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ARTICLE

Some Aspects of Fretting Fatigue under Complex Cyclic Contact Load Condition

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ARTICLE INFO

Article history:
Received: 25 October 2018
Accepted: 10 December 2018
Published: 28 December 2018

Keywords:
Fretting Fatigue
Wear
Cyclic normal load
Tribology
Al7075-T6
Contact mechanics.

ABSTRACT

Fretting fatigue has been studied mainly under constant normal loading, as it requires simple equipment which can be assembled on a universal fatigue testing machine. Recently, the authors[1-3] have introduced an innovative fretting fatigue apparatus in which the contact pressure can independently be varied during the test. It was found that the low frequency of normal load has drastic effect on fretting fatigue life. The authors have compared the results of constant normal loading with those of in phase, 90° and 180° degrees out-of-phase loadings. The case of constant normal load is found to be the least damaging, while the in-phase loading is found to be the most damaging. When load is varied in phase with the axial stresses in the specimen, contact mechanics would predict that no slip should be obtained, whereas apparently larger slip is found with respect to the constant normal load. When loads are out-of-phase, the "full sliding limit" is also time-varying and less frictional force is developed so it becomes hard to interpret why life is nevertheless shorter than in the case of constant normal load. Hence, the objective of this article is to present further discussion of the experimental results. The authors hope that this discussion could lead to some progress.

1. Introduction

Most of the previous studies on fretting fatigue, have been accomplished under constant normal loading and a less attention has been paid to the effects of cyclic normal loading. One of the most important issues with rareness of investigations under cyclic normal loads is the difficulties associated with design and manufacturing the apparatus capable of simulate such complex load conditions. Recently [1] the authors have developed a new electromechanical test-rig to investigate the fretting fatigue behavior of material under cyclic contact loads.

Examination of fretting scars using optical microscopy, SEM and EDS revealed that the abrasive wear of debris

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DOI: https://doi.org/ 10.30564/jmer.v1i1.186

particles and higher oxidation rate due to the normal load release at each cycle, severe delamination of the wear particles and the dominant partial slip condition with wider slip region compared to constant normal loading, are the most important reasons for significant reduction of fretting fatigue life, under cyclic normal loading, especially for low normal load frequencies [2,3]. Huq et al. [4,5] Hojjati-Talemi et al al.[6] Xin et al.[7] found that the presence of cyclic normal loading condition reduces fatigue lifetime drastically. Madge, et al. [8] simulated fretting fatigue using FEM, taking into account wear and concluded that the dominant mechanisms in gross slip and partial slip condition are wear and cracking, respectively.

Vingsbo and Soderberg [9] introduced a fretting map shown in Figure 1 and showed that as the tangential displacement amplitude increases, the wear rate increases, the partial slip regime dominates and the fatigue life reduces. Maximum damage occurs at relative tangential displacement amplitudes within the range of 10-20 microns. This map has been later found to give an erroneous interpretation in some cases [10]. Although, the Vingbo and Soderberg map [9] proposed 30 years ago was a significant step forward in the fretting fatigue context at the beginning but with the ever increasing progress in the this area, the map gradually lost its accuracy. For example, the range of 10-20 microns for tangential displacement that causes the maximum damage is not fully accurate and globally accepted and depends on the test equipment design. It has also been found that in general, the range of tangential displacement depends on contact type, specimen geometry, load and material.

More recently, Ciaverella et al [11] has proposed a simplified extension of the Crack Analogue (CA) model assuming Half-Space condition for fretting fatigue with varying normal load. They provided a very interesting approach to model the fretting fatigue situation as a crack or notch. This approach was first suggested by Giannakopoulos et al. in 1998 [12] arguing that the stress field created near the contact pad is similar to that created ahead of a sharp crack. If this Crack Analogy (CA) can be made, then it might be possible to predict the behavior in the contact problem by finding an equivalent crack. The first limitation of this model is that, in the real applications where these conditions are not met, half-plane theory cannot be applied for the solution of the problem. A second difficulty with this approach is that tribological features of the contact interface is not considered in their model. Crack initiation and consequently fretting fatigue lifetime is affected not only by the contact stresses but also by the localized surface damages and tribological features (fretting regime) of the contact interface. Unlike the constant normal load condition, in variable normal loading the normal load is released in each cycle exposing periodically the fretting area to more oxidation. Under oxidizing conditions, cracking and delamination of the wear particles will be accelerated by oxidation of the particles.

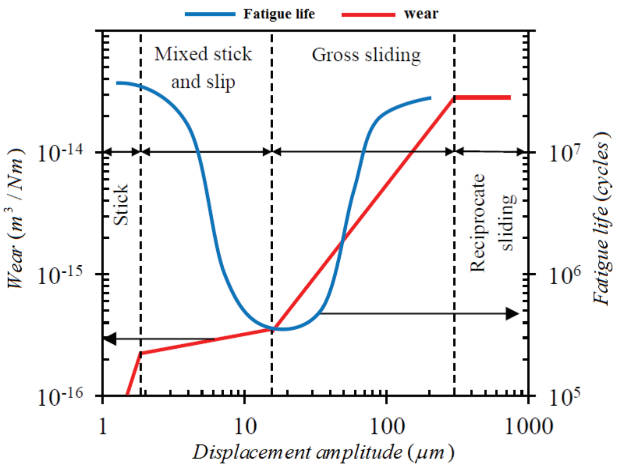

Figure 1. Schematic view of the fretting map [9]

Oxide debris forms at contact interface, acting as abrasive particles and are pushed into the fatigue crack as the process continues. ASTM International defines abrasive wear as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface [13]. Waterhous et al [14] believes that if the oxide layers are harder than the base material, fretting damage and crack initiation are accelerated. On the other hand, if the oxides are soft relative to the base material, it lowers friction and fretting damage reduces significantly. The detached particles are generally trapped between the contacting surfaces and subsequently are crushed into smaller fragments by the mechanical action of fretting. Because the oxides are usually harder than the underlying metal, the fragmentation will be enhanced by oxidative conditions, especially in the case of cyclic normal load. In the slip region, the fragmented particles will roll between the surfaces causing grooving damage until they finally, leave the contact area.

Recently, Ciaverella [15] has published a discussion on author's publications [1-3]. He believes that some of the experimental results don't conform to the existing theories and requested a discussion on the results. Therefore, the objective of this article is to answer three main points he raised in [15], in the hope that this discussion could lead to some progress.

2. Features and Considerations

The interplay of fretting fatigue and wear has remained largely unexplained and particularly the region when tangential displacements are above the gross sliding conditions where it is unclear why a large improvement of fatigue live is observed in fretting maps, despite wear is not so largely increased. Hence, further discussion of the experimental results is needed and is the main objective of present study. With this state of affair, it is quite naive to expect very detailed predictions of fretting fatigue to be possible, given we have in one go the uncertainties typical of fatigue problems, of tribological prediction of friction coefficients and its evolving in time, the wear problem, and the interplay of all of them at the same time. In the case with cyclic normal load condition, the frequency of normal contact load is the most important parameter because it interacts with several parameters (e.g. contact stresses, friction force, oxidation rate, slip amplitude etc.) and influences the fretting fatigue behavior. In this section, the effects of frequency on fretting fatigue response and tribological behavior of contact interface is presented in details.

2.1 Frequency and Slip Regimes

The major drawback of this kind of loading in the newly designed fretting apparatus [1] is that the frictional forces are dependent on the axial strain in the dog bone specimen and on the stiffness of the bridge type fretting pad. Therefore, by oscillating the normal load in-phase with the axial load, the level of frictional load also varies accordingly. This means that by introducing cyclic normal load the level of frictional forces becomes an extra variable, hence true contact stresses and overall fatigue load changes accordingly. Let's consider the case where normal load is constant. In full stick conditions, the tangential friction force increases in-phase with specimen elongation until gross sliding occurs while the contact stresses increases at the same time. On the other hand, if normal load oscillates between zero and preset maximum value (in-phase condition), then the situation is different. When normal load is zero, then tangential forces will be zero also. Depending on the normal load frequency, with respect to the bulk stress frequency, limitations will be applied to the magnitude of tangential friction load. If the normal load frequency is very large, then the maximum friction force amplitude will be about the same than in the case of constant normal load, although the stress history will be different. When the normal load frequency is low, the tangential friction forces is released alternatively when the normal load reduces to its lowest level and there will be no net friction force at all. This is confirmed by the numerical simulation shown in Figures 2 and 3 in which shear stress increases and slip region decreases with the increase in contact load frequency.

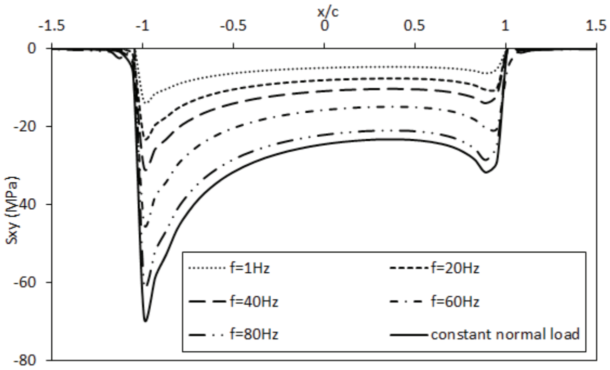

Figure 2. Shear stress distribution along the contact interface [2]

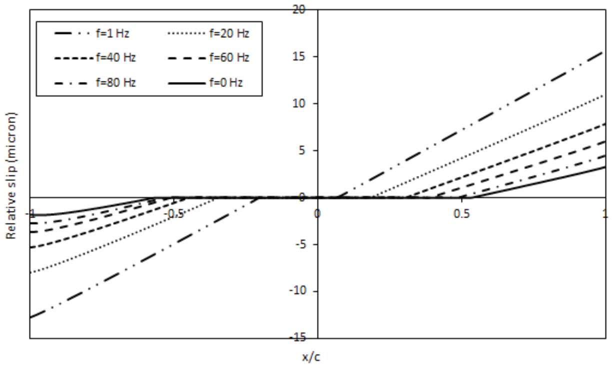

Figure 3. Relative displacement distribution along the contact interface [2]

Let's explain further why shear stresses in the case of constant normal load is higher than cyclic one. The loading sequence for both the constant and in-phase cyclic contact load conditions for one cycle with the time period of T is depicted in Figure 4. As it is seen, the axial load is the same for both the constant and cyclic contact loading conditions. However, the contact load for cyclic loading conditions is always (except at T/2 where the contact load is the same for both loading conditions) lower than that for the constant loading condition. Therefore, the shear stress due to the contact load and friction will be higher in constant loading conditions. Since, the shear stresses affecting the slip region depends on the history of loading, less effective shear stress and subsequently larger slip zone is expected for the case of cyclic normal contact loading.

The fretting fatigue behavior (and hence the resulting stresses and displacements in the contacting bodies) and also tribological condition of the contact interface depends on the history of loading. Therefore, as expected, at very low normal load frequencies the contact interface experiences less average amount of frictional stresses with respect to those in constant normal load where the normal

DOI: https://doi.org/ 10.30564/jmer.v1i1.186

load is maximum at all axial load cycles. In the case with high normal load frequency, the number of points in the load cycle in which the normal load is maximum increases and the condition of contact interface, tends to the conditions of the constant contact loading, thus further average normal load is expected to apply on the contact interface. As a result, having the same axial load, higher frictional resisting force and subsequently lower tangential displacement occurs on the contact interface.

The authors think that this explains partly (i) why slip size for in-phase loading is larger than that for constant normal load and (ii) why slip size decreases and fatigue life increases when the normal load frequency is increased, although the presence of cyclic normal load will bring about its own fatigue component.

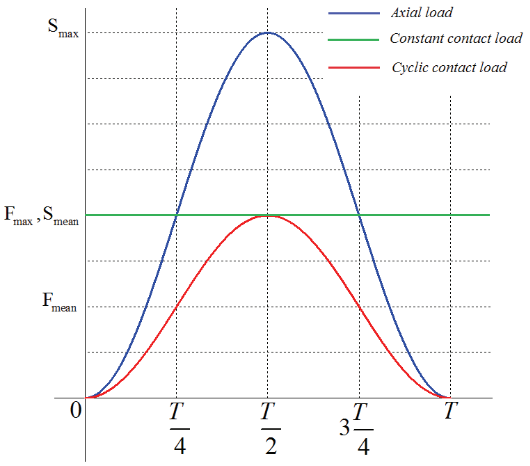

Figure 4. Loading sequences for constant and cyclic contact loading

2.2 Frequency and Wear Rate

It should be emphasized that, cyclic normal load tests with load ratio of R=0, induce contact opening at each cycle, so air reaches the fretted interface. As the authors have stated in [2] "At higher contact load frequencies, there is less time for chemical reaction". Here it is necessary to make a distinction between "reaction time" and "opening time". Reaction time is the time during which oxygen reacts with base material in the slip region. Opening time is the time during which the contact is open in each fatigue cycle. Hence, due to the flow of the air and the normal load mechanical mechanism, reaction time is lower than the opening time. At high normal load frequencies, the contact closes immediately at each cycle before the air have chance to reach the wear particles (this is because there is no mechanism to return the pad after it's touching to the specimen). The higher the frequency, the shorter is the time available for chemical reactions to occur. Therefore, low wear rates can be obtained at high frequencies. However, at low normal load frequencies more oxygen can reach the fretting surface, thus debris are exposed longer to the atmosphere giving rise to a homogenous oxidation over the whole interface. This conclusion has also been reported in several investigations dealing with the effect of normal load frequency on fretting in the literature [16-18].

For more clarification let's consider the case where normal and axial load frequencies are 1Hz and 10Hz respectively as shown in Figure 5. In this case where the normal load frequency is very low, during the time period of 1 second, 10 cycles of axial load is applied for each cycle of normal load. The exposure time (when the contact is open) for one axial load cycle is higher than the closure time (when the contact is closed), i.e. more time for chemical reactions to occur in the contact between the pad and specimen. Now let's consider the case where normal and axial load frequencies are 80Hz and 10Hz, respectively, as shown in Figure 6. In this case, where the normal load frequency is high, during the 0.1 second, 8 cycles of normal load is applied for each cycle of axial load. In this case, the number of points in the load cycle in which the normal load is maximum increases and the condition of contact interface, tends to the conditions of the constant contact loading. In this case, the exposure time for one axial load cycle is lower than that of the closure time, i.e. less time for chemical reactions between the pad and the specimen. Therefore, wear and oxidation occur at lower rates for higher frequencies.

As a matter of fact, the condition of contact interface at high frequencies is very similar to that at constant contact load. This point is more clearly in Figure 7 where the peak points of cyclic normal load forms a line that is tangent to the constant normal load. In this case, the sum of time intervals when the contact is close is higher than those when the contact is open. Therefore, lower oxidation occurs at higher frequencies. The above reason may explain why in Figure 13 in reference [2], the slip area decreases with increase in normal load frequency. This also explains partly why fatigue life increases when the normal load frequency is increased and at f=80Hz it converges to its corresponding life at constant contact load condition.

Other possibilities could be related to the impact like conditions at higher frequencies, local temperature rise at the contact interface, and or changes/transfer of the oxides between the mating surfaces. The contact temperature is a dependent variable, being a function of thermal properties of the contacting bodies as well as size and shape of the real contact area, frequency and sliding velocity, normal load amplitude and coefficient of friction. Temperature may affect the process of fretting because of two reasons:

DOI: https://doi.org/ 10.30564/jmer.v1i1.186

(i) the mechanical properties of materials change with temperature; (ii) the corrosion and oxidation rates usually increase with temperature. This subject has been neglected in most of investigations and the results given in the literature are controversial.

As a suggestion for future works, more realistic and documentary discussions can be presented by measuring the slip amplitude, exposure time, wear rate, contact interface temperature rise, amount of oxide debris, possible change in COF (coefficient of friction) and providing more meaningful illustrations such as variations between normal load frequency and oxide debris, wear rate and exposure time. These would necessitate that the testing device is equipped with more sophisticated measuring instruments.

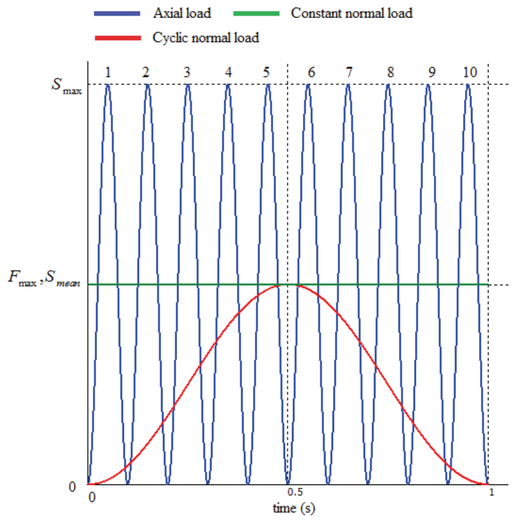

Figure 5. Loading sequence for normal load frequency of 1Hz and axial load frequency of 10Hz.

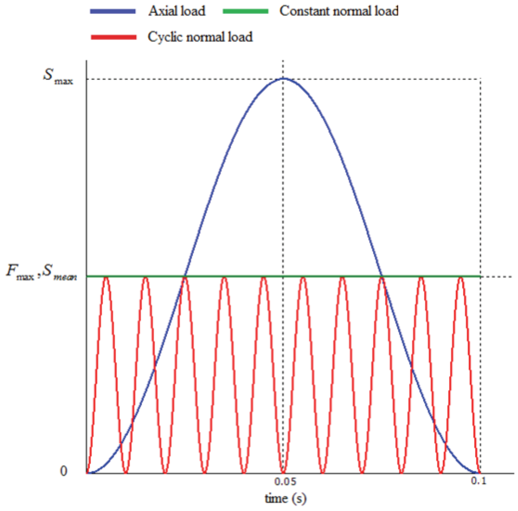

Figure 6. Loading sequence for normal load frequency of 80Hz and axial load frequency of 10Hz in time period of 0.1s

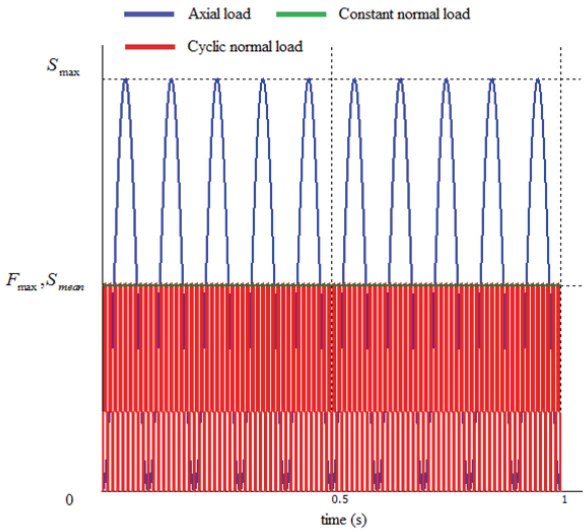

Figure 7. Loading sequence for normal load frequency of 80Hz and axial load frequency of 10Hz in time period of 1s

2.3 Tribological Effects

Fretting fatigue and contact mechanics calls for some new models under cyclic normal loading. The main founding of the investigation [2,3] was to show that the fretting fatigue life is closely related not only to the contact stresses but also to the tribological behavior of the contact interface and relative tangential displacement of two contacting surfaces. However, these factors are more influential at very early stages of fretting fatigue life i.e. crack initiation phase. The results suggests how difficult is to interpret "fretting fatigue", and even "crack and notch" analogues which do not consider the tribological effects of wear and the change of contact area, can be oversimplified.

Generally, fretting fatigue life could be divided into two main phases, namely crack initiation and crack propagation. The fraction of each phases depends on many factors, e.g. slip regime, load frequency, environmental conditions, contact stresses, axial bulk stress, slip amplitude, etc., and varies from one practical application to another. The initiation process in fretting contact is a mixture of wear, corrosion, and fatigue phenomena. Early attempts to explain the initiation of fretting fatigue cracks were based on stress criteria alone. However, such an approach is bound to fail since the effects of slip amplitude are not taken into account. Therefore, some other parameters such as slip amplitude, which is sensitive to small variation of applied stress, should be taken into account. As stated by Hills and Nowell [19] one of the principal goals of any mechanic's analysis of crack initiation in fretting must be to incorporate the effects of relative slip or displacement amplitude. However, at the present time there is no theory to model these effects for fretting fatigue life estimation.

3. Final Remarks

Until now, only a few authors have used experiment to study the effect of cyclic normal loading on fretting fatigue life. Moreover, no investigation has so far been performed to assess the influence of normal load frequency and out-of-phase loading on fretting fatigue under cyclic normal loads. The authors believe that, what has been done in [1-3] is only a beginning and needs complementary works to be done in future for eliminating the deficiencies of the work. However, the more complex fretting loading, the more complex fatigue analysis will be. If the cyclic bulk stress and contact loading are applied in a non-proportional manner, much care must be taken when analyzing frictional contacts in partial slip, whether by use of the classical methods or numerical techniques such as finite element analysis (history-dependence may also be important). The authors believe that more investigation (both experimental and analytical) are now required for a better understanding of the fretting fatigue phenomenon under cyclic normal loading including Archard wear modeling, tribo-oxidation processes and damage mechanics analysis. To the best of author's belief, developing a fatigue model considering these effects is necessary to understand fretting fatigue behavior under cyclic normal loading. Furthermore, some simplifications and assumptions have made in the analysis and simulation, as is usual in engineering analysis, for some of which the authors may not have convincing answer. Definitely, there are still many latent aspects which must be clarified in the context of fretting fatigue under fluctuating contact loads. The authors have travelled some of the way but there is a long way still ahead to travel.

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