Application of the Cracking Energy Density (CED) multiaxial fatigue criteria for fretting fatigue life prediction: case of mono-contact steel/Al

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ABSTRACT. *The aim of this study is to use the multiaxial fatigue parameter to predict the fatigue life of the 6082 T6 aluminum alloy subjected to the fretting fatigue conditions. In addition to the critical plane based multiaxial fatigue parameter, Smith-Watson-Topper (SWT), the Cracking Energy Density (CED) criterion was used to predict fretting fatigue life. A volumetric approach were applied to take account the effect of the size of elementary volume.*

INTRODUCTION

Many mechanical or engineering components are subejected in service to the complex multiaxial, irregular stresses and strains where fretting is an important failure mode due to loading variation and vibration during long-time service. To estimate the fatigue life, various multiaxial criteria are available in the technical literature for structure integrity assassment and life estimation under such complex stress states [1, 2]. The field of multiaxial fatigue theories can classify into three catergories namely, amperical approaches, critical plane approaches and globale approaches.

Fretting fatigue damage occurs when two contacting wire surfaces are subjected to a normal clamping force and they undergo a relative movement on the two surfaces due to a cyclic tangential shearing. During fretting fatigue processes, multiaxial stress states are produced close to the contact zone. Near the contact surfaces there are areas in which there is also a non-proportional variation of the stresses [3]. This is why there are many authors have already used conventional multiaxial fatigue criteria to predict fretting fatigue strength [4–7] by considering the stress/strain states calculated at the surface near the training edge. The main limitation in the use of such an idea is that stresses/strains obtained on this point (training edge) were seen not to be capable of completely capturing the size effect phenomenon [8]. These results suggest that these methods will not be adequate for evaluating fretting fatigue life with different geometries, especially in the presence of a high stress gradient condition.

Araujo and Nowell [9] calculated total fatigue lives analytically and compared them with experimental values under fretting fatigue conditions calculated the total fatigue life was evaluated analytically using two critical plane models. From the analytical calculationsusing Smith-Watson-Topper (SWT) and Fatemi and Socie (FS) parameters, they demonstrated that the analytically calculated fatigue lives using surface stress distribution only was not adequate for predicting the fatigue lives, especially in the presence of a high stress gradient condition. The results suggest that these methods will not be adequate for evaluating fretting fatigue life with different geometries, especially in the presence of a high stress gradient condition.

The aim of this study is to use the multiaxial fatigue parameter to predict the fatigue life of the 6082 T6 aluminum alloy subjected to the fretting fatigue conditions. In addition to the critical plane based multiaxial fatigue parameter, *SWT*, the *Cracking Energy Density* (*CED*) [12] criterion was used to predict fretting fatigue life. A volumetric approach were applied to take account the effect of the size of elementary volume.

MATERIALS AND TEST PROCEDURE

An experimental device, based on a cylindrical-plane configuration was designed and rigidly mounted to a multiaxial servo hydraulic set up (**figure 1**). The pad is made of a tool steel Z160CDV 12, the cylinder radius being 12.7 mm. The material which was tested is an aluminum alloy 6082 − T6. The normal load (taken constant in this work) of 1 kN is applied by the pad on one side of the specimen using an hydraulic actuator. To avoid bending of the specimen due to the normal force, a bearing was placed on the opposite side of the specimen. A cyclic loading applied to the specimen is performed by using a second hydraulic actuator; it consists in a sinusoidal wave form of a frequency of 20Hz using two stresses ratios $R = 0.1$ and 0.01 . Two load cells attached to either side of the specimen in the direction of cyclic loading allow to determine the tangential force which is simply equal to the difference between the two measured forces. The crack initiation is assumed to occur when a certain limit of the amplitude variation of displacement has been reached, which leads to the detection of crack about 1 mm length.

Moreover, fatigue tests under uniaxial tension were also achieved in order to get a reference Wohler curve (S-N).

FRETTING FATIGUE ANALYSIS METHODLOGY

Finite Element Model

To determine the stress/strain field induced by the loading. A finite element model representing the case of fretting fatigue of a mono-contact are developped using an ABAQUS code [13], figure 2 represents this fretting fatigue assembly. The fretting pad is cylindrical with a radius of 12.7 mm. The pad is fixed in the x direction, the speciem is constraint in the left and fixed in the y direction.

A mapped mesh with element width of 5 µm was used near the area of contact in a region 3 mm (length) ×1 mm (depth). A triangular mesh was used else place. A four-node, plane strain quadrilateral element was used in all bodies: the specimen and the pad. The contact between the pad and the specimen was defined by using the master-slave algorithm between two surfaces. The master surface is on the fretting pad and the slave surface is on the fretting fatigue specimen.

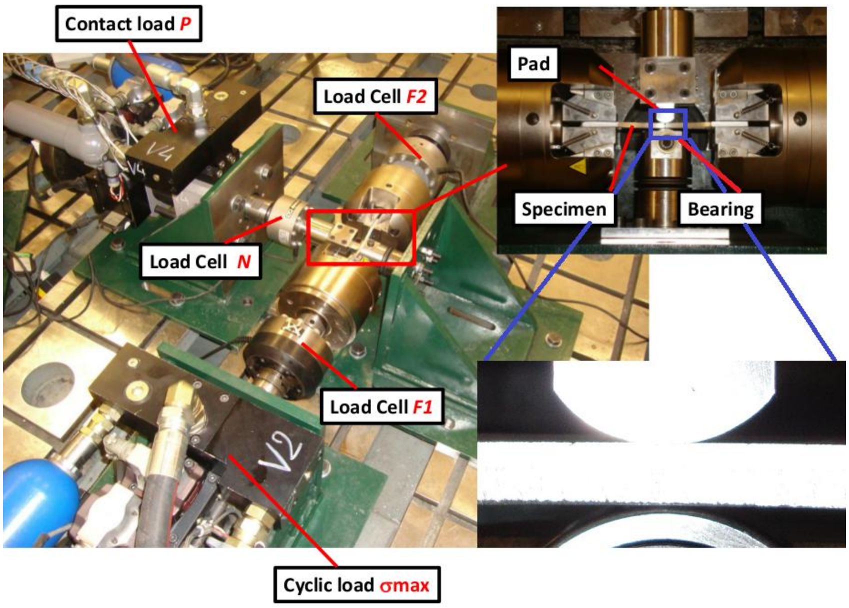

Figure 1 Fretting-fatigue setup.

Smith-Watson-Topper critical plane approach (SWT)[10]

Szolwinskl and Farris [4] modified the Smith-Watson-Topper parameter for the fretting fatigue crack initiation. This modified parameter assumed that crack initiation occurs on the plane where the product of normal strain amplitude, εa , and maximum normal stress, σmax is the maximum. Using the computed stresses and strains from the finite element analysis of the fretting fatigue experiments, this parameter was calculated at all planes ranging from $-\pi/2 \leq .\theta \leq .+\pi/2$ which provided this parameter's maximum value.

$$SWT = \sigma_{max}.\Delta\varepsilon/2 \qquad (1)$$

Where σ_{max} is the maximum stress normal to the critical plane and $\Delta\varepsilon$ is the range of strain normal to the critical plane

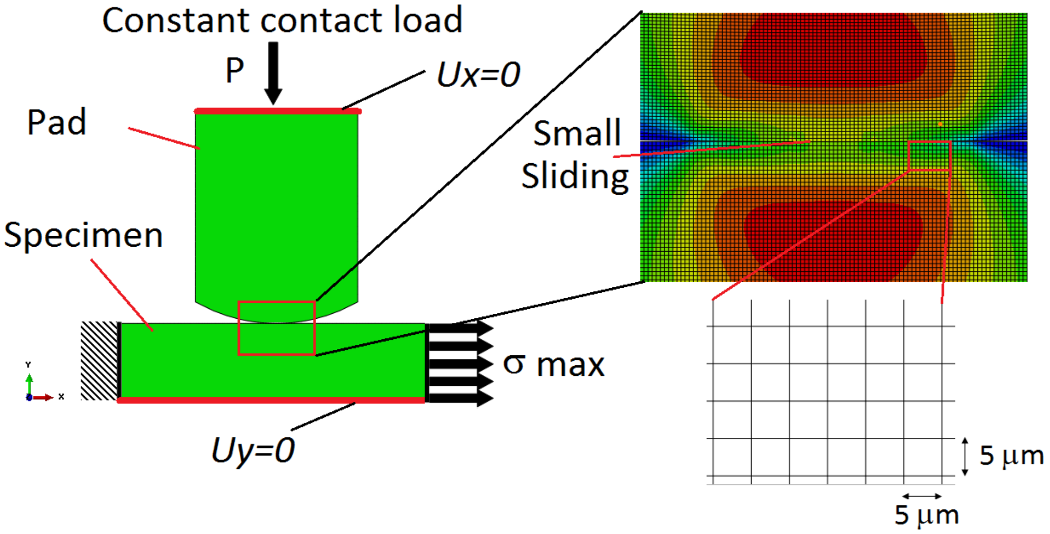

Figure 2 Illustration of FEM fretting-fatigue model of mono-contact.

Cracking energy density criterion (CED)[12]

Cracking energy density, W_c , proposed for the analysis of fatigue crack nucleation under multiaxial loading of rubber, represents the portion of the strain energy density that is available to be released by virtue of crack growth on a specified plane. It is defined in terms of its increment dW_c as:

$$dW_c = \vec{\sigma}\cdot\vec{\varepsilon} = \left(\vec{r}^{\,T}\cdot\overline{\overline{\sigma}}\right)\left(d\overline{\overline{\varepsilon}}\cdot\vec{r}\right) \qquad (2)$$

where r $\vec{r}$ is a unit vector that defines the normal to the virtual crack plane, $\overline{\overline{\sigma}}$ is the stress tensor, $d\overline{\overline{\varepsilon}}$ is the strain tensor increment.

It can be seen that dW_c depends on both the strain state, and the cracking plane of interest. A detailed explanation of the algorithm is presented in reference [14].

Then, an alternative averagin technique are used by arguing that high stresses must be sustained over a critical volume, Vc , in order for a crack to breach the strongest microstructural barrier [8]. A square area element surrounding the initiation site is used to delineate the volume (figure 3).

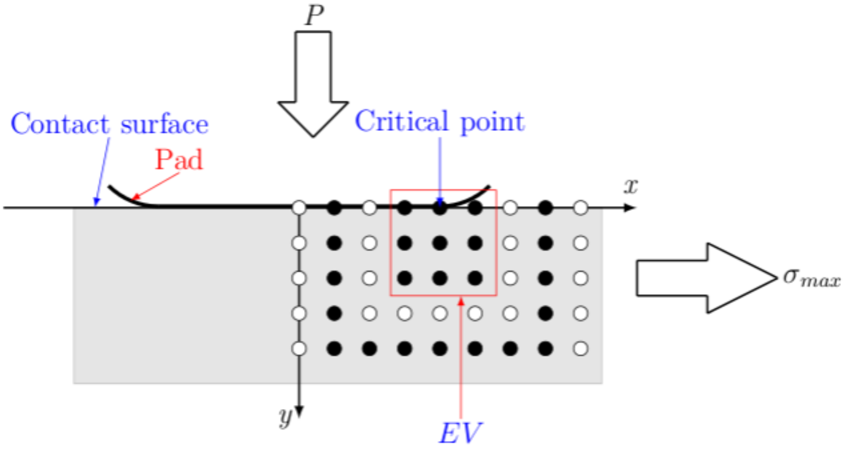

Figure 3 Schematic description of averaging method.

RESULTS AND DISCUSSIONS

Establishing a correlation between the fretting fatigue lifetime and plane fatigue is always desirable since it reduces the fretting fatigue experiments, which are significantly time consuming and relatively expensive to achieve.

The two different parameters (SWT) and (CED) previously introduced were used to predict the lifetime in the fretting fatigue conditions. The crack initiaion location was determined by observing the maximum of value of the SWT and CED parameters on the surface. Figure 4 shows the relationship between SWT, CED averaging parameters and life crack initiation N. This parameters were averaged over different critical distances dc.

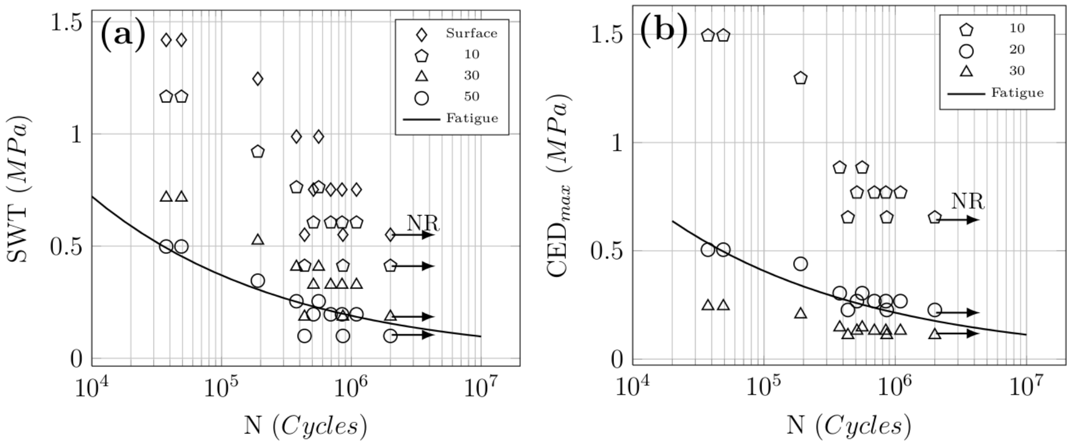

Figure 4 Schematic Total life versus contact size.

The evolution of the maximum (CED) and (SWT) value as function of the orientation of the normal of plane (θ is angle between the normal of the crack plane (or the normal of virtual crack) and the cyclic loading direction) is shown in **figure 5 a and b** for different cyclic loadings and for a particular value of the loading ratio (R=0.1). Is also plotted the evolution obtained on the contact surface. Note that the same result in terms of critical plan orientation was obtained using averaging method at 20 µm for (CED) and at 50 µm for (SWT). A maximum value is clearly pointed out corresponding to the critical plane depicted by this parameter. This figure also shows that the plane orientation (identified by the normal of plan) remains fairly constant (56°+/-2) in the case of (σ_{max} < 240 MPa) for (CED) and (67°+/- 2°) for (SWT) in all cases of the loading. For high cyclic loading (σ_{max} >240 MPa), the plane orientation has changed in the (CED) case. This deviation is certainly a result of the presence of the plastic deformation which has a major role for crack nucleation. As these values of applied load are large, the effect of the plastic deformation on the crack initiation must not be disregarded.

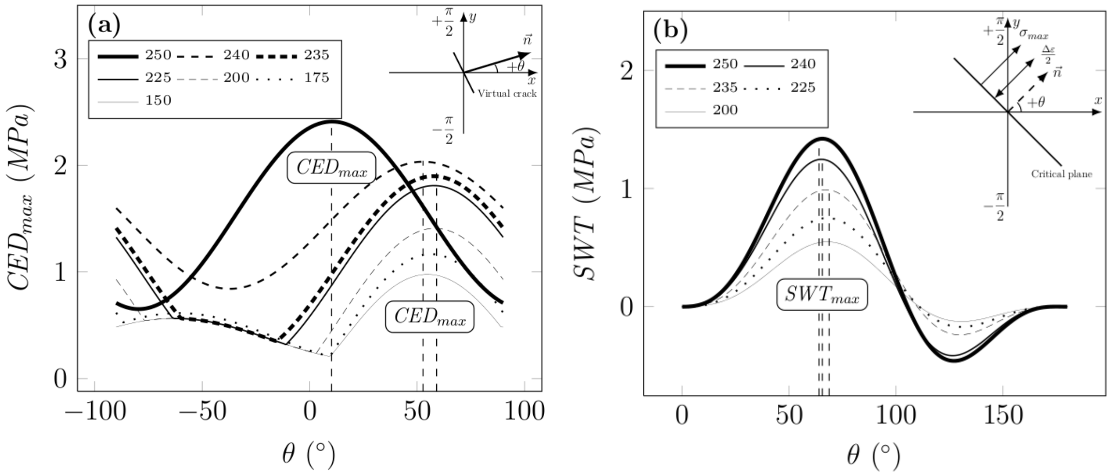

Figure 5 Evolution of (a) CED (b) SWT parameters versus plane orientation.

It is clear that the use of the averagin method, for the low cycle fatigue, provides an adjustment of results with respect to the plain fatigue curve. The parameter SWT seem to provide a best fit to the results when averaged over dc = 50 µm, where the curve in the range of data between 5 × 104 and 5 × 105 cycles. Beyond, the prédiciton of life is underestimated. However, CED parameter gives good correlation with the fatigue curve when averaged over dc = 20 µm.

Figure 6 shows comparaison of the calculated and experimental lives between SWT and CED parameters. A solid line represents a perfect conformity of results, and the dashed lines represents a scatter band with coefficient of 3, Pexp = 3 (1/3).

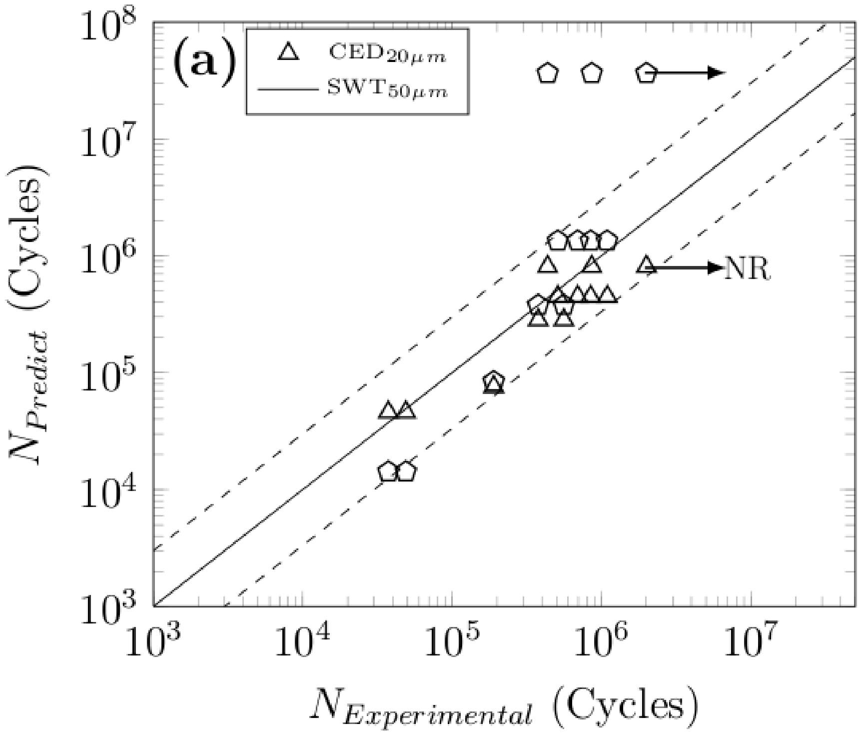

Figure 6 A comparaison between SWT and CED life prediction.

CONCLUSIONS

In this study, two different multiaxial fatigue parameters, SWT and CED, were used to see their ability to predict fretting fatigue crack nucleation. A volumetric approach is used to account for the stress gradient near the contact surface. Once the averaged stress values were calculated over the critical distance dc, the averaged value of the critical plane parameter was calculated.

We can show that the quantity of multiaxial parameters have an inverse relationship with the dimension of process volume.

Among these parameters, the CED was demonstrated as an appropriate parameter to estimate fatigue life when dealing with fretting fatigue.

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