FRETTING FATIGUE STRENGTH PREDICTION THROUGH MULTIAXIAL FATIGUE CRITERIA FOR 7050-T7451 AL ALLOY

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Abstract. *The aim of this work is to analyze the Susmel and Lazzarin multiaxial fatigue criteria from associated with critical distance methodology is able to prevent efficiently the fretting fatigue strength of 7050-t7451 Al alloy. Fretting fatigue tests under the partial slip conditions were performed in order to compare the acquired resistance experimentally with the produced estimate by using the proposed multiaxial strength criterion. The fretting fatigue tests were done by keeping the contact loads stable and the fatigue alternate stress, varying the applied mean stress, which allow us to observe the effect of fatigue mean stress in fretting fatigue life in the studied specimen. The results show that the decrease in the mean stress increases the resistance of the specimen for the cases of fretting fatigue. For cyclical loading totally compressive, there are cracks initiations due to the fretting stress field, presenting cracks arrests, which did not propagate causing the material infinite life. The analyzed criterion made it possible to efficiently foresee the crack initiation for the studied tests conditions, nevertheless it determined failure for all the tests done, contradicting the acquired results experimentally, since those specimens under fatigue compressive loads reached infinite life.*

Keywords*: fretting fatigue, mean stress effect, multiaxial fatigue, Al 7050-T7451, fretting fatigue strength prediction*

1. INTRODUCTION

Components that work together with other parts, exposed to vibrations or cyclic stress, always present some relative movement between the surfaces in contact, which may cause superficial wear and failure in service. The fretting fatigue is one of the most common contact fatigue and it refers to the sliding of small amplitude between two surfaces in contact, favoring the cracks nucleation that, due to the cyclic loading applied to the component, can propagate and cause the component failure (Fouvry, 2000). The appearing of fretting simultaneously to a fatigue request reduces considerably the component life.

One of the factors that can contribute to the deterioration of the components due to fretting fatigue and causing the early initiation of cracks is the high concentration of stress caused by the friction force due to contact and the displacement between the surfaces, producing a state of non-proportional multiaxial stress that falls quickly as it gets apart from the contact surface. Then, the stress field generated by the fretting fatigue is considered the driving power for the early initiation and propagation of cracks, being extremely important the quantification and observation of the stress fields caused by this phenomenon (Araujo, 2001). This behavior suggests the use of a multiaxial fatigue model to foresee the strength and the initiation life of cracks in components liable to fretting fatigue conditions.

It was analyzed in this paper the efficiency of the Susmel and Lazzarin (2002) high cyclic multiaxial fatigue model associated with the Taylor theory for notches bodies (1999), based on critical distance theory, to estimate the fretting fatigue strength of an 7050-T7451 aluminum alloy. The fretting fatigue tests done in the partial slip conditions were. The endurance trials by fretting done in the partial slip conditions were performed so that it kept all the tests parameters constant but the mean fatigue stress, that in terms of the modified Wöhler's curve methodology corresponds to keep constant the value of the shear stress amplitude and to vary the maximum normal stress in the critical plane. Then, it was possible to observe whether the effect of the mean stress in the fretting fatigue tests is similar to the one found in the conventional fatigue, determining whether the theories, such as the multiaxial fatigue criteria are suitable to estimate the behavior of the materials facing such tests conditions.

2. MATERIAL AND METHODS

The material used in the development of this work was an 7050-T7451 aluminum alloy, provided by EMBRAER-LIEBHERR (ELEB) in the way of laminated plates. Tab. 1 shows the chemical composition of the studied material. Its mechanical properties are presented in Tab. 2.

To perform the fretting fatigue tests were used an experimental device that was coupled in the MTS-810 servo-hydraulic machine as shown in the Fig. 1(a). In this configuration, the hydraulic wedge grip in the machine is responsible for applying the remote fatigue load F_0, and the device produces the tangential load Q in the contact, in other words, it works as a spring component. The involved loads in the fretting fatigue phenomenon are shown in Fig.

1(b). The value of tangential force is measured by the half of the difference between the measured force in a cell coupled in the lower wedge grip, $F_0(t)$ with the measured force in another cell coupled in the upper wedge grip, $F(t)$, as illustrated in the diagram of forces in Fig. 1(c). The P load is applied by a pair of hydraulic auxiliary cylinders connected to a pressure accumulator by gas (nitrogen/oil). This system allowed that the contact loads were controlled and measured along the tests and then possible to determine analytically the stress field generated in the performed tests. The complete description of the steps taken to analyze the device feedback used under the mechanic stress is detailed described by Martins *et al.* (2008).

Table 1. Chemical composition, wt% of 7050-T7451 Al alloy (ASM Handbook, 1990).

	Zn	Ti	Mg	Cu	Zr	Fe	Mn	Cr	Si
Nominal	5.7-6.7	0.06	1.9-2.6	2.0-2.6	0.08-0.15	0.15	0.1	0.04	0.12
Obtained	5.85	0.024	1.96	2.11	0.12	0.07	0.01	-	0.03

Table 2. Mechanical properties of alloy Al 7050-T7451 (Rossino, 2008)

Yield Limit (σ_e) [MPa]	454 ± 3
Ultimate Tensile Strength (σ_R) [MPa]	513 ± 4
Elastic Modulus (E) [GPa]	73 ± 2
Poisson's Coefficient (υ)	0.33

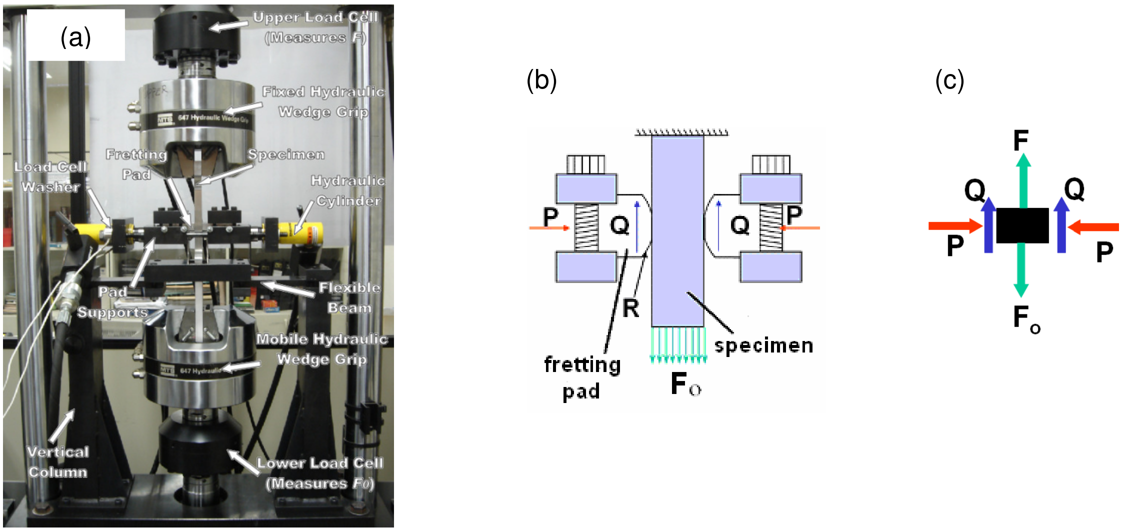


Figure 1. (a) Fretting device coupled in a MTS-810 machine, (b) forces involved in the contact and (c) diagram of forces.

The specimen dimensions and the fretting pads used in the tests are illustrated in Fig. 2, where it must be observed that the fretting pads have the same length of the specimen so that it minimizes the influence of the border effects that exist in this setting of contact.

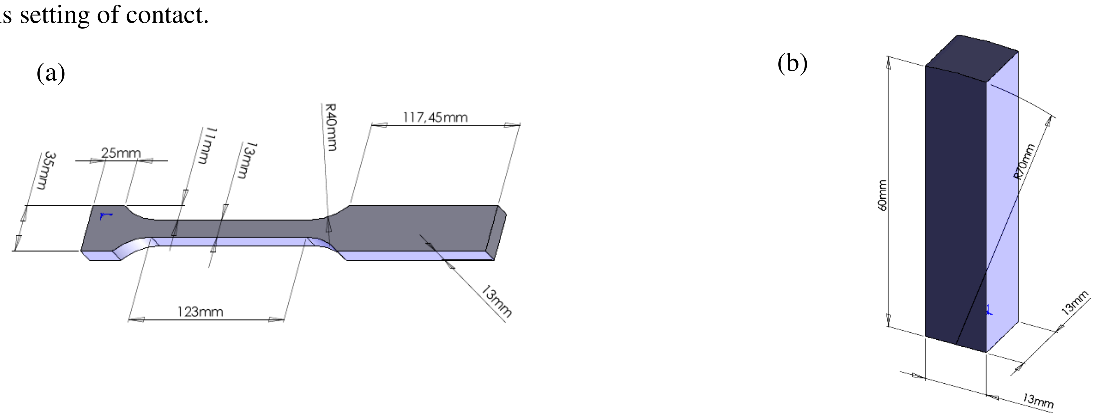


Figure 2. Dimensions of (a) the specimen and (b) the fretting pads used in the fretting fatigue tests.

Araujo and Nowell (2002) observed that the strength of an 4%Cu Al alloy submitted to fretting fatigue test is sufficiently determined by the multiaxial fatigue theory for those cases where the mean fatigue stress was zero, the maximum contact stress 157 MPa, the maximum fatigue alternate stress 92.7 MPa and *Q/fP* equals 0.6. In order to prove the efficiency of such method, the conditions of loading applied in this experiment were chosen to increase the severity of the contact loads, keeping the loading conditions in the elastic regime.

Consequently, it was determined the value of p_0 of 350 MPa for the testes, corresponding to a normal contact load of 8.5 kN, for an fatigue alternate stress of 92.7 MPa. The relation of *Q/P* determined for the tests was 0.25, assuring that the tests conditions were done in the partial slip regime. The test done to estimate the friction coefficient (*f*) in the slip zone is described by Martins et al. (2008), and its average value estimated in f_s = 0.54, that corresponds to a relation of *Q/fP* of 0.47.

In order that the fretting fatigue tests were done, the alternate fatigue stress remained constant, $\sigma_{a,}$ for all the performed tests, varying the applied mean fatigue stress σ_m. This type of consideration will allow that, with the steadiness of maximum shearing stress amplitude in the critical plane and the maximum normal stress variation acquired, the effect of mean stress in the fretting fatigue life can be observed, besides it makes possible to verify the practice of multiaxial fatigue theories in the prediction of strength in fretting fatigue in the aluminum alloy for the given test conditions.

As an experimental procedure, the specimen was attached in the test device and the mean fatigue load was applied to the specimen before it was submitted to the contact stress so that it will not change the stress in the component caused by the contact stress. The pads are pressed against the specimen by a normal static load generated by the component coupled to the fretting device. Then, it is applied the alternate fatigue load. While the specimen extends according to its deformation under the force of an oscillate remote load, the contact point is dislocated and the flexible beams apply, through the pads, a tangential load in the specimen. The loads are applied as described in Fig. 3. So, the alternate fatigue load has an effect of dislocating the adhesive zone along the loading cycle, however, as the mean component F_m was applied before the normal load, *P*, this is not detected by the contact and its estimate can be done by simply superposing a uniform and constant stress field. The frequency used during the tests was 10 Hz. Tab. 3 shows the parameters used to perform the tests. The criterion of experimental failure applied was the material rupture, by determining infinite life for 10^7 cycles reached without the rupture of the specimen.

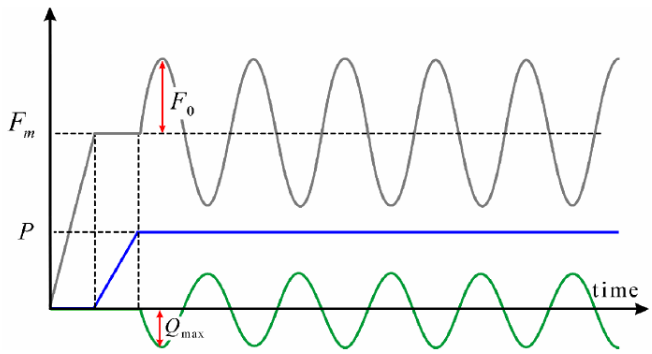


Figure 3. Loading program for the fretting fatigue tests

Table 3. Parameters used to perform the fretting fatigue tests

σ_a [MPa]	F_0 [kN]	p_0 [MPa]	*P* [kN]	*Q/P*	*f*	*Q* [kN]	σ_m [MPa]
92.7	15.7	350	8.5	0.25	0.54	2.13	15, 0, -15, -60, -92.7, -145

3. FRETTING FATIGUE STRENGHT PREDICITON

To predict the fretting fatigue strenght of the studied material, it was applied the Susmel and Lazzarin high cycle multiaxial fatigue model (2002), associated with point method, proposed by Taylor (1999).

Initially, the cyclic stress field must be calculated. The first step to obtain a solution for the stress field is to solve the contact problem, it means, to find the magnitude and the stress distribution in the contact surface. Details regarding the formulation of the contact problem can be found in Hills *et al.* (1993). The Hertz' results (1882) predict that, for the adopted contact conditions as shown on Fig. 4, due to the normal elastic force, a distribution of elliptic pressure is developed, as described by the Eq. (1):

$$p(x) = -p_0\sqrt{1-\left(\frac{x}{a}\right)^2} \tag{1}$$

$$-p_0 = \frac{2P}{\pi a} \tag{2}$$

$$a = \sqrt{\frac{4PR}{\pi E^*}} \tag{3}$$

where a corresponds to the half of the contact size, R is the pad radius and E^* is defined by the relation:

$$E^* = \left(\frac{1-\upsilon_1^{\ 2}}{E_1} + \frac{1-\upsilon_2^{\ 2}}{E_2} \right)^{-1} \tag{4}$$

where the subscripts 1 and 2 stand for body 1 (for instance, the fretting pad) and body 2 (tensile specimen) and E is the elastic modulus of material

The application of a tangential force, Q, and the existence of friction, comes up with shearing stress in the surface of the bodies. The tendency of displacement is counterpoised by the forces $fp(x)$ where f is assumed constant and smaller than the unity. In the cases of fretting where the developed shearing stress is smaller than the limit for the total slip, such process is characterized by the Eq. (5). Thusly, two distinct regions were developed inside the contact zone: a central region ($/x/ < c$) called adhesive zone, limited by the radius c and determined by the Eq. (6), where there is no relative movement between the correspondent contact point of the surfaces, and another peripheral region located between the ends of the contact and the adhesive zones ($c \leq /x/ \leq a$), this region usually called slip zone. Fig. 4 illustrates the contact applied in cylinders against a plain plate with normal load P, which can be equally applied to spherical contacts where two distinct regions are determined inside the contact zone, which develops in partial slip regime.

$$|q(x)| \langle -fp(x) \tag{5}$$

$$c = a\left(1 - \frac{Q}{fP}\right)^{1/3} \tag{6}$$

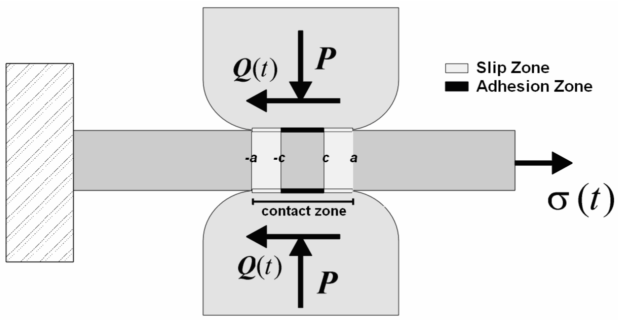


Figure 4. Contact of cylinders with plain surface in partial slip regime.

The distribution of surface shearing stress for each formed region in partial slip regime during the slip phase are presented in Tab. 4 where c'/a is given by the Eq. (7):

$$\frac{c'}{a} = \sqrt{1 - \frac{Q_{\max} - Q(t)}{2fP}} \tag{7}$$

The resultant sub-superficial stress field can be obtained by superposing the stress fields generated by $p(x)$ and $q(x)$. the component of σ_{xx}/p_0 during the unloading and reloading, where the subscripts N and T refer to the stress strainer produced by the normal and tangential loads, are given by the Eq. (8) as:

$$\frac{\sigma_{xx}\left(\frac{x}{a},\frac{y}{a}\right)}{p_0} = \left(\frac{\sigma_{xx}^N\left(\frac{x}{a},\frac{y}{a}\right)}{p_0}\right) \pm f\left(\frac{\sigma_{xx}^T\left(\frac{x}{a},\frac{y}{a}\right)}{p_0}\right) \mu\, 2f\frac{c'}{a}\left(\frac{\sigma_{xx}^T\left(\frac{x-e'}{c'},\frac{y}{c'}\right)}{fp_0}\right) \pm f\frac{c}{a}\left(\frac{\sigma_{xx}^T\left(\frac{x-e}{c},\frac{y}{c}\right)}{fp_0}\right) + \sigma_a \tag{8}$$

where:

$$\sigma_a = \sigma_a(t)\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{9}$$

Table 4. Shearing surface stress for each region during the variation of the tangential load along the time.

$q(x)/fp_0$	application zone
$-\sqrt{1-\left(\frac{x}{a}\right)^2}$	$c' < /x/ \le a$
$-\sqrt{1-\left(\frac{x}{a}\right)^2}+2\frac{c'}{a}\sqrt{1-\left(\frac{x}{c'}\right)^2}$	$c < /x/ \le c'$
$-\sqrt{1-\left(\frac{x}{a}\right)^2}+2\frac{c'}{a}\sqrt{1-\left(\frac{x}{c'}\right)^2}-\frac{c}{a}\sqrt{1-\left(\frac{x}{c}\right)^2}$	$/x/ \le c$

The next step is to determine the multiaxial fatigue criterion to be used in order to estimate the strength in fretting fatigue of the studied material. Many models of multiaxial fatigue are based in the relation described by the Eq. (10):

$$f(\tau) + g(\sigma) \le \lambda \tag{10}$$

where $f(\tau)$ is a function of the shearing stress, $g(\sigma)$ is a function of the normal stress and λ is the material parameter.

Susmel and Lazzarin (2002) considered that the fatigue cracks are originated in certain material plains, called as critical plain (ϕ^*,θ^*), where the association of the shearing and normal stress in the applied stress along the loading are particularly severe. This way, Susmel and Lazzarin propose in their model that the failure will happen when the uniformity of the Eq. (11) were obeyed. The parameters $f(\tau) = \tau_a(\phi,\theta)$ e $g(\sigma(t)) = \sigma_{n,max}(\phi,\theta)$ are calculated from material plain to plain, where $\tau_a(\phi,\theta)$ is calculated by using some equivalent stress method and the value of $\sigma_{n,max}(\phi,\theta)$ is determined, in the critical plain where $\tau_a(\phi,\theta)$ is the maximum.

The employment of the Susmel and Lazzarin's criterion determined by the Eq. (11) requires, besides the stress strainer along the time, the determining of two material parameters, such as the fatigue limit in fully reversed loading (R = -1), σ_{-1}, and for the repeated loading (R = 0), σ_{-0}, being $\sigma_{m,-0}$ the mean stress applied in this test condition. These parameters were experimentally acquired as it is detailed presented by L. S. Rossino (2008).

Once the material parameters are defined, the fretting fatigue strength will be assessed by taking into account Susmel and Lazzarin's index error (I_{SU}). For $I_{SU} > 0$ the criterion forecasts failure and for $I_{SU} < 0$ the component achieves infinite life (> 10^7 cycles).

$$\tau_a(\phi^*,\theta^*) + m_1 \frac{\sigma_{n,\max}}{\tau_a}(\phi^*,\theta^*) - \lambda = 0 \tag{11}$$

$$\lambda = m_1 + \frac{\sigma_{-1}}{2} \tag{12}$$

$$m_1 = \frac{\sigma_{-0} - \sigma_{-1}}{2\left(1-\left(\frac{\sigma_{-0}+\sigma_{m,-0}}{\sigma_{-0}}\right)\right)} \tag{13}$$

The multiaxial fatigue criteria estimate that the life or strength of mechanical components is a function of the stress state (or deformation) in a severely requested point, and they don't take into consideration the effects of different stress gradients over fatigue life. By trying to characterize the effect of these stress gradients, the methods basically aim the "critical distance" or "process zone". This critical distance has been considered by some authors (Flavenot, 1989; Fouvry, 2000) as some greatness of microstructural size or a material property, assuming then that this parameter is not dependent of the concentration behavior of stress that acts in the component (Araujo, 2007).

Recent studies show that the problem that involves fatigue under fretting conditions can be assumed as similar to what happens in a component with notch under conventional fatigue, due to the similarity of the stress concentration and the stress gradient, very characteristic of both damaging processes. The critical volume and distance method based

on stress has been widely used to determine the life in notch components. Under fretting conditions, a component is subject to severe stress in the surface that can fall quickly as it gets apart from the contact region. Possible cracks will appear in the regions where the high stress is, but it will grow towards the low stress regions. The failure based in these methods may supposedly happen when the stress average exceeds the fatigue limit of the material over some critical volume generated by the stress concentration (Dini, 2006).
The stress calculus over a critical volume is very complicated; satisfactory estimates of strength in notch components subject to fatigue has been acquired by critical distance methods such as the point, line or area method, as shown on Fig. 5(a) (Dini, 2006). In this work, the point method will be employed to simplify the analysis of the results, where *L* corresponds to the critical distance.

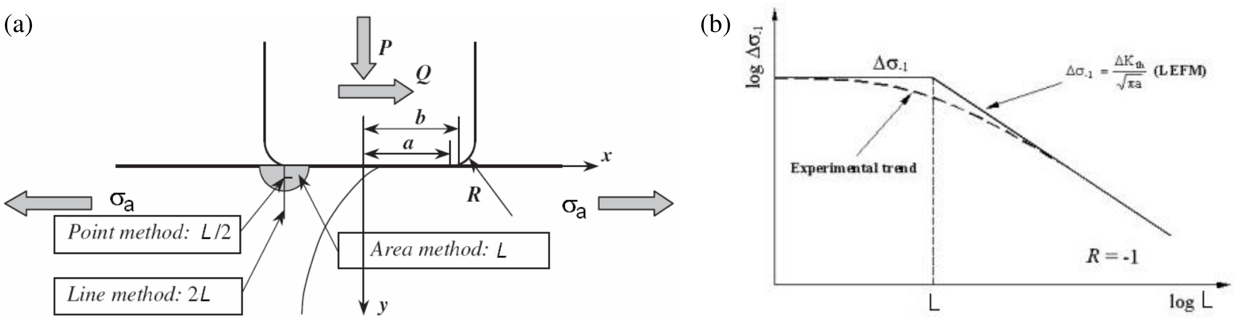


Figure 5. (a) Schematic definition of the critical distance method for fretting fatigue for plain/cylindrical contact, (b) Kitagawa and Takahashi diagram (Dini, 2006, Araújo, 2007)

Then, the next step to use this methodology comprises in determining the *L* parameter or critical distance for the studied material. According to the fact that the critical distance is not influenced by the stress field, this should be determined by a material property. Recently, the critical distance method has been reported due to the material fatigue limit (Tanaka, 1981). To define the critical distance, consider the Kitagawa and Takahashi's diagram as shown on Fig. 5(b), and the Mechanics Theory of Linear Elastic Fracture. Researches observe that many materials present a factor of limit stress intensity (ΔK_{th}) for long cracks regardless the size of the cracks. However, for short cracks, it can be observed that the cracks can be propagates when submitted to a ΔK value smaller than ΔK_{th} of the material as long as the stress is high enough, that is, the range of tractive stress variation experienced by the crack, $\Delta\sigma$, must be bigger than the fatigue limit for the material (Araujo, 2007).

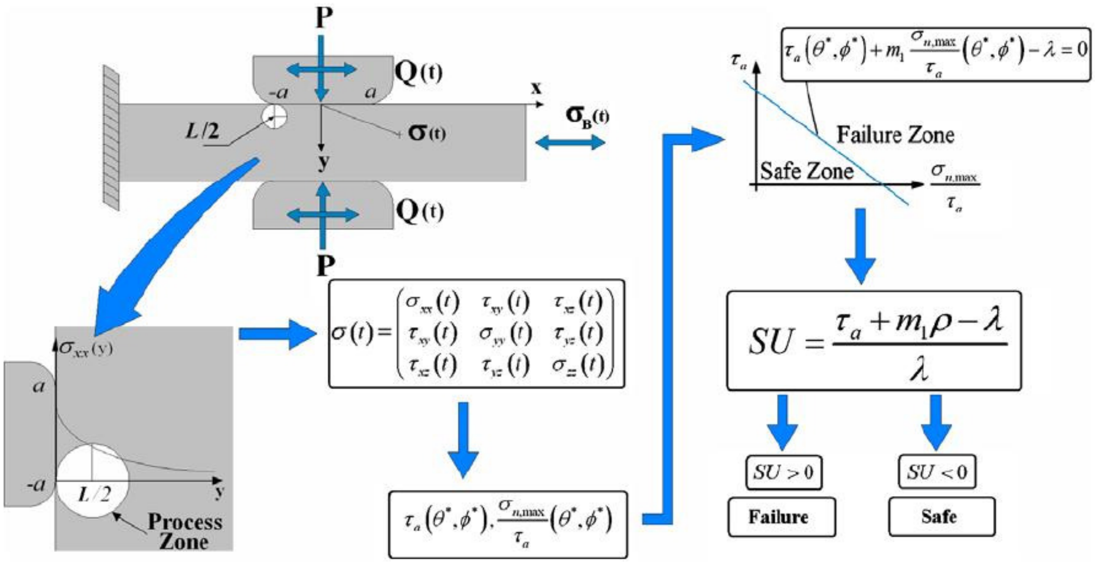


Figure 6. Scheme for applying Susmel and Lazzarin's model in terms of Point Critical Distance Methodology.

Thus, the crack length for transition between the regimes of short and long cracks can be found by the equality of the conditions shown by the Eq. (14). Then, any pair among three parameters that composes the Eq. (14) (ΔK_{th}, $\Delta\sigma_{fl}$ *e L*) can be considered as fundamental property of the material. In practice, of course, there is a huge difference in the transition behavior between short and long cracks, but the experimental and theoretical study of cracks behavior done by Kitagawa and Takahashi (1976) and Tanaka et al. (1981) show that the proximity is reasonable and they ease the studied problem.

$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_{-1}}\right)^2 \tag{14}$$

where ΔK_{th} is the threshold stress intensity factor range and $\Delta\sigma_{-1}$ is the axial fatigue limit range, both under fully reversed loading.

Taking into account that all the described formulation above, Susmel and Lazzarin's multiaxial fatigue criterion will be assessed as in the hot spot (y = 0 and and x = -a), as in depth (y = L) and in the edge end of the contact (x = -a), where the stress strainer will be extract in twelve moments of time along the load cycle. The schematic procedure is represented on Fig. 6.

4. RESULTS AND DISCUSSION

4.1. Fretting Fatigue Life of 7050-T7451 Al Alloy

As a rule, the mean compression stress is favorable while the traction stress are damaging for life in conventional fatigue in the same stress amplitude. This happens because the traction stress (σ_m > 0) favors the opening thus propagation of micro cracks, while the compression stress (σ_m < 0) has the opposite effect (Sharp, 1996). This effect is well known for the cases of conventional fatigue, as observed on Fig. 7(a).

Fig. 7(b) shows the material strength experimentally obtained facing the fretting fatigue tests already performed. It can be observed that the decrease of the mean stress also increases the strength for those cases of fretting fatigue of the studied material, corresponding to the less severe load conditions. For the conditions where the mean stress is null, for the same acquired life of $2,37*10^5$ cycles, the achieved stress amplitude for conventional fatigue condition is about 219,5 MPa, while this value decreases to 92,7 MPa for the cases of fretting fatigue. This reduction in the acquired stress amplitude for the same number of achieved cycles shows that the conditions become much more severe when the fretting load is applied simultaneously to the fatigue load. In this manner it is evident that *fretting* reduces substantially the fatigue strength of the studied material.

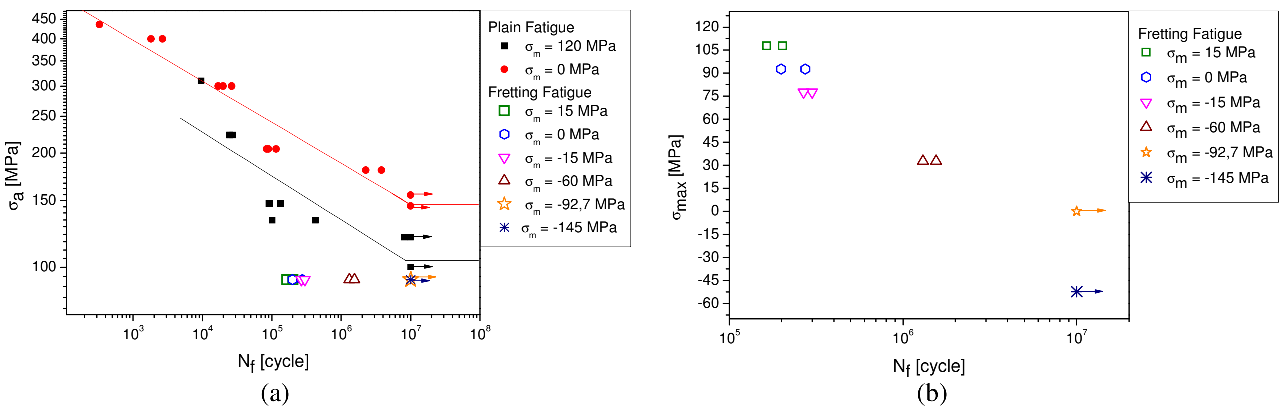


Figure 7. Effect of the mean stress in life (a) by fatigue (b) and by fretting fatigue in the studied material.

Even with a significantly mean stress decrease for negative values, the cracks initiation happens due to the severity of the load conditions caused by fretting, and the fatigue loads that, initially would be very low to cause the cracks initiations (as shown on Fig. 7(a)) for the case of conventional fatigue, are able to propagate it, causing the material rupture. This result was found in cases of mean stress up to -60 MPa where a low maximum stress of traction exists in the material remotely to the surface, Fig. 7(b). When the mean stress is negative enough, keeping the material in compressive cyclic load conditions far from the contact interface, for the cases of mean stress of -92.7 MPa (σ_{max} = 0 MPa e σ_{min} = -185.4 MPa) and -145 MPa for instance, the cracks initiations starts but these become stiff as they separate from the region free of influence of contact loads, making the specimen infinite life. Fig. 8(a) shows these crack arrest for the mean stress test of -92.7 MPa that was interrupted after 10^7 cycles. Fig. 8(b) shows the variation of the maximum value of $\sigma_{xx,max}$ in relation to *y/a*, for *x/a* = -1 (hot spot). This material point is the more requested, so it is called hot spot (Szolwinski, 1998; Proudhon, 2005). It is observed that, in the contact surface (*y/a* = 0) the component $\sigma_{xx,max}$ (responsible for Mode I of crack growth) is positive and of great magnitude for all applied mean stresses. This demonstrates the severity of the stress field for these test conditions, what can be associated to the cracks initiation, even in the presence of compressive mean loads. However there is a strong stress gradient. For a case where the mean stress is -92.7 MPa, the component $\sigma_{xx,max}$ becomes negative for values about y/a = 0.15. In these cases, the high value of $\sigma_{xx,max}$ in the proximity of the contact surface favor the cracks initiation, which did not propagate due to the significant compressive stresses that still appear very close to the surface.

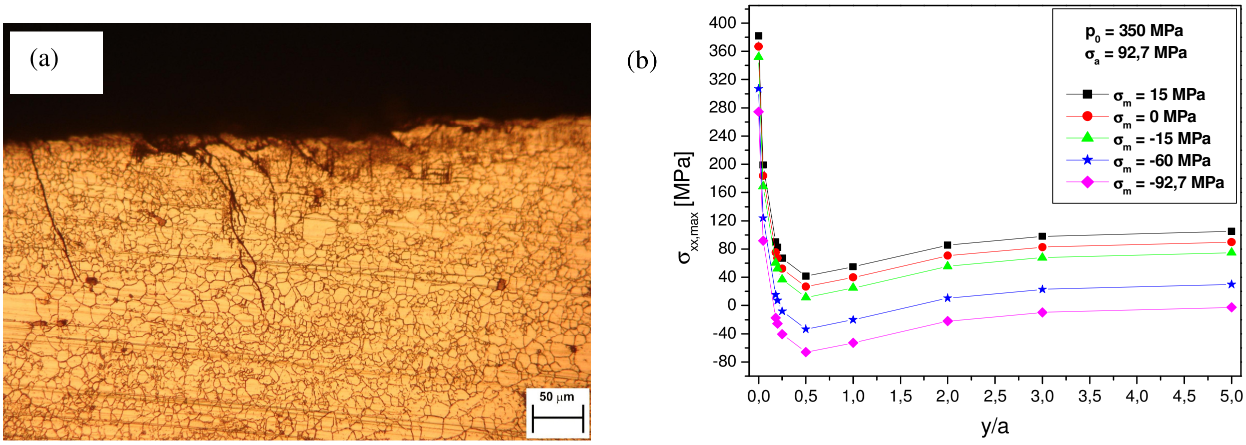


Figure 8. (a) Crack arrest observed in the slip zone of the contact region for σ_m = - 92.7MPa and (b) variation of $\sigma_{xx,max}$ versus depth y/a in x/a = -1

4.2. Fretting Fatigue Strength Prediction

The use of high cycle multiaxial fatigue models, allied to a notch method based on the critical distance theory has been satisfactory to estimate the fretting fatigue strength of aluminum alloys (Araujo, 2002). Then, in order to analyze the efficiency of this theory when determining the fretting fatigue strength for alloy Al 7050-T7451, a series of tests were projected so that the shearing stress amplitude remained constant from test to test, varying only in the values of normal maximum stress over the critical plain. For that, it was kept constant the contact loads and the remote stress amplitude in all tests but the value of mean stress was changed.

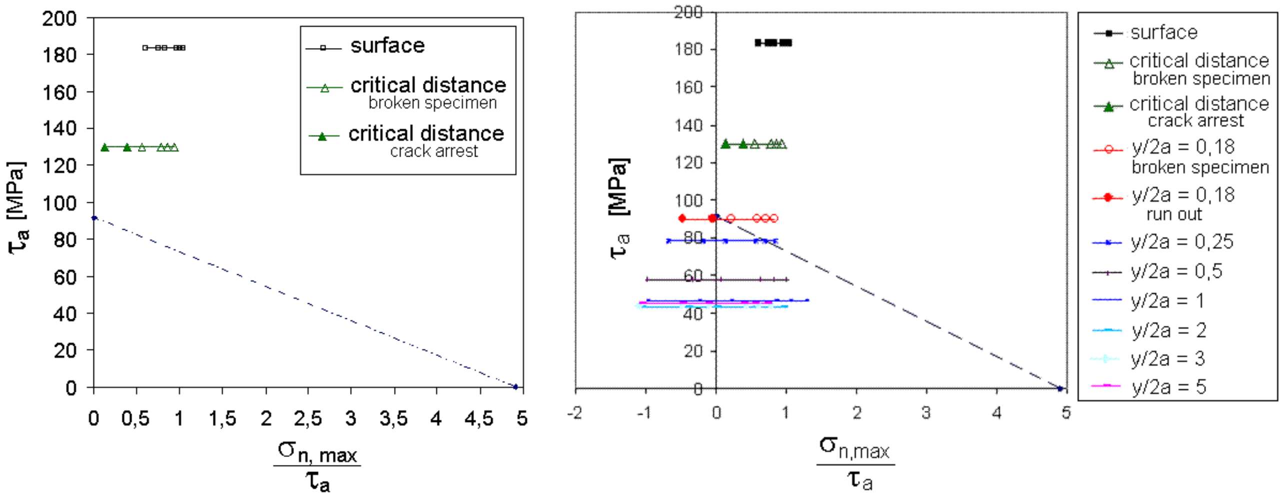
From the values of ΔK_{th} = 5.5 MPa$\sqrt{m}$ to R = -1, for an fatigue limit range it was determined that $\Delta\sigma_{fl}$ = 292.8 MPa, the value of L for the studied material, through the Eq. (14) is 0.1124 mm. Thus, the value of the normalized critical distance related to the contact size (a = 1.19 mm, Eq. (3)) is 0.047 for the test conditions performed in this work.

The material parameter L for a 4%Cu Al alloy corresponds to a 0.1 mm value. This value is very close to the calculated parameter in this work, for Al 7050 Al alloy, using the notch methodology, that is, 0.1124. Araujo et al. (2004) used the experimental data from Nowell's test (1988) observing that the use of the high cycle multiaxial fatigue model combined to the theory of the critical distance proposed by Taylor, it is sufficient to foresee the strength of the 4%Cu Al alloy under the fretting fatigue conditions, being able to determine the effects of the contact size more precisely than the classical hot spot approximation. It must be stated that the maximum value of p_0 applied to the experiments done by Nowell was 157 MPa, that means, mild contact circumstances if compared to the load applied in the test in this work.

Fig. 9(a) shows the fretting fatigue strength based on the high cycle multiaxial fatigue model combined with the critical distance methodology, where the open spots match the estimates for tests that the specimens broke and the closed spots match to the forecast for the tests that achieved infinite life results.

It is observed that the then model foresees the cracks initiation for all the conditions in the contact surface, due to the severe loads which this position is exposed. Considering the critical condition approach, the model also foresees the crack initiation for all test conditions including the tests that achieved infinite life. There are no doubts, thus, about the efficiency of this model on estimating the crack initiation for the analyzed test conditions. However, by analyzing whether such criterion is efficient to determine the component integrity, it is observed that the material strength is wrongly predicted by this method, since the performed tests under the mean stresses -92.7 MPa and -145 MPa achieved infinite life. The practical implication of this is that the use of such criterion could unnecessarily discard components that already experienced infinite life despite of having small cracks arrests.

The stress field was calculated in the hot spot (-1,0), in the critical distance (-1,$L/2a$) and in other depths, (-1, $y/2a$), to determine whether this analysis, calculated in other positions, would be capable to efficiently foresee the integrity (rupture) of the specimen facing the fretting fatigue conditions applied to the then alloy. Fig. 9(b) shows the obtained estimate. It is observed that the fretting fatigue strength is sufficiently foreseen by performing the multiaxial fatigue analysis for different distances of those calculated by the notch methodology. This fact must be carefully analyzed. A possible explanation for this is that the calculus of *L* would not only correspond to a material parameter but also would rely on the contact conditions.



(a) (b)

Figure 9. Fretting Fatigue strength prediction for tests performed under different values of σ_m applied (a) to the critical distance $L/2a$, and for (b) different distances of the contact surface.

Some authors (Chambon, 2006; Dini, 2006; Munoz, 2006; Araujo, 2007) suggest methods that determine the distance of analysis whose cracks are not influenced by fretting and they propagate due to fatigue, however it has not still determined the best way to calculate this parameter taking into consideration the contact conditions. Navarro et al. (2007) estimate fretting fatigue life using the multiaxial fatigue models for Nowell experimental series, where the critical distance is calculated in two ways. In the first case, the critical distance is calculated case by case, considering the stress field generated in each performed test (variable crack size). In the other case, the crack size is predetermined by a material parameter, general for all the experiments. It was observed that the forecast considers the critical size of the foreseen cracks initiation leads to estimates less accurate when compared to another method of variable crack size, mainly in the cases where the initiation phase is more significant than the propagate phase of fretting fatigue cracks. It is suggested that the life forecast under fretting fatigue must also consider the analysis of history of loading, as applied forces and contact geometry, besides the material properties.

Dini et al. (2006) also observed that in a comparative study of determining the critical distance through the notch analogy and short cracks analogy, this last analogy was able to foresee the fretting fatigue strength limit in contacts with more severe stress gradients as the ones applied to an alloy Ti6Al4V, with maximum contact pressure of 665 MPa.

5. CONCLUSION

It is observed that the fretting, applied simultaneously to a fatigue load reduces considerably the component life. The decrease in the applied mean stress increases the material strength facing the performed tests of fretting fatigue. Due to the severity of the contact loads applied in this work, the crack initiation in the sub-surface contact level was inevitable, independent of remote fatigue load; however, its propagation was controlled by the stress field located in the crack around. Remote traction stress fields, even in small magnitudes (σ_m = -60 MPa) were able to propagates the initiation cracks. By the other hand, under more severe compressive stress conditions (σ_m = -92.7 MPa for instance) the existence of cracks arrest was found.

The Susmel and Lazzarin high cycle multiaxial fatigue criterion using the critical distance through the point methodology was able to estimate the fretting fatigue strength of 7050-T7451 Al alloy concerning the existence of cracks. The model was able to precisely determine the effects of the mean stress in fretting fatigue life conditions as well as the existence of cracks arrest in the material. Even so, the theory was not able to determine the ideal critical distance to estimate the full rupture of the studied material under the applied load conditions. Perhaps, by attempting to extend this methodology of crack initiation prediction to assess the final condition of specimen integrity, it will be necessary to calculate the critical distance not only by using the uniaxial fatigue parameters but also it must be considered the contact conditions. This analysis is yet to be studied.

6. ACKNOWLEDGEMENTS

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