Scientia Iranica B (2023) 30(4), 1255–1264

SCIENTIA
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Sharif University of Technology
Scientia Iranica
Transactions B: Mechanical Engineering
http://scientiairanica.sharif.edu

A new model for predicting fretting fatigue crack initiation life based on effective slip amplitude

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Received 1 June 2022; received in revised form 14 October 2022; accepted 5 December 2022

KEYWORDS
Fretting fatigue;
Slip amplitude;
Life prediction;
Crack initiation;
Damage parameter;
Damage severity factor.

Abstract. In this study, a new model is developed for fretting fatigue crack initiation life prediction based on the slip amplitude as a macroscopic feature of the contact interfaces. The main difference between the presented model and many other fretting fatigue life prediction models is the focus on the fretting specific characteristics. In this model, a damage parameter is combined with a damage severity factor to obtain a new fretting fatigue crack initiation life prediction parameter. To investigate the accuracy of this new parameter, a series of fretting fatigue tests were conducted. Also, crack initiation life data from the literature were added to enhance parameter accuracy investigation. It was shown that the effective slip amplitude was an unbiased geometric-independent parameter in fretting fatigue crack initiation life prediction. Also, comparison of the prediction results from the effective slip amplitude with those of Smith-Watson-Topper and Ruiz parameters illustrated that the new parameter could outperform available fretting fatigue life prediction parameters.

1. Introduction

Fretting is a relative movement that occurs between two contacting solid surfaces and fretting fatigue is the combination of fretting and fluctuating stresses and strains [1]. This phenomenon results in surface wear or/and cracking and a remarkable reduction in the life of contacting components. Although fatigue life assessment and prediction of components and structures have become relatively routine tasks and there exist life models that have been accepted universally [2,3], prediction of fretting fatigue life is not an easy task [4,5].

Many different research and methods have been conducted on predicting fretting fatigue behavior and life [6–15]. Ruiz et al. [6] introduced two purely empirical parameters that were used in different engineering applications due to their simplicity [5]. They combined normal and tangential stresses with the slip amplitude in different manners and proposed their parameters. Vidner and Leidich [7] modified Ruiz fretting specific parameters for a key-shaft-hub problem under the action of torsional and bending moments.

Hojjat-Talemi and Wahab [8] used an uncoupled damage evolution rule along with the finite element simulation to obtain the value of the fretting fatigue crack initiation life parameter. Majzoobi and Minaii [9] attempted to apply plain fatigue data along with the Fatemi-Socie (FS) multi-axial fatigue parameter [3] to predict the fretting fatigue life of Al7075-T6 specimens.

In a recent study, Pinto et al. [10] combined critical distance theory with a multiaxial fatigue parameter and proposed different methods for predicting the fretting fatigue life of components made from Al2024-T345 on a cylinder-on-flat contact problem.

Lin and Xu [11] developed a new damage con-

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doi: 10.24200/sci.2022.60534.6849

stitutive model to predict the fretting fatigue crack initiation life. In their study, an equivalent damage model was used instead of moving mesh to account for wear effect. This resulted in a lower computation cost, while prediction accuracy was not reduced. Rangel et al. [12] calibrated the plain fatigue strain-life curve of Al 7075-T651 for predicting initiation and total fretting fatigue life. They suggested an iterative procedure to obtain the initial crack length and the Smith-Watson-Toper (SWT) method [2] was used to estimate the location and orientation of the initiated crack. The crack propagation phase was assumed to be straight and perpendicular to the surface and propagation life was determined using Paris' law.

The dovetail joint is one of the most attractive cases of fretting problems. Glodek and Talemi [16] investigated available data in the literature and presented an applied method for estimating the fretting fatigue life of dovetail joints. They obtained stress data of the contact problem from finite element method simulation and used coupon scale test data for life prediction. They concluded that this approach could be a good estimation if coupon test data were chosen, carefully. Shen et al. [17] used an accumulative damage model to consider the debris layer evolution effect on the fretting fatigue life of Ti-6Al-4V specimens. They found that numerical prediction of fretting fatigue lifetime with debris layer was slightly better than without it.

Nowell and Nowell [4] noted that available methods were not generally accepted; therefore, they proposed a new specific approach to fretting fatigue life prediction based on a neural network.

While there are many different methods for fretting fatigue crack initiation and propagation life prediction, they can be categorized into some general approaches. In a comprehensive study, Bhatti and Wahab [18] categorized fretting fatigue life prediction models into four different categories: fretting specific parameters, continuum damage mechanics approach, stress invariant approach, and critical plane approach. In this regard, Sunde et al. [5] divided fretting models into six methods: (i) design parameters, (ii) critical plane methods, (iii) analytical methods, (iv) asymptotic methods, (v) notch analog model, and (vi) crack analog model. In another study, Ding et al. [19] broadly divided predictive approaches into (i) multiaxial fatigue models and (ii) surface damage models.

Although these categorizations may seem to be different, they all have a common group for specific fretting parameters, called "surface damage models" by Ding et al. [19], "design parameters" by Sunde et al. [5], or "fretting specific parameters" by Bhatti and Wahab [18].

The available fretting fatigue life models, except for a limited number (e.g., [6]), often try to establish analogies between fretting fatigue and other well-known phenomena and adapt their life prediction models to the fretting fatigue life problem. Multiaxial fatigue is one of the most similar phenomena for fretting fatigue because of loading, boundary conditions, and stress distributions in the fatigue specimen. Since the best multiaxial fatigue life models are modified plain fatigue life models, one may think that there could be some modifications that generalize those models to predict fretting fatigue life. This may make the main difference between fretting fatigue and multiaxial fatigue irrelevant, facilitating the possibility of sliding in the location of normal force application.

Also, life models with computational complexity are not favorable in engineering applications. A good life model in terms of engineering is the one with minimum computational cost and maximum physical sense, examples of which are S-N approach and Basquin's equation. In order to propose such a life model, the approach should be focused on the macroscopic parameters of the problem so that it can be easily computed and used in engineering applications and structural design.

One of the distinguishing parameters of fretting fatigue damage characteristics is the relative slip amplitude, which plays a vital role in determining the fretting regime. The authors of this paper argue that it is possible to use this parameter as a fretting fatigue life predictor, which is the goal of the present study. In that respect, a new specific fretting fatigue parameter is introduced based on relative slip amplitude and then, the effectiveness of this new parameter is investigated by setting up a series of experimental tests and finite element analyses. Finally, the results of this study and other investigations from the literature are used for parameter accuracy evaluation.

2. Slip-based fretting fatigue life prediction parameters

According to ASTM E2789-10 [1], slip is the local movement of surfaces in contact, while the relative slip is the amount of tangential displacement between a point on the interface of one body and a point on the surface of the second body. Relative slip divides fretting into three different regimes: Partial Slip Regime (PSR) which experiences cracking, Gross Slip Regime (GSR) which is characterized by wear debris, and Mixed Fretting Regime (MFR) which experiences both of these.

The life of components in contact under fretting fatigue conditions varies widely in different fretting regimes. Vingsbo and Söderberg [20] summarized test data generated by many researchers and presented a graph of variation of wear and fatigue life to slip amplitude. They showed that fretting fatigue life decreased exponentially by simply increasing the relative slip amplitude in the region of MFR and PSR.

Ruiz et al. [6] used the slip amplitude parameter for fretting fatigue life prediction of a dovetail joint. They introduced the product of shear stress (τ) and relative slip range (δ_r) at the contact interface as shear-slip work and multiplied it by the tangential stress (σ_t) to estimate the fretting fatigue life of the dovetail joint. They obtained two similar fretting fatigue life parameters χ and κ which are the 1st and 2nd Ruiz parameters, respectively as shown in Eq. (1):

$$\chi = (\sigma_t)_{\max}(\tau\delta_r)_{\max},$$

$$\kappa = (\sigma_t\tau\delta_r)_{\max}. \tag{1}$$

Vidner and Leidich [7] enhanced Ruiz parameters for predicting key-shaft-hub fretting fatigue life. They introduced specific frictional power to be the integration of the shear-slip work during a complete load cycle and multiplied it by SWT and FS parameters. They obtained two enhanced fatigue-fretting damage parameters and found that these new parameters successfully predicted the fretting fatigue life of key-shaft-hub connections.

Although these have some beneficial understandings about parameters affecting fretting fatigue life, they are limited to specific problems.

2.1. Effective slip amplitude

Considering previous studies, some notable findings on the relation between fretting fatigue life and the slip amplitude are obtained:

- From [6,7], it can be seen that the fretting fatigue life is not merely dependent on the stress distributions and slip amplitude should be involved, too;
- Vingsbo and Söderberg [20] showed that the relative slip amplitude was a good representative of the fretting damage at the macroscopic level;
- Although relative slip amplitude defines the fretting regime and characterizes fretting damage type, it does not say anything about Damage Severity (DS). This may be the reason why it is possible to have two widely different lives at the same relative slip amplitude. Such a condition is shown in experimental data in Section 4.

Therefore, as a general methodology, a fretting fatigue life predictor should combine a damage parameter with a DS factor in order to:

(1) Distinguish different fretting regimes and damage types and;
(2) Apply the severity of the loading conditions and differentiate between two identical damage types.

As mentioned before, relative slip amplitude is generally accepted as a fretting fatigue damage parameter, but must be enhanced by a DS factor to make a suitable parameter for fretting fatigue life assessment.

Fretting contact pressure mainly affects the slip amplitude and the DS is essentially dependent on the fatigue stresses. Thus, the DS can be defined as the ratio of the fatigue stress to the material yield strength.

Walker effective stress [21] is one of the most-used methods to combine the cyclic fatigue stresses into a single nominal stress component, S_e, as shown by Eq. (2):

$$S_e = S_{\max}(1 - R)^m, \tag{2}$$

where m is a material fitting parameter, usually around 0.5 in value for metals [22], R is the stress ratio of the loading, and $S_{\max}$ is the maximum fatigue stress. Therefore, the DS factor can be written as in Eq. (3):

$$DS = S_e/S_y, \tag{3}$$

where S_y is the material yield stress. By combining the damage type parameter with the DS factor, we obtained a new parameter, the effective slip amplitude, δ_e, as shown by Eq. (4):

$$\delta_e = \delta^{DS}. \tag{4}$$

In the above equation, δ is the relative slip amplitude defined by ASTM [1] to be half of the relative slip range (δ_r). The fretting fatigue crack initiation life prediction model based on the effective slip amplitude can be defined by Eq. (5):

$$\delta_e = a_1 N_i^{b_1} + a_2 N_i^{b_2}, \tag{5}$$

where the coefficients (a_1, a_2) and exponents (b_1, b_2) of the life model should be determined based on the experimental data and N_i is the crack initiation life. Figure 1 shows the life prediction process using this new parameter. At first, damage type should be determined from the relative slip amplitude, which can be approximated using Finite Element Analysis (FEA). If the fretting condition lies in the partial slip or MFR, the DS is determined from Eq. (3). The next step is determining δ_e from Eq. (4). Finally, the fretting fatigue crack initiation life can be predicted by Eq. (5).

The life prediction capability of this new parameter is investigated through a series of experimental tests followed by numerical simulation, to be presented in the following sections.

3. Experimental and numerical procedures

3.1. Experimental details

Many engineering applications deal with flat-on-flat contact conditions. This type of contact condition is simulated in our experiments by holding bridge-type flat pads in contact with dog bone specimens through a proving ring. Specimens and their fretting pads were wire cut from Ti-6Al-4V sheets. Their geometry and the experimental setup are shown in Figure 2 and Figure 3, respectively.

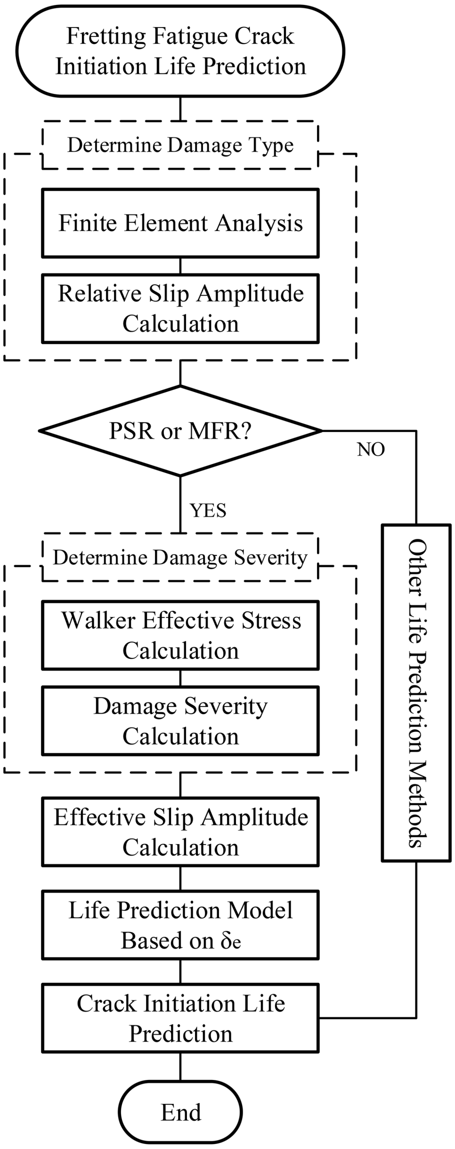

Figure 1. Fretting fatigue crack initiation life prediction algorithm.

Also, the mechanical properties of Ti-6Al-4V alloy were obtained by the tensile test conducted on the standard specimen before fretting fatigue tests, as shown in Table 1.

Contact surfaces of the pads and gauge sections of the specimens were ground at six different levels (from 400 to 2000) followed by mirror polishing to remove micro-cracks induced by the cutting process.

Although friction coefficient may vary during the fretting process [23], we assumed a stabilized friction between the pad and specimen surfaces, which was measured via two different interrupted fretting fatigue tests at 50000 and 75000 load cycles, respectively. Measurements were performed based on ASTM G115-10 [24] and it was determined that the coefficient of friction stabilized around 0.4 (Figure 4).

Uninterrupted fretting fatigue tests were con-

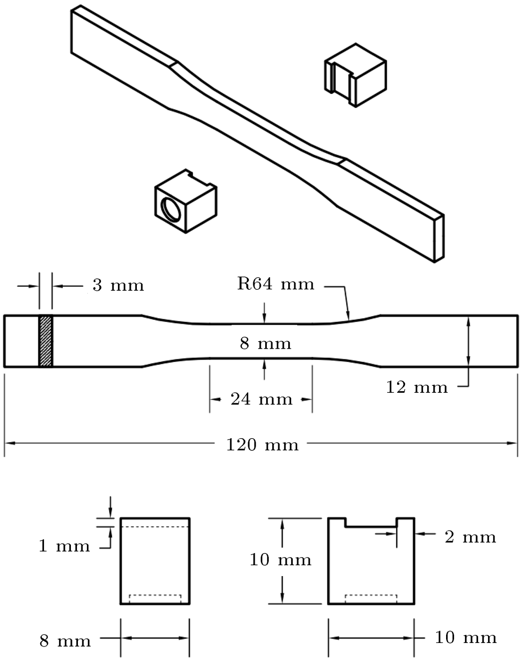

Figure 2. The geometries of pads and specimens used in fretting fatigue tests.

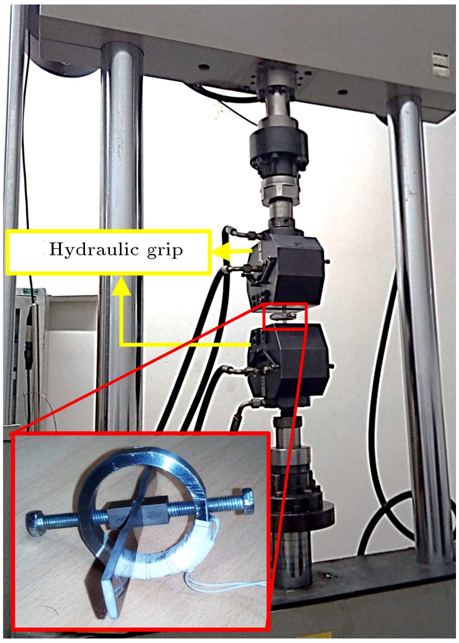

Figure 3. Fretting test in a fatigue testing machine.

Table 1. Mechanical properties of Ti-6Al-4V material.

Elastic modulus	Yield strength	Ultimate strength	Elongation at break
101 GPa	930 MPa	960 MPa	10.2%

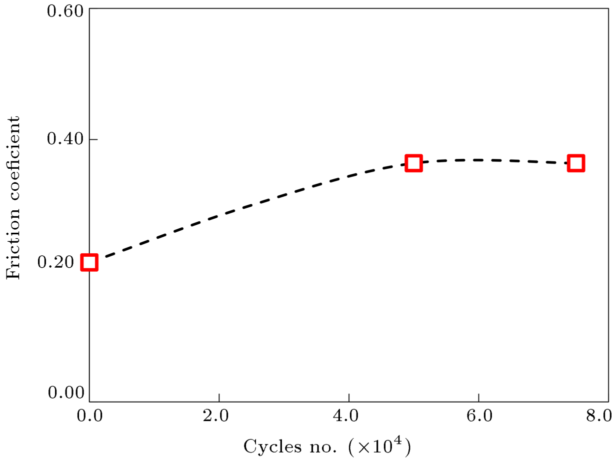

Figure 4. Variation of friction coefficient of the contact surface versus life cycle.

ducted with maximum axial stresses ranging from 300 MPa to 500 MPa and contact forces from 750 N to 1250 N. Also, two different stress ratio levels, 0.1 and 0.6, were used. Cyclic loads were applied using a servo-hydraulic fatigue testing machine at 30 Hz (Figure 3). Tests were conducted without any preloading and maximum fatigue stress and cyclic load frequency smoothly increased during the first thousands of cycles.

3.2. Crack initiation life

Lykins [25] made a comprehensive experimental investigation into the crack initiation life of the Ti-6Al-4V material under different fretting conditions. He counted fatigue striation lines on the fracture surfaces of different fretting specimens, utilized Paris crack growth method, and calculated the crack initiation lives. Then, he proposed that a suitable choice for estimating the fretting fatigue crack initiation of a Ti-6Al-4V specimen be about 83% of its total fretting fatigue life.

To investigate the crack initiation life, we conducted a specific fretting fatigue test twice, interrupted test and rupture test. A specimen was tested under the action of a 500 MPa maximum fatigue stress at an R ratio of 0.1 and a normal force of 750 N until rupture which took 57490 cycles and another fretting fatigue test with the same condition interrupted at 50000 cycles. Figure 5 shows the optical microscopy of the interrupted specimen cross-section and a crack depth of about 500 μm is visible in the picture. This shows that 83% of the total life proposed by Lykins [25] could be used as a good approximation for fretting fatigue crack initiation life.

3.3. Finite Element Analysis (FEA)

FEA was utilized to find contact interface macroscopic features such as stress and strain fields. Figure 6 shows the finite element model used to simulate fretting fatigue test conditions. Due to the symmetry of loading and geometry, only one-fourth of the specimen was modeled using 4-node bilinear plane strain quadrilateral elements.

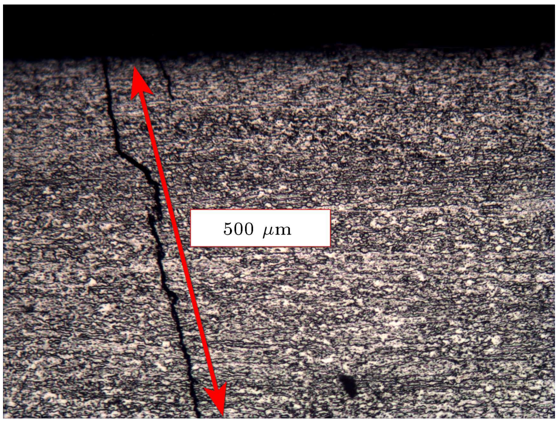

Figure 5. Initiated crack in an interrupted fretting fatigue test at 50000 cycles.

In order to study the mesh size effect, shear stress distribution and maximum relative slip amplitude at the contact interface were measured at different element sizes and results converged at 5 μm. It should be noted that due to singularity at the contact edges, stress components would increase to infinity by decreasing mesh size. This singularity problem was investigated by other researchers like [26–28]. Also, evaluating stress fields at different depths showed that 0.1 mm fine mesh would give accurate results. Therefore, mesh sizes smoothly increased from 5 μm at the contact interface to 1 mm far away from the contact line (Figure 6).

Also, loading and boundary conditions are shown in Figure 6. Two symmetric planes prevent out-of-plane movements. Fretting normal force (P) is applied at the top of the pad, while cyclic stresses (S_f) are applied to the specimen gauge section.

The numerical simulation of each test gives the stress and strain fields and the relative slip in maximum and minimum load cases. To verify our simulation, the analytical results of punch on a flat contact problem reported by Ciavarella et al. [29] were compared with the present FEA results, as shown in Figure 7. According to this figure, finite element results are in complete agreement with the analytical results throughout the contact interface.

4. Results and discussion

Test results from this study were used in conjunction with Lykins test data [25] to investigate the effectiveness of the new parameter proposed in predicting fretting fatigue crack initiation life. Table 2 shows all the test data used in this investigation.

Lykins [25], in his study, conducted a series of fretting fatigue tests with Ti-6Al-4V material flat pads

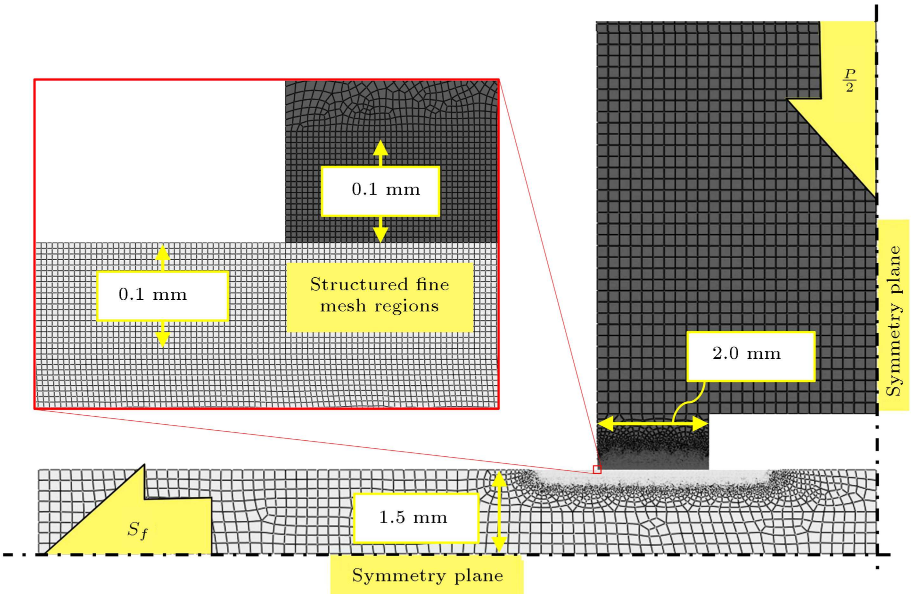

Figure 6. Loads and boundary conditions applied in the finite element model.

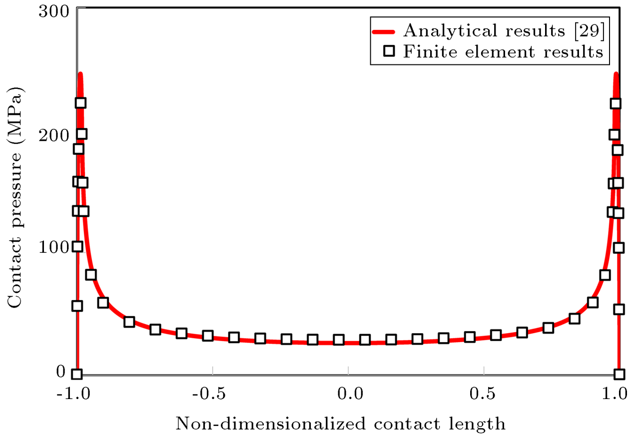

Figure 7. Analytical and numerical results of the punch on the flat contact problem.

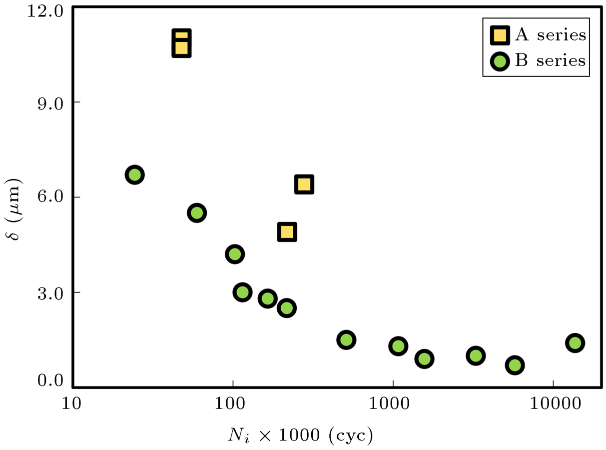

Figure 8. Relative slip amplitude versus fretting fatigue crack initiation life.

on the same flat specimens with coefficientsof friction equal to 0.5 on the contact interfaces. Contact length in Lykins' pad was approximately 2.5 times the present pad length with the maximum axial stresses ranging from 400 MPa to 700 MPa and stress ratios from zero to 0.7. He used a constant normal force of 1330 N in all his tests. Also, Lykins obtained the fitting parameter of Eq. (2) to be around 0.45 for Ti-6Al-4V alloy from plain fatigue tests.

Figure 8 shows the variation of fretting fatigue crack initiation life with respect to relative slip amplitude. As mentioned by other investigators such as Vingsbo and Söderberg [20], fretting fatigue life generally decreases by increasing relative slip amplitude in PSR and MFR regions, with some exceptions which are shown in Figure 8. From this figure, it can be observed that the relative slip amplitudes for points A2 and B1 are close such that they can experience the same damage type, but B1 fails at an order of magnitude lower cycle than A2 because DS is much higher at 700MPa than 300 MPa. In other words, even due to similar slip amplitude, micro cracking in both A2 and B1 may be similar, but those micro-cracks nucleated in B1 will grow much faster due to higher fatigue load.

On the other hand, B5 with half of the relative slip amplitude of A3, which indicates that it should be closer to the PSR, experiences the same life cycle as A3, perhaps because even though B5 is not close to the cracking state, it still experiences a more severe loading condition that shortens its life. The combination of these two factors resulted in the same life cycle with A3, which is closer to the mixed region with low effective stress (i.e., higher damage with lower severity).

A similar condition exists between A1, A4 and B1, B2. Despite the notable difference between their relative slip amplitudes, their life cycles are very close.

Table 2. Fretting fatigue test conditions and crack initiation life data.

Test no.	Contact area (mm^2)	Frequency (Hz)	Normal force (N)	$S_{\max}$ (MPa)	R	δ_{Ra} (μm)	δ_e	N_i ($\times$1000 cycles)	Ref.
A1	16.00(2.00 × 8.00)	30	750	500	0.1	11.0	3.33	47.9	Present study
A2				300	0.1	6.4	1.75	279.2	
A3				500	0.6	4.9	1.74	218.2	
A4			1250	500	0.1	10.7	3.28	477.7	
B1	32.26(5.08 × 6.35)	200	1330	692	0.05	6.7	3.87	24.4	Lykins [25]
B2				574	0.06	5.5	2.71	59.6	
B3				407	-0.03	4.2	1.86	103.0	
B4				704	0.48	3.0	1.82	115.0	
B5				565	0.41	2.8	1.61	165.0	
B6				484	0.36	2.5	1.47	217.0	
B7				424	0.42	1.5	1.15	511.0	
B8				613	0.62	1.3	1.12	1080.0	
B9				556	0.64	0.9	0.95	1570.0	
B10				607	0.64	1.0	1.01	3290.0	
B11				534	0.67	0.7	0.89	5770.0	
B12				394	0.46	1.4	1.10	13700.0	

In some other cases, upon decreasing relative slip amplitude and getting closer to the cracking state, the fretting fatigue crack initiation life would pass ten million cycles, as in the case of B12. Therefore, although δ could be used for damage characterization in fretting fatigue, it is not accurate enough to be used as a life parameter.

In Figure 9, fretting fatigue crack initiation life is plotted against effective slip amplitude. As can be seen, δ_e which is a combination of damage parameters and DS factors, in the form of Eq. (4), could result in a better prediction of the fretting fatigue life behavior. From this, the life model constants of Eq. (5) for Ti-6Al-4V material are $a_1 = 591.3$, $b_1 = -0.496$, $a_2 = 0.007$, and $b_2 = 0.293$.

Figure 10 compares the crack initiation life predicted by the new model based on δ_e with the experimental data. The dashed lines show the values for 20% above and below the prediction (continuous) lines. As can be seen, all the test data lay between two bands, and the majority of data are very close to the corresponding estimated life. Except for one, in all cases, errors are below 10%. A near-zero average of errors (1.2%) confirms that the effective slip amplitude is not biased in over/underestimating fretting fatigue crack initiation life.

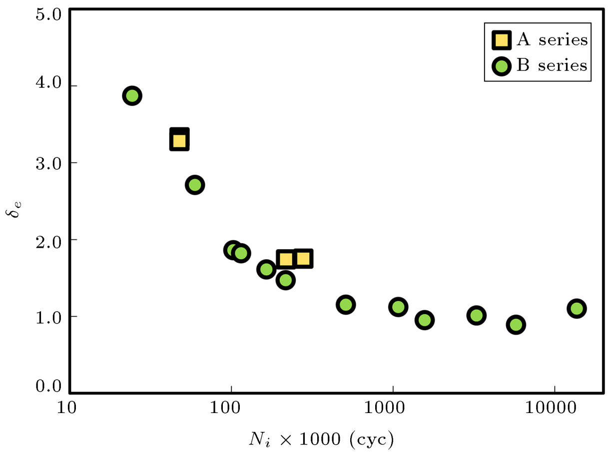

Figure 9. Effective slip amplitude versus fretting fatigue crack initiation life.

Also, the test results show that the effective slip amplitude is geometry independent since the B-series pads have twice larger contact areas than the A-series. Indeed, effective slip amplitude suggests that although there are many parameters affecting fretting fatigue life, their consequential effects may emerge in damage type and DS factors.

To compare the life prediction accuracy of the effective slip amplitude with other fretting fatigue

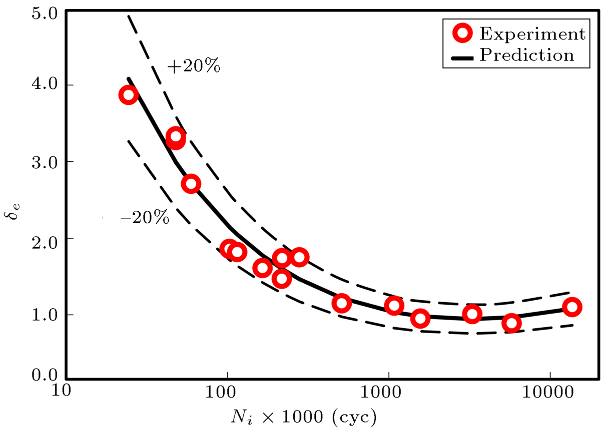

Figure 10. Predicted and experimental fretting fatigue crack initiation lives versus effective slip amplitude.

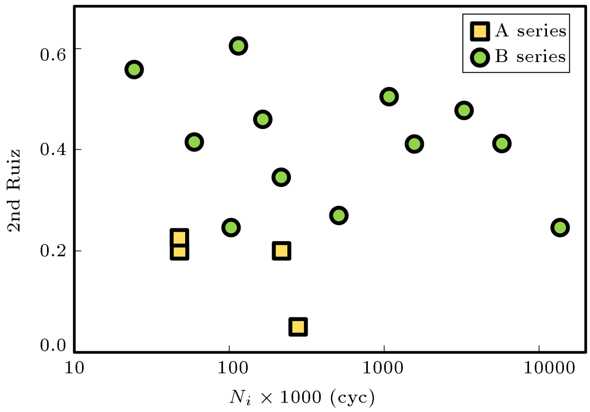

Figure 11. 2nd Ruiz parameter versus fretting fatigue crack initiation life.

parameters, its accuracy is compared with two popular fretting parameters, Ruiz parameter and critical plane SWT, in the following sections.

4.1. Ruiz parameter

Ruiz parameters are introduced in Section 2 by Eq. (1). It is shown that the 2nd Ruiz parameter is better in predicting fretting fatigue characteristics than the 1st parameter [25]; thus, the fretting fatigue crack initiation lives of test data in Table 2 are plotted versus the 2nd Ruiz parameter, as shown in Figure 11. As can be seen from the figure, the Ruiz parameter is not able to predict any general trend for the present test conditions.

4.2. The critical plane SWT model

Smith et al. [2] presented a stress-strain fatigue model (Eq. (6)) which is widely used for different fatigue life assessment problems, from multiaxial fatigue to fretting fatigue problems (e.g., [30]).

$$SWT = \sigma_{n,\max}\epsilon_a. \tag{6}$$

Successive implementations of the SWT parameter, in critical plane form, have been reported by many investigators [25]. In this equation, $\sigma_{n,\max}$ is the maximum normal stress on the critical plane and ϵ_a is the strain amplitude on it.

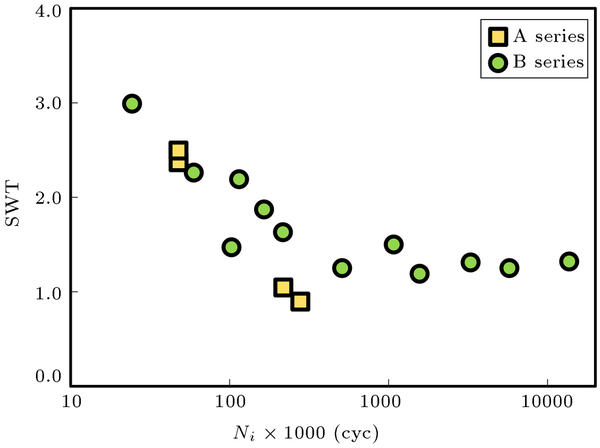

Figure 12. SWT parameter versus fretting fatigue crack initiation life.

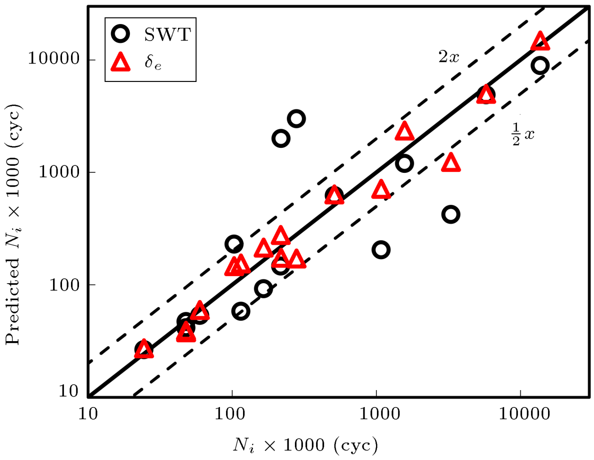

Figure 13. Comparing SWT and δ_e accuracy in fretting fatigue crack initiation life prediction.

Figure 12 shows the variation of fretting fatigue crack initiation lives against critical plane SWT for the test data given in Table 2. The general form of Eq. (5) can be fitted to the data shown in Figure 12 to obtain a crack initiation life model based on the critical plane SWT parameter as shown by Eq. (7):

$$SWT = a_3 N_i^{b_3} + a_4 N_i^{b_4}, \tag{7}$$

where a_3 and a_4 are the model coefficients and b_3 and b_4 are its exponents for the available experimental data: $a_3 = 575.4$, $b_3 = -0.533$, $a_4 = 0.088$, and $b_4 = 0.163$.

The main difference between the critical plane SWT and the effective slip amplitude is that in the new method, slip amplitude which is a determining parameter in fretting fatigue running condition and material response [1] is used as the main parameter, while the stress and strain are the main parameters of the SWT method.

Figure 13 shows comparison of the life prediction accuracy based on the critical plane SWT and the effective slip amplitude models. The closer the data are to the solid diagonal line, the more accurate the life model is. It can be seen that although the critical plane SWT is quite precise in some cases and partially unbiased, predictions based on the effective slip amplitude are still much closer to the solid line.

5. Conclusion

In this study, it was shown that the higher damage severity would not always result in faster fretting fatigue failure and the corresponding damage type was also a determinant. In order to obtain a comprehensive parameter, the relative slip amplitude, representative of the damage type, was combined with the nondimensionalized Walker effective stress, representative of the damage severity factor. This resulted in a new parameter named "effective slip amplitude".

Experimental test data and available literature reports were used to study the accuracy of this new parameter. It was shown that the average estimation error of this new parameter was very close to zero. Also, all the predicted lives by this parameter lay between a scatter band of 2, while most of them had an estimation error of less than 20%.

This study showed that with a more detailed investigation of the fretting fatigue phenomenon, life models could be presented based on distinguishing characteristics of it, which managed to accurately predict the fretting life behavior. One of the interesting features of the presented model is that it is based on macroscopic parameters and can be easily used in engineering and design applications.

Although effective slip amplitude seems to be a good approximator for fretting fatigue crack initiation life, there are some limitations that require much more investigation in the future including size effect, multiaxiality, severe stress gradients, and non-proportional loading.

The effective slip amplitude parameter aspired a new fretting fatigue life predicting methodology for flat-on-flat contact conditions discussed in this paper. This methodology has the potential to be used for other types of fretting conditions as well, requiring further investigation.

6. Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

Nomenclature

a_1, a_2, a_3, a_4	Life model coefficient
b_1, b_2, b_3, b_4	Life model exponent
DS	Damage Severity parameter
m	Walker effective stress constant
N_i	Crack initiaion life cycle
R	Fatigue stress ratio
S_e	Walker effective stress
$S_{\max}$	Maximum faitgue remote stress
S_y	Material yield stress
SWT	Smith-Watson-Topper parameter
δ	Relative slip amplitude
δ_e	Effective slip amplitude
δ_r	Relative slip range
χ, κ	1st and 2nd Ruiz parameters, respectively
σ_t	Tangential stress
τ	Shear stress
σ_n	Normal stress amplitude
ϵ_a	Normal strain amplitude

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