



Multiaxial fatigue crack path prediction using critical plane concept

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ABSTRACT. Prediction of fatigue crack orientation can be an essential step for estimating fatigue crack path. Critical plane concept is widely used due to its physical basis that fatigue failure is associated with certain plane(s). However, recent investigations suggest that critical plane concept might need revision. In this paper, fatigue experiments that involve careful measurement of fatigue crack were reviewed. Predictions of fatigue crack orientation using critical plane concept were examined. Projected length and angle were used to characterize fatigue crack. Considering the entire fatigue life, this average representation suggests that it is more reasonable to assume the plane of maximum normal strain as the critical plane even though fundamentally the plane of maximum shear strain is more likely to be the critical one at early initiation stage.

KEYWORDS. Multiaxial fatigue; Crack growth; Critical plane; Crack path.

INTRODUCTION

There is still no unified definition of fatigue crack initiation. Yet, there is an agreement that there are three classes of fatigue crack growth: microscopic, small and macroscopic [1]. Still these classes are not exactly defined and there is an overlap between them. In general, cracks with lengths less than $10^2 \mu\text{m}$ are considered microscopic and their growth is governed by the microstructure texture. Based on the literature, such crack size marks the initiation size [2]. Cracks with lengths between 10^2 to $10^3 \mu\text{m}$ are considered small and such range represents what is so-called early growth stage [3, 4]. It is widely accepted that fatigue correlations are valid during initiation and early growth stages. After that, fracture mechanics is used to predict propagation life that is dominated by growth of macroscopic cracks. The concept of critical plane was developed based on the experimental observations that fatigue cracks initiate at specific planes [3, 5]. The current practice for evaluating critical plane models consists of three steps. Considering a maximum shear strain damage parameter, the first step is to search for critical plane by transforming hysteresis loops at different planes using plane stress-strain transformation relations. The critical plane is the plane at which shear strain is maximum. This plane may only correspond to the orientation of the inception or early initiation of crack, with length scale in the order of microns. In the second step the corresponding axial and shear stresses are obtained from the hysteresis loops on this critical plane. Finally, fatigue life is predicted by coupling the damage with a life equation. This procedure implies that crack will initiate at the plane of maximum shear strain and it will grow, within early growth stage, in the same orientation. Of course, this is not always the case as fatigue cracks may grow in a zigzag paths. Recently, Albinmousa and Jahed [6] examined the predictions of fatigue crack orientation on smooth specimens subjected to multiaxial loading using critical plane concept. They showed that reversed analysis for predicting fatigue life by assuming the critical plane as the experimentally observed plane showed that the predictions of strain-based models were mostly non-conservative.



Conversely, satisfactory predictions were obtained by evaluating the Jahed–Varvani [7] energy model on the observed planes. Albinmousa and Jahed suggested that the assumption of critical plane based on maximum driving parameter such as normal or shear strains might be idealistic. It was rather suggested that redefining the physical size of the analysis by adopting an average measure could resolve the aforementioned conflict. They proposed that if a crack grows in zigzag path, in average and for a limited size it could still be considered as a single crack with a single orientation as illustrated in Fig. 1. In this figure, the projected crack length, l_p , is defined as the straight distance between the tips of the crack and the orientation of this line is defined by the angle β . The objective of this study is to investigate the applicability of the proposed idea by Albinmousa and Jahed [6].

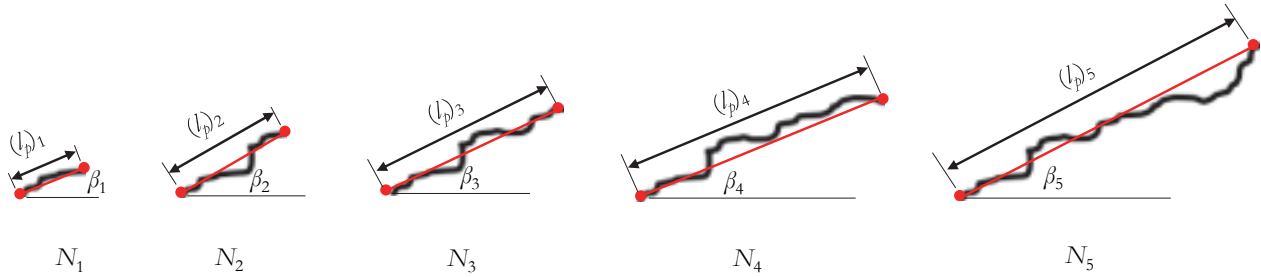


Figure 1: Definition of the projected crack length, l_p , and its orientation, β . $N_{i+1} > N_i$.

EXPERIMENT AND RESULTS

Because the focus of this paper is fatigue, which includes both initiation and early growth stages, tests should be performed on smooth specimens. Unlike fracture mechanics experiments in which a determined flaw size is required or introduced before the application of loading, detection and monitoring fatigue crack growth in fatigue tests is a demeaning task. Experimental analysis considered in this study was conducted by Hoffmeyer *et al.* [8]. Combined axial-torsional cyclic tests were performed on smooth specimens machined from and aluminum Al5083 (AlMg4.5Mn). The monotonic and cyclic properties of this alloy are as listed in Tab. 1 [8]. Summary of investigated cases in this paper is listed in Tab. 2.

Monotonic		Cyclic	
E (MPa)	68,000	K' (MPa)	544
ν	0.33	n'	0.075
$S_{j0.2\%}$ (MPa)	169	σ'_f (MPa)	780.3
S_{ut} (MPa)	340	ϵ'_f	1.153
$\%AR$	20	b	-0.114

Table 1: Monotonic and cyclic properties Al5083 aluminum [8].

Incremental measurements of actual crack length, projected crack length l_p and orientation β were performed for the tests listed in Tab. 2. Variations of projected angle β and crack actual crack length with cycling are plotted in Fig. 2. In addition, planes of maximum normal and maximum shear strains were also determined for each case.

Three general observations can be made from Fig. 2. Fatigue crack grows exponentially with cycling. The variation of the projected angle β with cycling is relatively steady and closer to the plane of maximum normal strain than the plane of maximum shear.

No.	Loading	ϵ_a (%)	γ_a (%)	σ_a (MPa)	τ_a (MPa)	N_f
1	Axial	0.300	0.00	207.1	0.0	28,600
2	0	0.231	0.40	161.0	103.0	47,500
3	0	0.202	0.35	138.0	103.1	57,845
4	90	0.346	0.60	247.7	157.8	2,700
5	90	0.231	0.40	161.8	105.9	28,500
6	90	0.202	0.35	143.8	113.8	40,860
7	45	0.231	0.40	163.9	131.8	20,900

Table 1: Summary of cyclic tests for AlMg4.5Mn [8].

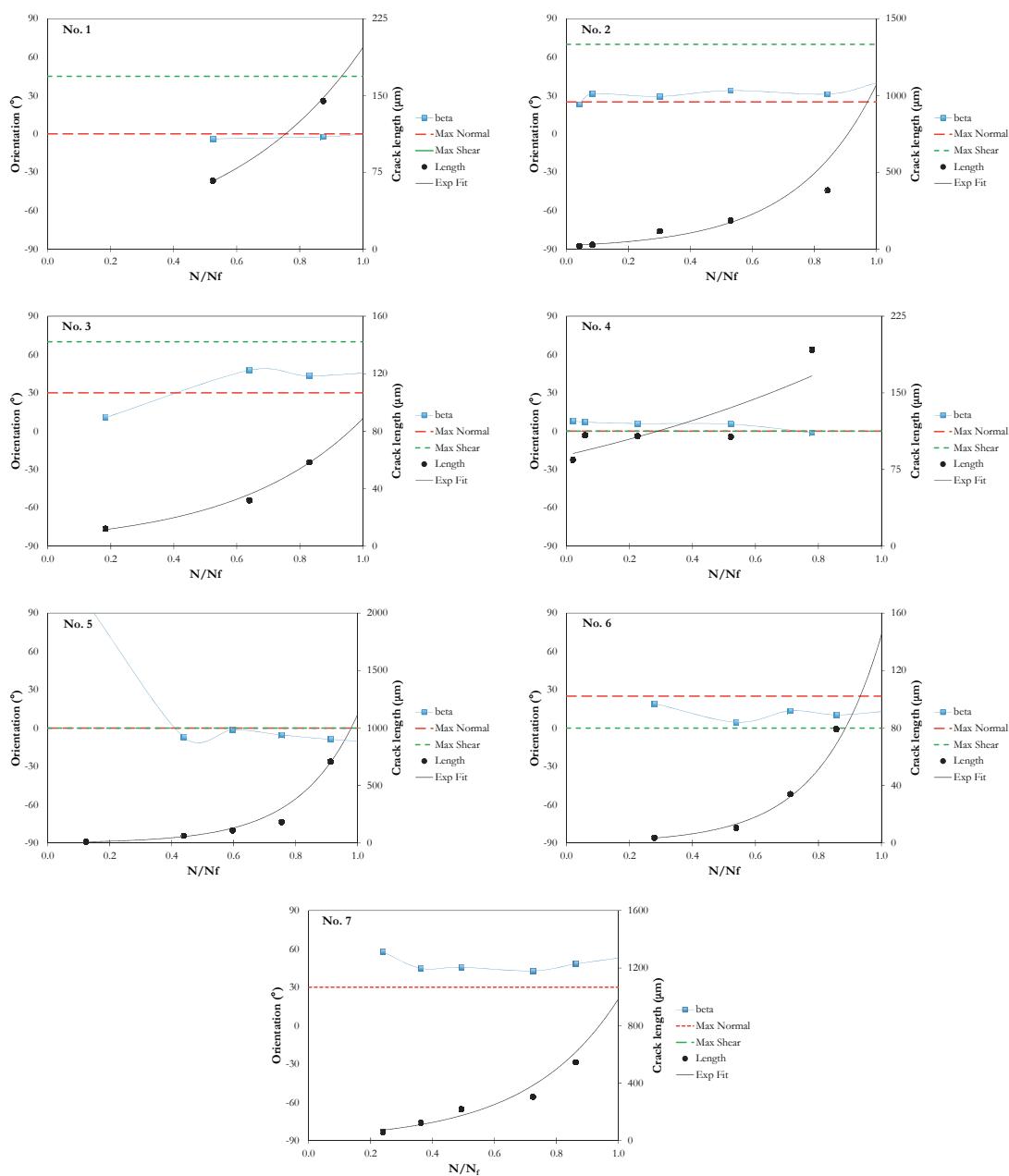


Figure 2: Variations of projected angle β and crack length with cycling. Planes of maximum normal and maximum shear strains are indicated by red-dashed and green-dashed lines, respectively.



DISCUSSION

There is no single fatigue failure model that can be viewed as widely accepted by the research community to be applicable to varieties of materials and loading conditions. Because it has been found that the effectiveness of an individual fatigue model depends on the material, the loading conditions and the failure mechanisms involved. Experimental observations on fatigue failure indicate that fatigue crack nucleation occurs at the persistent slip bands (planes). The critical plane approach was originated on the basis of this observation. As a result, component of stress or strain are evaluated at specific planes for fatigue damage calculation. The fact that critical plane models can predict both fatigue life as well as fatigue cracking plane gives these models an advantage over other models that provide predictions for only fatigue life. Critical plane models became popular because of their success in predicting fatigue life for various engineering materials and under different loading conditions [5, 9, 10]. However, it was pointed out by several investigations [4, 6, 9] that even though these models can predict fatigue life with good accuracy (as compared to experimental observations) they may not succeed in providing acceptable estimations of the fatigue cracking planes. For example, models that assume the maximum tensile plane as the critical plane fail to predict the cracking plane of material that fails under shear mode and vice versa. Furthermore, in a recent experimental investigation [6] the fatigue crack planes were determined using uniaxial and multiaxial cyclic loading tests and then fatigue lives were successfully predicted using critical plane approach. However, the predictions of fatigue lives were far from being reasonable by pre-defining the critical plane as the measured cracking plane. The discrepancy in the aforementioned experimental observations suggests that damage parameters in critical plane models need revision or the definition of critical plane needs revision. However, this argument is still subject to valid criticism due to the size range of the measured crack. Metallurgical factors such as texture, grain size, grain boundary, defects and inclusion, and second phase particles can influence the fatigue cracking behavior. Also, as crack length increases the size of the plastic zone around the crack tip increases that can also influence the fatigue cracking behavior. Incorporating all of the aforementioned factors in a single fatigue model is a challenging task. An incremental fatigue model might be a suitable tool to predicting both fatigue life and crack path. On the other hand, the proposed method can be considered as an average approach.

In general, the results in Fig. 2 indicate that by considering a crack size of about $10^3 \mu\text{m}$, it is more reasonable for the critical plane to be assumed as the plane of maximum normal strain even though fundamentally the plane of maximum shear strain is more likely to be the critical one. Fatigue cracks initiate at the plane of maximum shear strain where slip bands occur, however, they change their direction quickly approaching the plane of maximum normal strain. The exponential growth rate of fatigue crack length with cycling has long been observed and modelled in literature [1, 11]. A comprehensive investigation with detailed real time measurements of crack evolution is needed.

SUMMARY

Fatigue experiments on smooth specimens machined from aluminum Al5083 (AlMg4.5Mn) were analyzed. Specimens were tested under multiaxial cyclic loading. Detailed measurements of crack length and orientation were made. Fatigue crack was characterized using an average projected crack length and an angle. Such representation suggests that plane of maximum normal strain could be used as the critical plane for fatigue damage calculations. Further detailed investigation is required to examine the applicability of the proposed idea and to determine both fatigue damage parameter and fatigue life equation.

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REFERENCES

- [1] Shamsaei, N., Fatemi, A., Small fatigue crack growth under multiaxial stresses, *International Journal of Fatigue*, 58 (2014) 126-135.
- [2] Sakane, M., Zhang, S.D., Kim, T., Notch effect on multiaxial low cycle fatigue, *International Journal of Fatigue*, 33 (2011) 959-968.
- [3] Socie, D., Critical plane approaches for multiaxial fatigue damage assessment, *ASTM Special Technical Publication*, 1191 (1993) 7-7.
- [4] Reis, L., Li, B., De Freitas, M., Analytical and experimental studies on fatigue crack path under complex multi-axial loading, *Fatigue & Fracture of Engineering Materials & Structures*, 29 (2006) 281-289.
- [5] Fatemi, A., Shamsaei, N., Multiaxial fatigue: An overview and some approximation models for life estimation, *International Journal of Fatigue*, 33 (2011) 948-958.
- [6] Albinmousa, J., Jahed, H., Multiaxial effects on LCF behaviour and fatigue failure of AZ31B magnesium extrusion, *International Journal of Fatigue*, 67 (2014) 103-116.
- [7] Jahed, H., Varvani-Farahani, A., Upper and lower fatigue life limits model using energy-based fatigue properties, *International Journal of Fatigue*, 28 (2006) 467-473.
- [8] Hoffmeyer, J., Döring, R., Seeger, T., Vormwald, M., Deformation behaviour, short crack growth and fatigue lives under multiaxial nonproportional loading, *International Journal of Fatigue*, 28 (2006) 508-520.
- [9] Jiang, Y.Y., Hertel, O., Vormwald, M., An experimental evaluation of three critical plane multiaxial fatigue criteria, *International Journal of Fatigue*, 29 (2007) 1490-1502.
- [10] Albinmousa, J., Jahed, H., Lambert, S., Cyclic behaviour of wrought magnesium alloy under multiaxial load, *International Journal of Fatigue*, 33 (2011) 1127-1139.
- [11] Navarro, A., de los Rios, E.R., Short and long fatigue crack growth: A unified model, *Philosophical Magazine A*, 57 (1988) 15-36.