Analysis of initial crack path in fretting fatigue

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ABSTRACT. The initial crack path is analysed in a fretting fatigue test with cylindrical contact, where there is a stress gradient and a multiaxial and non-proportional stress state. For this, a cylindrical pad is pressed, with a constant normal load, N, against a dog-bone type fatigue test specimen. Then, the test specimen is subjected to a cyclic axial stress, σ. Due to the cyclical axial stress, the assembly used and the friction between the contact pair, a tangential cyclic load Q is generated. In these tests, both components are made of Al7075-T651 alloy. The crack initiation path along the fracture surface is optically measured using a focus variation technique. The contact stress/strain fields obtained analytically, in junction with the Fatemi-Socie (FS) and Smith-Watson-Topper (SWT) multiaxial fatigue parameters, allow us to determine the controlling parameters of the crack initiation process observed in the tests and to estimate the crack path during the early stage of the crack growth.

KEYWORDS. Fretting Fatigue; Cylindrical Contact; Initiation; Crack Path; Multiaxial Fatigue Criteria.

INTRODUCTION

Fretting is a mechanical contact related damage. This phenomenon is prone to arise in those mechanical joints subjected to time variable loads. As a consequence of these loads, and in most common situations, small relative displacements between contacting surfaces arise, leading to a contact strain/stress field which generates surface cracks [[1]]. In many actual situations, the mechanical joint is also subjected to a global fluctuating load, which by itself may be able to produce the failure of the joint, but in junction with the fretting-initiated cracks, make more likely the failure [[2]].

Today fretting fatigue is a well-documented phenomenon; agents are identified [[3]], many palliatives are available [[4]]-[[6]], the influences of many parameters have been investigated [[2]],[[7]]-[[9]], and some models have been developed in an attempt to predict the fatigue life [[10]]-[[14]]. Regarding the proposed fatigue models, although many of them incorporate the crack initiation phase in their predictions, it is modelled in a coarse manner [[11]],[[12]],[[15]]. Despite this, none of them makes an exhaustive analysis of the crack initiation path resulting in fretting/fretting fatigue. This work deepens into the crack path initiation shape, both experimentally and analytically. For this, a series of experimental tests have been carried out, and the resulting fracture surfaces were analysed in order to characterize the crack when it has only a few microns.

Two frequently multiaxial fatigue parameters were used for the crack initiation analysis: the Fatemi-Socie and Smith-Watson-Topper [[16]],[[17]]. The former is a shear strain based parameter, although it also incorporates the effect of the opening stress; tentatively, this is the most suitable fatigue parameter to be used in the analysis of fretting-initiated cracks. The latter, is a fully based opening stress parameter, and therefore, a less successful behaviour than the former is expected, although this parameter is used in the fretting bibliography giving good results [[12]].

EXPERIMENTAL RESULTS

The fretting fatigue tests analysed are better described elsewhere [[18]]. The material is Al 7075-T651. The setup is shown in Fig. 1. The rectangular cross section of the specimens were 7x10 mm, where the contact is produced at the 7 mm side. The specimens were photographed after failure with the optical microscope, SEM and confocal microscope with the objective of finding the crack initiation points and study the crack at the early stage. In a fretting fatigue test of this type, forces are applied on both sides of the specimen, therefore, there are two contact zones (one of them shown in Fig. 1). But final failure is due mainly to only one of them because usually cracks do not initiate exactly at the same time on both sides. Nevertheless, since the stress concentration in fretting is high, the initiation is fast and after fracture small cracks are always found growing from the other contact zone. These cracks are the ones analysed here. This paper shows the results obtained on a specimen with the following loads: $N = 5800$ N, $Q = 850$ N and $\sigma = 50$ MPa. The number of cycles to failure was 676704.
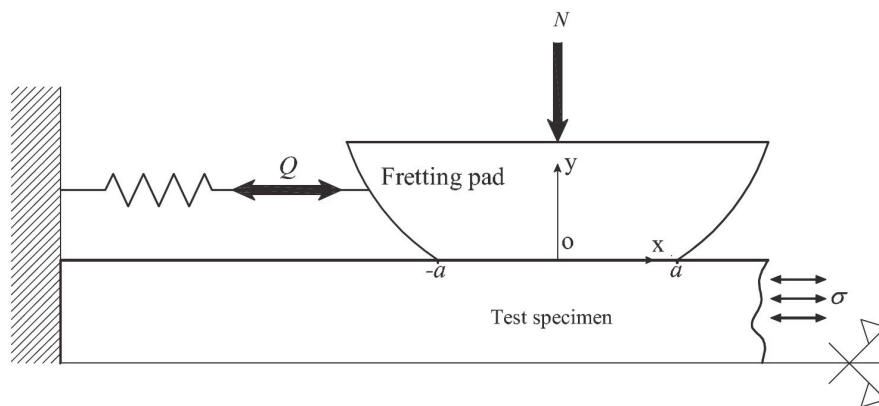

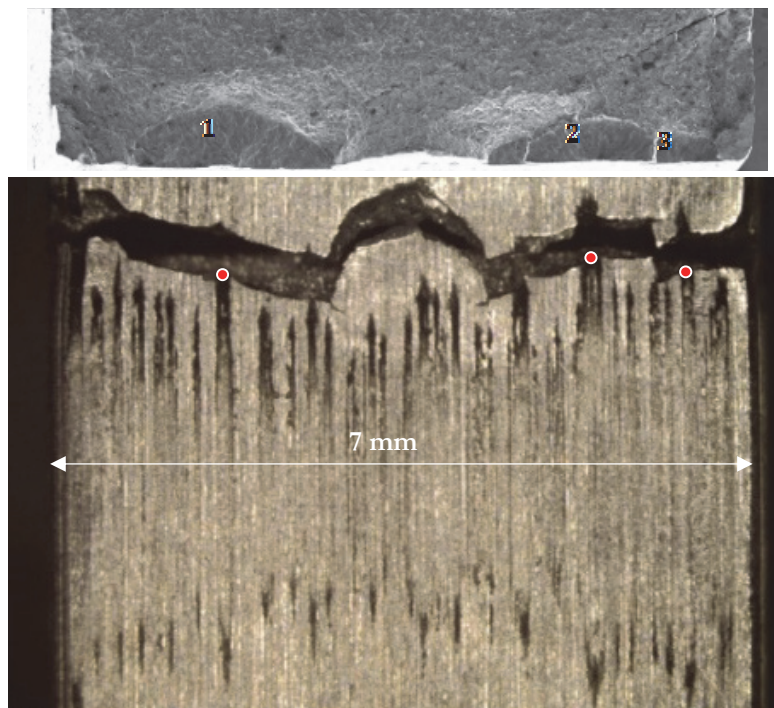Figure 1: Experimental setup in the fretting fatigue tests.

Figure 2: Fretting scar and the fracture surface.

Fig. 2 shows the fretting scar and the fracture surface in this test on the opposite side of the main crack. Three semi-elliptical cracks can be clearly seen. The initiation points are marked with a red dot. The fretting pad surface roughness caused the appearance of the scar with vertical bands. The black area corresponds to the slip zones of the contact. Also, it can be seen that the cracks initiated at the contact trailing edge ($x = a$) or inside the slip zone.

In order to measure the crack initiation angles and path, the fracture surface was analysed with a confocal microscope, obtaining the image shown in Fig. 3, where colour code means the distance from the failure surface to a reference plane. The resolution of the data obtained is 0.65 µm in the plane of the crack (yz plane) and 2 - 3 µm in the x direction. The initiation point is marked with a white dot. This image shows that the initiation point appears at the top of a "hill", i.e. the crack grows around the initiation point with a certain angle towards the inside of the contact and then becomes perpendicular to the contact surface. This paper pays attention to the first zone, which appears red coloured in the image.

The surface data was exported to a text file. Afterwards, several straight radial lines were drawn starting at the initiation point and at different angles (-45º, -35º, -25º, -15º, -5º, 5º, 15º, 25º, 35º, 45º), being 0º the line perpendicular to the surface. The crack surface along these lines is shown in Fig. 4 for each of the three cracks in the specimen. The cracks profile are adimensionlised with the fictitious (from a linear elastic analysis) semi-width of the contact, $a = 2.33$ mm in Fig. 1. This dimension is calculated assuming that the real contact length is not 7 mm but 3.45 mm, as explained later. It can be seen how the crack grows almost perpendicular to the surface for the first 20 µm and then turns towards the inside of the contact with an angle between 20 and 28 degrees from the line perpendicular to the contact.
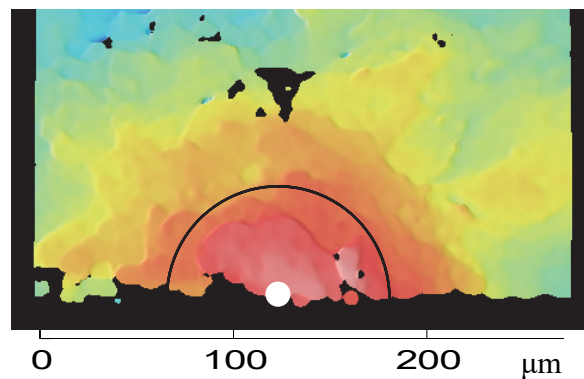

Figure 3: Confocal microscope image of crack 2.

CRACK INITIATION ANALYSIS

In this section, an attempt to reproduce the experimentally observed crack initiation path is made. Three different crack initiation procedures are used in this analysis. The three of them are based on the well known Fatemi-Socie (FS) [[16]] and Smith-Watson-Topper (SWT) [[17]] multiaxial fatigue parameters and will be described later.

As mentioned earlier, the fretting surface scar, Fig. 2, is not ideal and it is obvious that the contact zone is far from being uniform due to an excessive roughness -along the horizontal direction- in the specimen surface and mainly in the fretting pad. To consider this effect in the crack initiation procedures, it is assumed that both normal and tangential loads per unit length are obtained dividing the total load by the real contact length in the horizontal direction. By a digital image processing it is obtained that the real contact length in the horizontal direction is 3.45 mm, leading to a normal and tangential loads per unit length of 1682.2 and 246.4 N/mm respectively.

A 2D (plain strain) linear-elastic analysis using the analytical equations for the mechanical contact between a half-plane and a cylinder [[19]], and considering the above loads with an axial stress of 50 MPa, shows that the maximum von Mises stress produced is less than the yield stress for this material. If in addition, it is considered that the crack initiation phase is only influenced by the very-near surface strain/stress field, therefore, the use of the above linear-elastic model can be justified to analyse the crack initiation process.

First Crack Initiation Analysis Procedure

A scheme of such a procedure is shown in Fig. 5. First, at the trailing edge ($x=a$, $y=0$) the direction which gives the maximum value of the parameter (critical plane) is obtained. The search for this maximum is only done in the xy plane and using increments of 0.1 degrees for the search. Once the critical plane at the trailing edge is found, it is assumed that

the crack advances 1 μm in this direction, (point 2 in Fig. 5). Then at point 2, again the critical plane is determined and a new 1 μm increment of crack length in this direction is assumed, leading to a new point 3. Repeating again and again this procedure a crack path is obtained. This procedure is not orthodox since this is not the way a crack propagates but, nevertheless, it is interesting to see the results and compare them with the other alternatives.
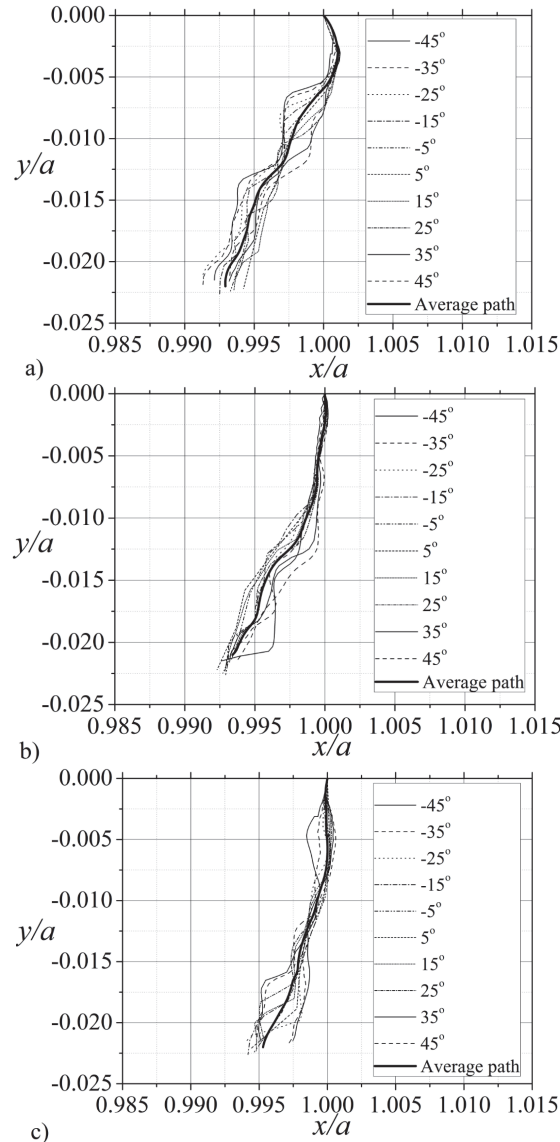

Figure 4: Crack profile at: a) crack 1, b) crack 2 and c) crack 3.

Fig. 6 shows, in addition to the averaged paths for the experimentally observed cracks, the paths obtained with this procedure. First, note that FS parameter, although being the most suitable fatigue parameter for fretting -it combines both shear and normal stresses and would therefore predict better the experimentally observed initiated cracks- produces the worst results, i.e., the predicted crack path grows outside the region beneath the contact zone. On the other hand, the SWT parameter predicts a crack path growing into the region beneath the contact zone, similar to the one obtained experimentally. It is important to recall that the FS parameter and, therefore, the critical plane orientation, depend on the value considered for the k parameter. This parameter, k, measures the relative importance of the stress normal to the crack plane in the Fatemi-Socie criterium. Nevertheless, the results are very similar even when varying the value of k from 0.44 [[12]] –being this value used for the path shown in Fig. 3– up to an exaggerated value of 100.
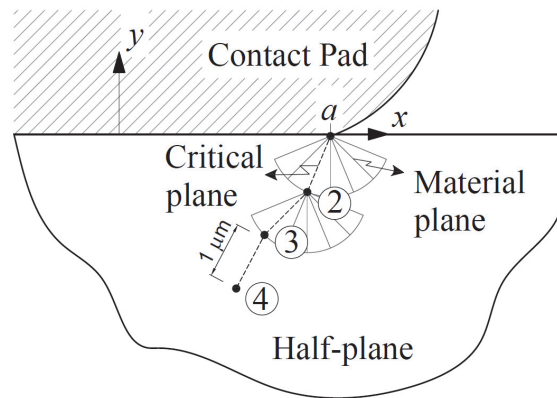
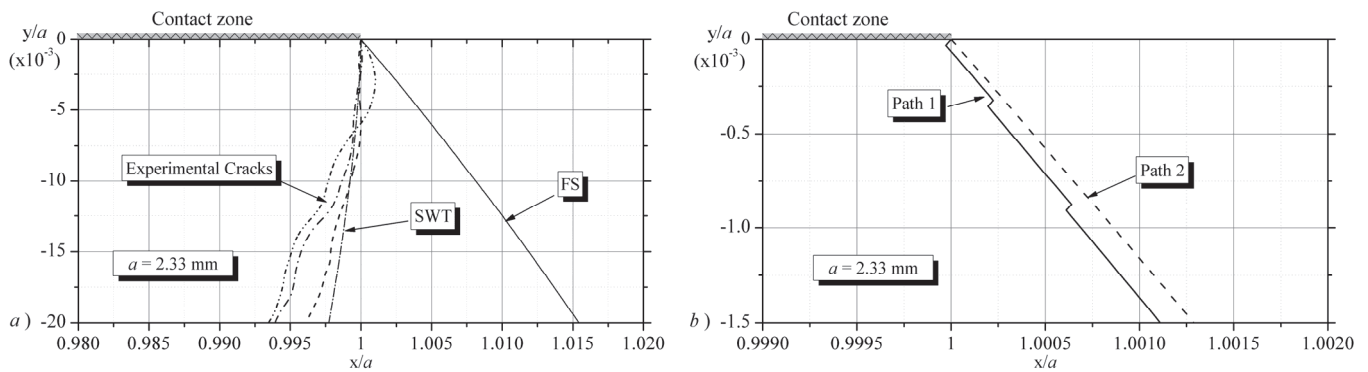Figure 5: Scheme for first crack initiation procedure.

Figure 6: Crack paths predicted with the first procedure.

It is worthwhile pointing out that in the analysis using the FS parameter, and at the trailing edge, two possible critical planes appear, i.e., two planes producing the same maximum value for the parameter. One critical plane points towards the region beneath the contact zone (path 1) and the other outside (path 2), Fig 6b. The path considering the first critical plane (path 1) rapidly and abruptly rotates and follows a path nearly identical to that pointing towards the region outside the contact zone (path 2). According to this, it is virtually irrelevant whether one or the other initial critical plane is considered.
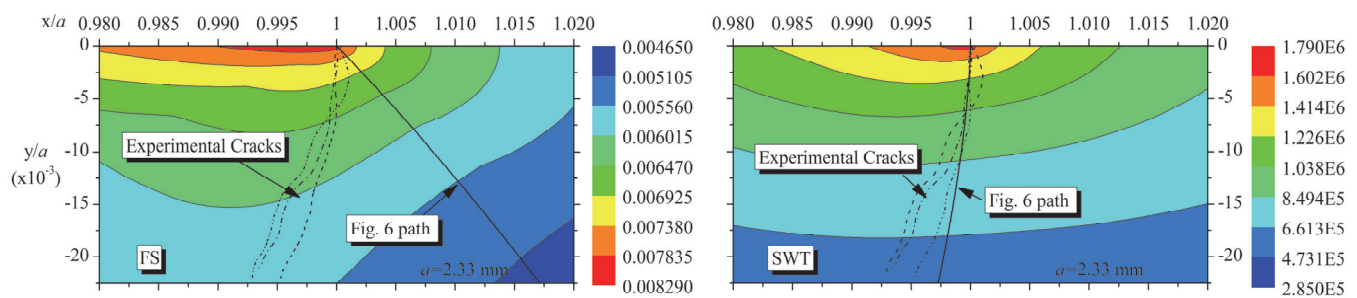

Figure 7: Contour plots for the FS and SWT parameters.

Second Crack Initiation Analysis Procedure
This procedure only shows the zones with a higher level of damage and gives a hint of the crack initiation path. Fig. 7 shows, in addition to the paths of Fig. 6 and the experimental cracks, the contours plot obtained using both fatigue parameters. Regarding the FS parameter contour plot, it is clear that the most likely area for crack initiation is that beneath the contact, and the reasoning for this fact is clear, this area presents, in terms of the parameter value, a lower gradient than the region that is not beneath the contact zone. Therefore, beneath the contact any possible crack initiation path presents higher mean values of the FS parameter than a crack path growing outside the region beneath the contact zone.

For the SWT parameter, although less significant than in the FS parameter, the same behaviour is observed but now only in the very close area to the surface.

While this procedure may give a "*visual approach*" to the crack initiation path, it is important to note that only the maximum values of the parameter are here considered, and no specific information is given about the critical plane orientation (crack initiation angle). Under this circumstance, it is possible that nearby points have completely different critical plane orientations.

Third Crack Initiation Analysis Procedure

This is a variation of the second procedure, introducing the information of the critical plane. However, this third procedure has the drawback that only assumes straight crack initiation paths. A scheme of this procedure is shown in Fig. 8. First, a straight line starting from the contact trailing edge and forming an angle θ related to the vertical is considered. Then, the parameter value is calculated along this line, but with the characteristic that for all these points, the material plane orientation considered for the parameter evaluation coincides with that defined by θ. This is repeated for different values of θ obtaining the contour plot in Fig. 9. Now, and because all points along a straight line have the same material plane for the fatigue parameter evaluation, it is feasible to pose that those lines having the higher mean values of the parameter along a certain length are more likely to initiate cracks. Fig. 9 also includes the paths of Fig. 6 and the experimental cracks. Now, clearly both, FS and SWT parameters, predict crack initiation paths that point toward the region beneath the contact. To obtain more precisely the preferred direction, the mean values obtained for each parameter in a distance of 50 μm -which is the average grain size for the Al-7075-T65- are represented in Fig. 10 as a function of angle θ. This graph shows that angles of 54º and 9º offer the maximum mean values for the FS and SWT respectively. Lines having these angles are plotted in Fig. 9. First, note that, although with an angle far from the experimentally observed, now the FS parameter produces a crack initiation path that qualitatively has the right direction. On the other hand, once again the SWT parameter offers the best prediction, and also, note that this path is quite similar to the previous one obtained with the first procedure.
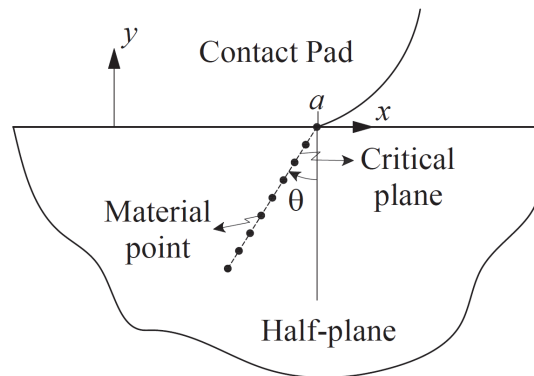

Figure 8: Scheme for the third crack initiation procedure.
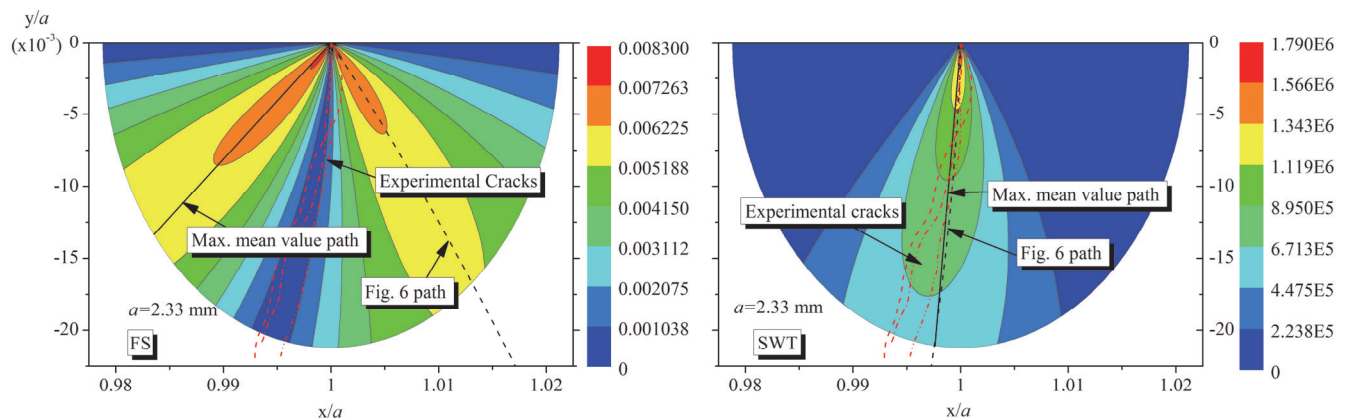

Figure 9: Polar contour plots for the FS and SWT parameters.

CONCLUSIONS

The experimental analysis shows several things about the initiation of cracks in fretting fatigue with cylindrical contact. One of them is that cracks, after a few microns of growing almost perpendicular to the surface, tend to grow at an inclined angle towards the inside of the contact. This angle, around 25° to the perpendicular of the contact plane, has been measured in one test. The cracks are semi-elliptical similar to the ones found in fretting fatigue with spherical contact. Not many cracks are initiated at the same time, three in this case, although this may be because of the high roughness of the surface. More tests with a lower roughness should be performed in order analyse this effect.

From a theoretical point of view, "growing" the crack using the critical plane at each point is not correct, although in the case of SWT it predicts a crack path very similar to the third procedure and similar to the experiments. Searching for the direction with lower gradient of the fatigue parameter or the direction of higher mean value over a certain distance is more suitable. From the multiaxial fatigue parameters used in this paper, it seems that SWT gives better results.
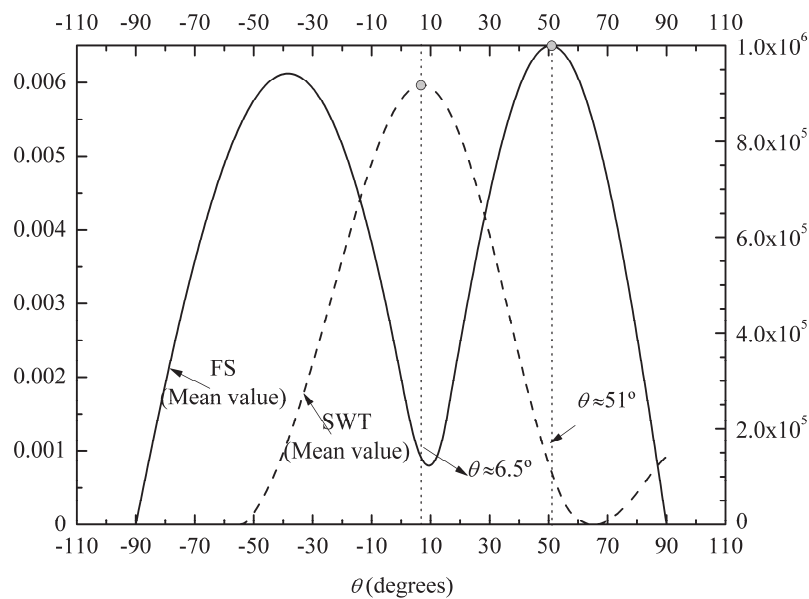

Figure 10: Mean value of FS and SWT vs. θ.

ACKNOWLEDGMENTS

REFERENCES

[1] Waterhouse, R.B., Fretting fatigue, London: Applied Science, Publisher (1981).

[2] Nishioka, K., Hirakawa K., Fundamental investigation on fretting fatigue: Part 4, the effect of mean stress, Bull. Jpn. Soc. Mech. Eng., 163 (1969) 408–414.

[3] Dobromirski, J.M., Variables of fretting process: are there 50 of them?, in: ASTM STP, vol. 1159, Standardization of fretting fatigue test methods and equipment, (1992) 60–6.

[4] Vázquez, J., Navarro, C., Domínguez, J., Experimental results in fretting fatigue with shot and laser peened Al 7075-T651 specimens, Int. J. of Fatigue, 40 (2012) 143–153.

[5] Hattori, T., Nakamura, M., Ishizuka, T., Fretting fatigue analysis of strength improvement models with grooving or knurling on a contact surface, in: ASTM STP, vol. 1159, Standardization of fretting fatigue test methods and equipment, (1992) 101-114.

[6] Chivers, T.C., Gordelier, S.C., Fretting fatigue palliatives: Some comparative experiments, Wear, 96 (1984) 153-175.

[7] Nishioka, K., Hirakawa, K., Fundamental investigation on fretting fatigue – Part 5. The effect of relative slip amplitude, Bull JSME, 12 (1969) 692–7.

[8] Nowell, D., Hills, D.A., Moobola, R., Length scale considerations in fretting fatigue, in: ASTM STP, vol. 1367, (2000) 141-153.

[9] Iyer, K., Mall, S., Analyses of Contact Pressure and Stress Amplitude Effects on Fretting Fatigue Life, J. Eng. Mater. Technol., 123 (2001) 85-93.

[10] Muñoz, S., Navarro, C., Domínguez, J., Application of fracture mechanics to estimate fretting fatigue endurance curves, Engng. Frac. Mech., 74 (2007) 2168–2186.

[11] Navarro, C., Muñoz, S., Domínguez J., On the use of multiaxial fatigue criteria for fretting fatigue life assessment, Int. J. of Fatigue, 30 (2008) 32–44.

[12] Navarro, C, Vázquez, J., Domínguez, J., A general model to estimate life in notches and fretting fatigue, Eng. Fract. Mech., 78 (2011) 1590–1601.

[13] Vázquez, J., Navarro, C., Domínguez, J., Two dimensional versus three dimensional modelling in fretting fatigue life prediction, J. Strain Analysis, 51 (2016) 109–117.

[14] Navarro, C., Muñoz, S., Domínguez, J., Propagation in fretting fatigue from a surface defect, Tribology International, 39 (2006) 1149-1157

[15] Szolwinski, M.P., Farris, T.N., Mechanics of fretting fatigue crack formation, Wear, 198 (1996) 93-107.

[16] Fatemi, A., Socie, D.A., Critical plane approach to multiaxial fatigue damage including out-of-phase loading, Fatigue Fract. Eng. Mater. Struct., 11 (1998) 145–165.

[17] Smith, R.N., Watson, P., Topper, A., A stress strain function for the fatigue of metals, J. Mater. JMSLA, 5 (1970) 767–78.

[18] Vázquez, J., Navarro, C., Domínguez, J., Effect of the model's geometry in fretting fatigue life prediction, Fratt. ed Integrità Strutt., 30 (2014) 109-117.

[19] Johnson, K.L., Contact Mechanics. Cambridge University Press, (1985).