle and the observed cracking plane. This can be done by comparing multiaxial tests that were performed at different phase angles but same normal and shear strain amplitudes as show in Fig. 6. This figure shows data for 21 tests. Most of the points in this figure represent the average of at least two tests. It is seen from this figure that the critical plane assumption of the SWT parameter shows better correlations with the experimental observation than the FS parameter. This is could explain the difference between Fig. 3c and Fig. 3d. An interesting observation [15] related to the phase angle indicates that phase angle has no influence on fatigue life of AZ31B magnesium extrusion especially in the LCF regime. On the other hand, Fig. 6 generally suggests that there is an inverse relation between the phase angle and the cracking plane angle.

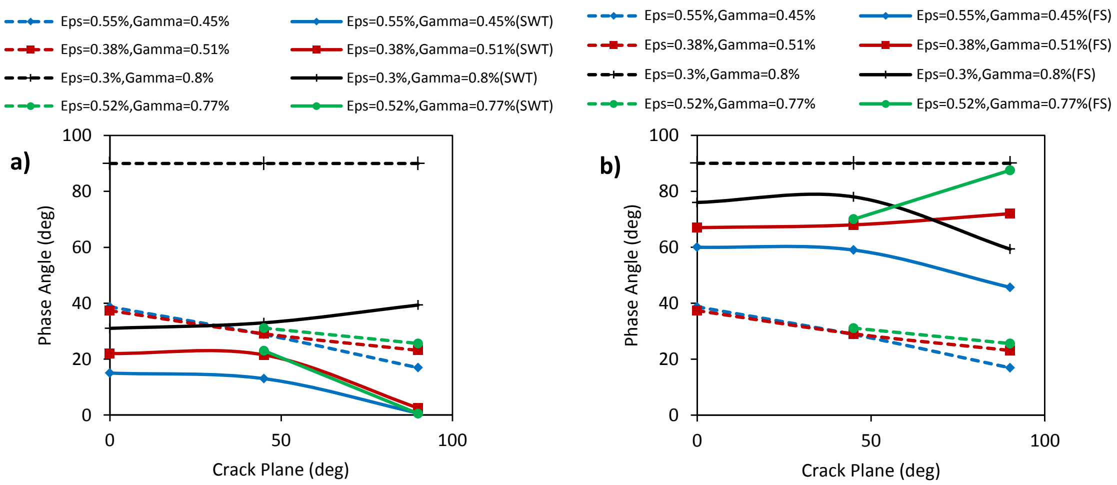

Figure 6. Phase angle effect on cracking plane angle. a) SWT and b) FS.

Conclusions

Crack plane prediction using the Smith-Watson-Topper and the Fatemi-Socie parameters was experimentally examined. It was generally found that while both parameters are capable of predicating multiaxial fatigue lives at different phase angles, their critical planes are not in agreement with observed cracking planes. Pre-defining the critical plane as the observed cracking plane in both parameters was found to overestimate fatigue lives. Analysis on the transformed hysteresis loops at the cracking plane showed that the magnitude of the strain, normal or shear drops significantly resulting in less damage and consequently overestimated life.

This investigation suggests that a carefully designed fatigue experiment needs to be conducted in order to understand the observed discrepancy.

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