

# Study on Fatigue Life of Aluminum Alloy Considering Fretting

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**Abstract.** To study the influence of fretting on Aluminum Alloy, a global finite element model considering fretting was performed using the commercial code ABAQUS. With which a new model for predicting fretting fatigue life has been presented based on friction work. The rationality and effectiveness of the model were validated according to the contrast of experiment life and predicting life. At last influence factor on fretting fatigue life of aerial aluminum alloy was investigated with the model. The results revealed that fretting fatigue life decreased monotonously with the increasing of normal load and then became constant at higher pressures. At low normal load, fretting fatigue life was found to increase with increase in the pad radius. At high normal load, however, the fretting fatigue life remained almost unchanged with changes in the fretting pad radius. The bulk stress amplitude had the dominant effect on fretting fatigue life. The fretting fatigue life diminished as the bulk stress amplitude increased.

## 1. Introduction

Fretting, the interfacial damage process that arises from a tripartite interaction among wear, corrosion and fatigue phenomena, is experienced by nominally-clamped surfaces subjected to oscillatory loads or vibrations. Fretting fatigue failures are commonly observed in fastened joint of mechanical industry, aviation and spaceflight industry, bridge engine, and so on. Fretting fatigue can greatly reduce fatigue life of materials, and has been one main disaster of many key parts.

For the study of fretting fatigue, it was focused on the mechanism before 1990, after which some reports about fatigue life started to appear. Based on experiment, Ruiz[2] advanced fretting fatigue damage parameter, with which the site of probable crack initiation was located. Christopher D. Lykins[3] investigated the fretting fatigue life of Ti-6Al-4V material with Manson-Coffin formula, this method was visual, but it was not easy to actualize. Harish Ganapathy[4] built the finite element model of skin and rivet, calculated stress distribution and predicted crack initiation life. At home, He Mingjian [5] studied the method of attached stress for determining fretting fatigue life, in this method the fretting fatigue damage was attached on the bulk stress, and the S-N curve was built with the total stress. Liu Jun[6] investigated fretting fatigue crack propagation life based on fracture mechanics method.

In this article, a new model for predicting fretting fatigue life was presented based on the factor of friction work. Then the rationality and effectiveness of the model were validated according to the contrast of experiment life and predicting life. At last influence factor on fretting fatigue life of aerial aluminum alloy LY12CZ was investigated with the model.



## 2. Prediction Model

### 2.1. Modeling Setup

Ordinarily, there are two aspects to consider of predicting fretting fatigue life, one is to locate the site of crack initiation, and the other is the modeling setup. For the study of the location of crack formation, Ruiz made through the Experimental Analysis of Fretting Fatigue comprehensive parameter,  $K$ , defined as  $K = \mu \sigma_N \delta \sigma_\tau$ . Where  $\mu$  is the coefficient of friction,  $\sigma_N$  is the normal stress,  $\delta$  is the relative slip distance,  $\sigma_\tau$  is the tangential stress. Many studies have indicated that Ruiz comprehensive parameter  $K$  can be relatively good description of the formation of fretting fatigue crack location.

Structure life is mainly the results of stress concentration and fretting damage. Therefore, in order to predict fretting fatigue life more accurately, it must be considered the impact alternating stress and the role of fretting wear on the fatigue life. When there is no fretting damage, and without consideration of environmental and other factors, the fatigue life of the structure is equal to the life of the role of a separate fatigue load,  $N_0$ . When considering the impact of fretting wear, the fatigue life will decrease, and the total life should be the difference of the two separate lives, that is,

$$\Delta N = N_0 - N = N_w = f(w) . \quad (1)$$

$f(w)$ . To calculate the influence of fretting damage on fretting fatigue life, the friction work parameter,  $w$ , was introduced.  $N_w$  should be a function of the variable,  $w$ , denoted by  $f(w)$ . Where  $w$  was the friction work for each cyclic loading, it could be expressed as:

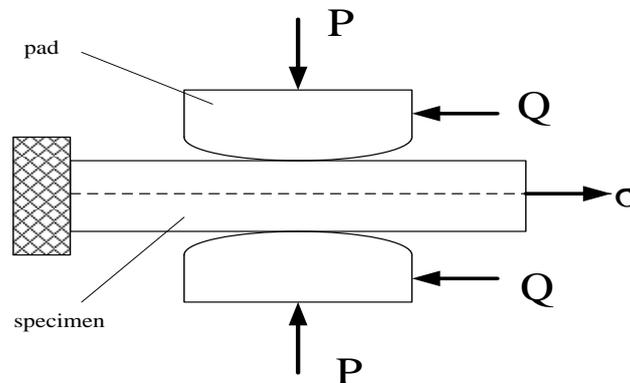
$$w = 0.5 \mu (\sigma_{\max} - \sigma_{\min}) (\delta_{\max} - \delta_{\min}) . \quad (2)$$

Where  $\sigma_{\max}$ ,  $\sigma_{\min}$ , respectively maximum and minimum values of the normal stress,  $\sigma_{\max}$ ,  $\sigma_{\min}$ , respectively maximum and minimum relative displacement, which could be obtained using finite element method.

### 2.2. Finite Element Model.

For the application of the models to predict fretting fatigue life, it is important to determine the stress distribution in the interface of contact region. However, it is in general difficult for the contact problem to obtain accurate analytical solutions. In this paper the finite element method was adopted, and the analysis software was ABAQUS.

The finite element model simulated the experimental configuration shown in Fig.1, one end of the specimen is fixed, the other is subjected to the cyclic axial stress  $\sigma$ . Stress ratio is 0.1. The material of all the fretting specimens and pads used in this study was aerial aluminum alloy LY12CZ, with a modulus of elasticity of 68GP, and Poisson's ratio of 0.33. The specimen has a cross-section 10mm by 4mm, and the pad cross-section with 10mm by 10mm.



**Figure 1.** Schematic of a Fretting fatigue model

Four noded plane strain elements were used. The element size within the contact region was  $12\mu\text{m} \times 12\mu\text{m}$ . The model had 57586 elements in total. The ABAQUS Standard analysis code was used

to perform the analysis and the contact pair option was used to model the contact. The pad was selected as the master surface, and the specimen the slave surface. The coefficient of friction was assumed to remain constant at 0.65.

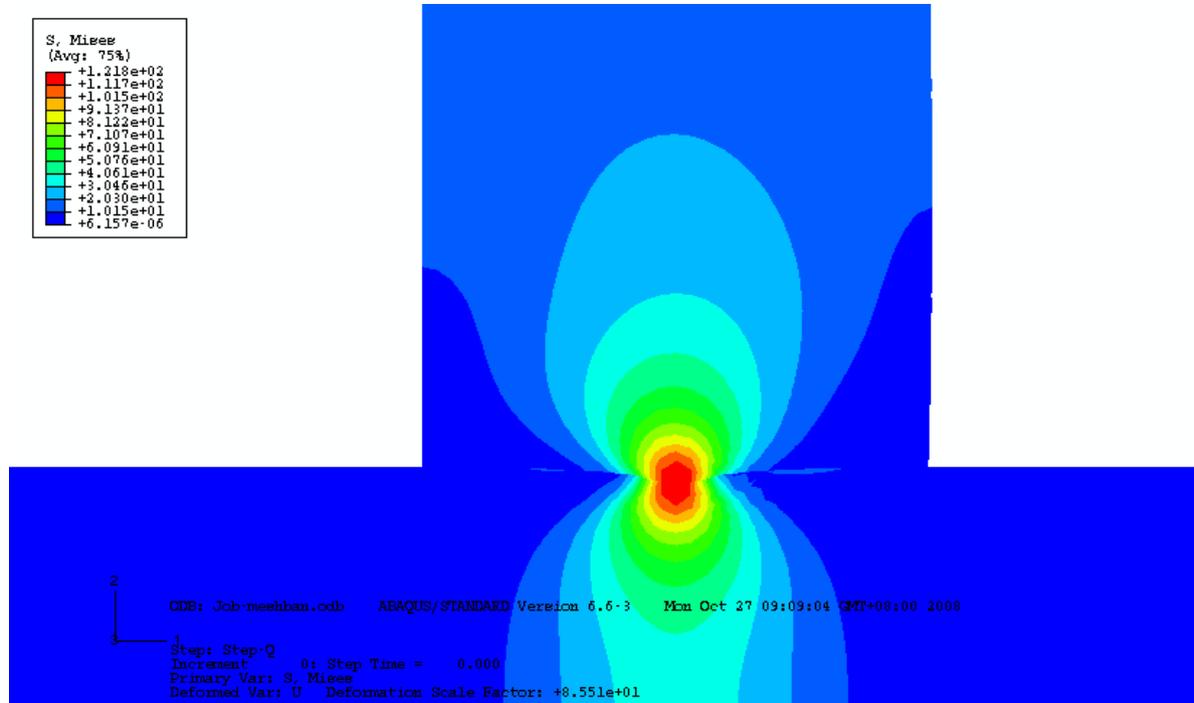


Figure 2. Stress contours

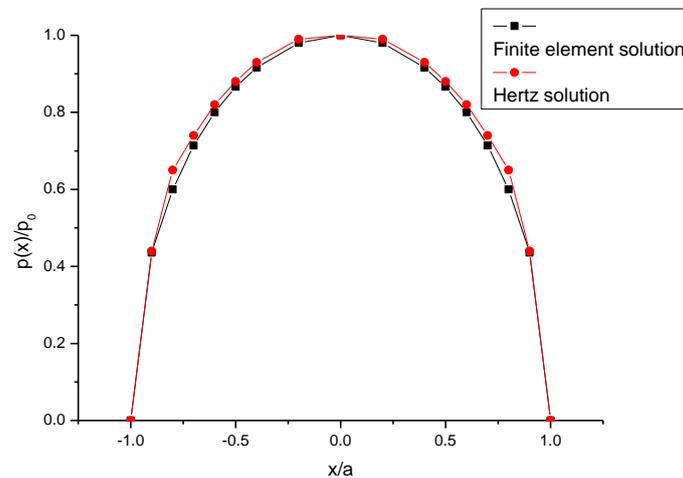


Figure 3. Comparison between FEM and analytical solutions

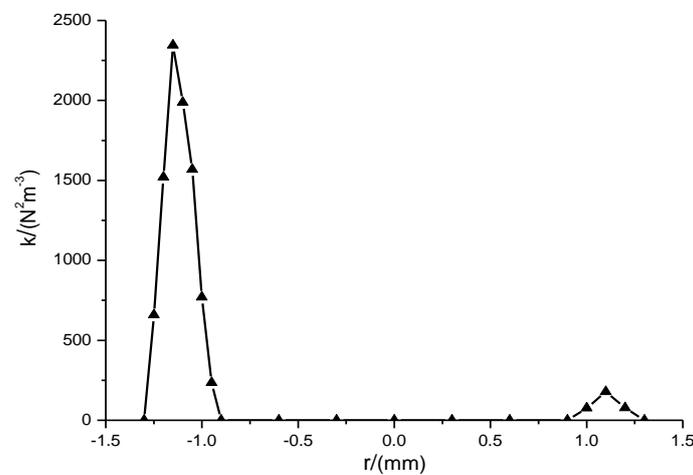
The loads were applied in three steps. In the first step, the normal load  $P$  was applied on the pad to establish the contact. In the second step, the maximum shear force,  $Q_{max}$ , and the maximum bulk stress,  $\sigma_{max}$ , were applied to match the experimental maximum cyclic load conditions. Finally, the minimum shear force,  $Q_{min}$ , and the minimum bulk stress,  $\sigma_{min}$ , were applied to match the experimental minimum cyclic load conditions. A Master-Slave algorithm was used to carry out the contact analysis.

In order to verify the correctness of finite element analysis results, the finite element solution was compared to the Hertz solution with surface contact stress  $p(x)$  and contact half width  $a$ . The calculate

result of a with finite element method (1.3mm) was very close to Hertz solution(1.31mm), the stress contours at the end of the first analysis step was shown in Fig.2 , it can be seen that the maximum stress appears in the center of the contact surface. Fig.3 showed the corresponding distribution of normal stress for the Hertz solution and the numerical solution, which demonstrated that the two results were also very close. All these indicated the model was correct, and the calculation model could be used for further analysis.

### 2.3. Fatigue Life Prediction Considering Fretting

Fig.4 showed the distribution of Ruiz damage parameter  $K$  throughout the contact region, it could be seen that there were two peaks of  $k$ ,  $2345\text{N}^2\cdot\text{m}^{-3}$  and  $178\text{N}^2\cdot\text{m}^{-3}$ , respectively. The distance from the contact center,  $r$ , is  $-1.15\text{mm}$  and  $+1.15\text{mm}$ . Cracks would produce where  $K=2345\text{N}^2\cdot\text{m}^{-3}$ , corresponding to the point, that was,  $r = -1.15\text{mm}$ .  $N_0$  was calculated with nominal stress method based on the stress distribution at this point. The data for the model were presented in Table I and Table II.



**Figure 4.** Fretting damage parameter

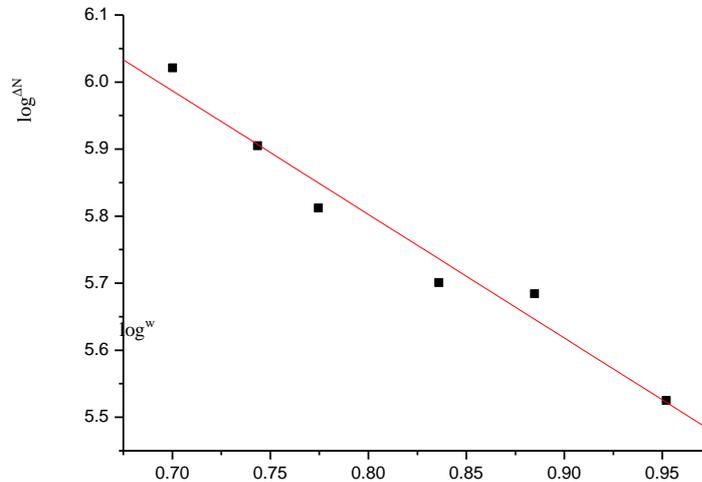
**Table 1.** Computation of the friction work

NO.	$\sigma_{\max}/$ MPa	$\sigma_{\min}/$ MPa	$\delta_{\max}/$ $\mu\text{m}$	$\delta_{\min}/$ $\mu\text{m}$	$w/$ $\text{N}\cdot\text{mm}/\text{mm}^2$
1	218.5	12.3	125.7	11.3	7.671
2	245.8	13.5	98.1	9.5	8.953
3	185.6	7.5	94.1	7.4	5.019
4	196.3	8.2	107.3	10.6	5.949
5	207.4	9.4	116.5	10.9	6.855
6	175.2	6.9	108.2	9.8	5.398

**Table 2.** Data for the model

NO.	$N/$ $10^5$	$N_0/$ $10^5$	$\Delta N/$ $10^5$	$\log^{\Delta N}$	$w$	$\log^w$
1	4.71	9.53	4.83	5.68	7.671	0.885
2	2.12	5.47	3.35	5.52	8.953	0.952
3	6.03	16.55	10.52	6.02	5.019	0.701
4	5.75	12.23	6.48	5.81	5.949	0.774
5	4.23	9.23	5.01	5.70	6.855	0.836
6	6.21	14.2	8.03	5.9	5.398	0.743

The difference  $N_0$  and  $N$  were plotted in Figure.5 against the friction work,  $w$ , in the dual-logarithmic coordinates. It was observed that the curve was approximately in liner relationship, and the correlation coefficient is 0.98284.



**Figure 5.**  $\Delta N$  to friction work  $w$

The expression by fitting was:

$$\text{Log}^{f(w)} = \text{Log}^{\Delta N} = 7.728 - 1.844 \text{Log}^w . \quad (3)$$

After finishing, it was:

$$f(w) = \Delta N = 5.3456 \times 10^7 w^{-1.844} . \quad (4)$$

Thus, the fretting fatigue life prediction model for aviation aluminum alloy LY12CZ was:

$$N = N_0 - 5.3456 \times 10^7 w^{-1.844} . \quad (5)$$

In order to verify the prediction model established above, the other three sets of experimental data were discussed with the same method. The calculated  $w$ , prediction life, experimental life, and the error were shown in Table III. It could be seen that the predicted values were larger than the experimental values, and the maximum error was 18.01%, which indicated that the fretting fatigue life prediction model established in this article was secure, reasonable and effective.

**Table 3.** Comparison between prediction and experiment values

NO.	$w/$ $N \cdot \text{mm}/\text{mm}^2$	$N_0/$ $10^5$	$N_{\text{prediction}}/$ $10^5$	$N_{\text{experiment}}/$ $10^5$	error/ %
7	5.051	15.73	6.15	5.20	18.01
8	7.291	9.42	4.55	3.99	13.65
9	4.886	16.64	6.47	5.56	16.35

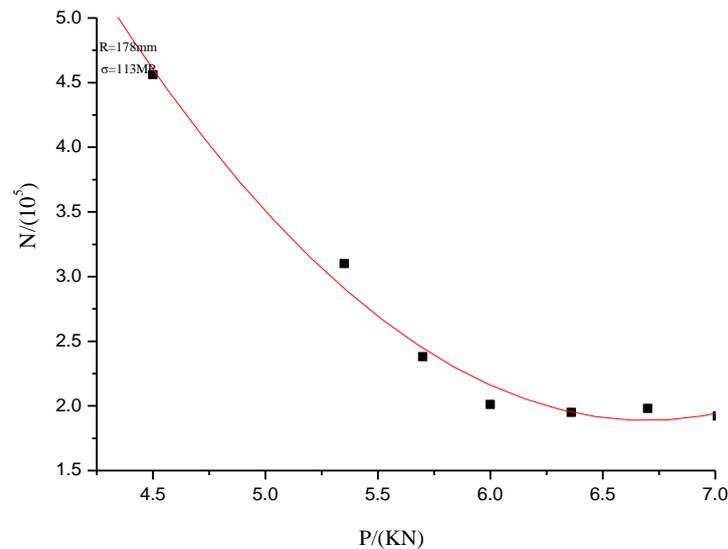
### 3. Influencing Factors

The phenomenon of fretting fatigue is not completely understood because several factors can affect the fretting behavior of materials. There are as many as fifty factors that can affect the fretting process. Some of these factors are normal load, coefficient of friction, slip amplitude, cyclic bulk stress, stress ratio, tangential shear stress at the interface, and the number of fretting cycles. Many experimental studies have suggested that there are strong relationships between some of these factors. These interrelationships imply that the effects of each individual factor on the fretting fatigue behavior should

be investigated systematically. Three factors were discussed in the following paragraphs with the model proposed in the front.

### 3.1. The Effect of Contact Load

The effect of contact load on life was shown in Fig.6. It could be seen that in the same bulk stress  $\sigma=113\text{MPa}$  and the pad radius  $R=178\text{mm}$ , the fretting fatigue life decreased monotonously with the increasing of the contact load and then became constant at higher normal load. The reason why this phenomenon occurs was mainly in the following two parts.



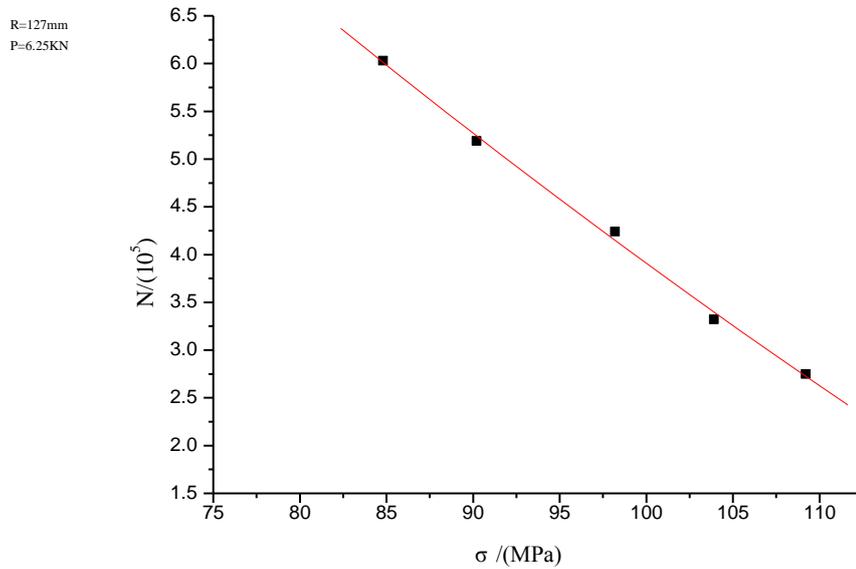
**Figure 6.** Effect of normal load on life

(1) Friction increases with the increasing of contact pressure, so that the power of crack formation and expansion increases. But the friction will not increase unboundedly, so they should be proportional within a certain range.

(2) Slip amplitude will decrease when the contact pressure get too much, for balancing the two power the fatigue life may not continue to decline.

### 3.2. The Effect of the Bulk Stress

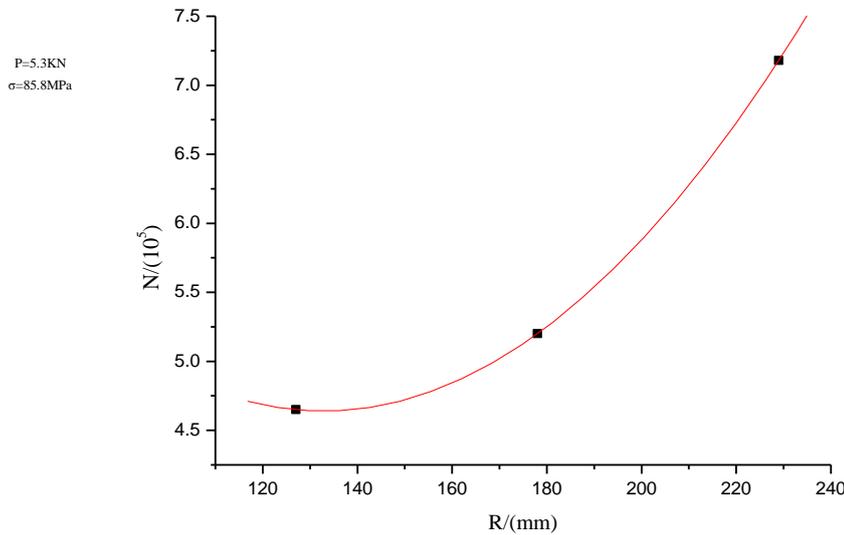
In order to analyze the relationship between fretting fatigue life and the bulk stress, 5 sets of life with different axial stress was calculated with  $P=6.275\text{KN}$  and  $R=127\text{mm}$ , the result was shown in Fig.7. It was clear that fretting fatigue life decreased with the increase of the bulk stress amplitude, which was consistent with the result of Wallace and Neu in the study of Ti-6Al-4V. This indicated that the bulk stress amplitude was the most important effecting factor on fretting fatigue life.



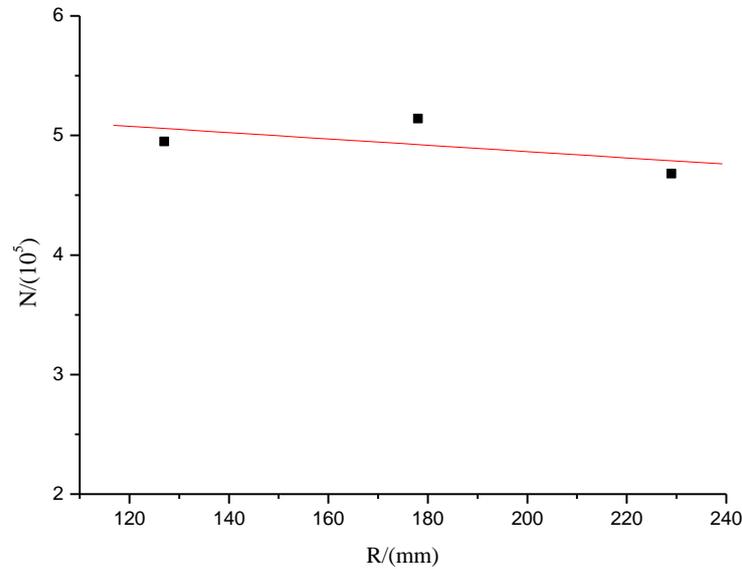
**Figure 7.** Effect of the bulk stress amplitude on life

*3.3. The Effect of Pad Radius*

For the cylindrical pad, the pad radius was also an important effect factor on the fretting fatigue life. The calculating result was shown in Fig.8 in the condition of two kinds of normal load and three kinds of pad radius. It can be seen that for a lower normal load, life increased with the increase of pad radius. At a higher normal load, however, fretting fatigue life remained almost unchanged with changes in the fretting pad radius.



(a) low normal load



(b) high normal load

**Figure 8.** Effect of pad radius on life

#### 4. Conclusions

One reasonable and effective prediction model of fretting fatigue life was set up according to use friction work parameter and Ruiz damage parameter with finite element method. Based on the theoretical and experimental observations following conclusions are drawn:

(1) With the increase of contact pressure, fretting fatigue life decreases rapidly, and then becomes constant at higher pressures.

(2) The bulk stress amplitude has the dominant effect on fretting fatigue life, and the fretting fatigue life decreases with increase of the bulk stress amplitude.

(3) At low normal load, the fretting fatigue life is found to increase with increases in the pad radius. At high normal load, however, fretting fatigue life remains almost unchanged with changes in the fretting pad radius.

#### 5. References

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