Fretting fatigue under variable amplitude loading
considering partial and gross slip regimes: numerical
analysis

A.L. Pinto^{a,c,*}, R.A. Cardoso^b, R. Talem^c, J.A. Araújo^a

^a*Department of Mechanical Engineering, University of Brasilia, 70910-900 Brasilia, DF, Brazil*
^b*Department of Mechanical Engineering, Federal University of Rio Grande do Norte, 59078-970 Natal, RN, Brazil*
^c*Department of Materials Engineering, KU Leuven, 3001 Leuven, Belgium*

Abstract

The main aim of this work was to numerically investigate the effect of sequences of variable amplitude shear loading on contact tractions/stresses and on the development of life estimation methodologies for these more challenging loading histories. In this setting, a finite element (FE) model has been implemented in order to simulate a cylinder on plane contact problem for an aeronautical Al 7075-T651 alloy. High-Low (H-L) and Low-High (L-H) shear amplitude loading sequences under partial and gross slip conditions were considered in three different case studies. For the case studies where gross slip was involved, the proposed life estimation procedure was enhanced to include the effect of material loss due to wear. More explicitly, such procedure was based on the use of (i) the SWT(Smith-Watson-Topper) multiaxial fatigue model, (ii) the Theory of Critical Distances, (iii) Miner’s cumulative damage rule and (iv) the numerical update of the contact surfaces profiles (for loading blocks under gross slip). The numerical analyses for the case studies under partial slip revealed that, when the presence of wear is neglected in the modelling, the Miner’s rule provided a divergence between the expected life for the H-L and L-H loading blocks. This difference was considerably larger when gross slip took place. For the case study involving the presence of gross slip in one of the shear loading blocks, the calculated life tended to infinite when the damage generated by the high amplitude block is greater than a certain critical value. These studies are the basis for an experimental programme which will be carried out in the 4 actuators fretting fatigue rig of the University of Brasilia.

Keywords: Fretting Fatigue, Multiaxial Fatigue, Variable Amplitude Loading, Wear.

*Corresponding author

1. Introduction

Fretting occurs when two contacting parts are subjected to fluctuating loads, which provokes relative slip of small amplitude between them. Strong stress gradients and wear due to the contact loads may lead to the early initiation of cracks. In this case, in presence of bulk fatigue loads, one has the so-called fretting fatigue phenomenon. Under such conditions, initiated cracks may propagate at high rates resulting in strong fatigue resistance reductions [1]. Fretting fatigue takes place in many practical situations such as gears, aircraft fuselages, connection between rotor and blades in jet engines, flanges, bolted joints in pipelines and overhead conductors [2, 3, 4, 5]. Fretting fatigue studies and tests have been carried under constant amplitude loads [6, 7, 8, 9]. However, in practice, under actual working conditions, components such as the blade and disk attachment and overhead conductors are subjected to variable amplitudes over time [10, 11]. In such cases, some questions are not trivial to respond, for instance: how to determine the fatigue life of a component subjected to variable fretting loading conditions from the knowledge of simple stress (S) $\times$ life (N) curves of the material? How to account the strong stress gradient inherent to fretting problems? Is it necessary to consider wear in such analysis?

In order to predict the fatigue life of a component subjected to variable amplitude loads, or to random loads, a cumulative damage law must be used. Palmgren-Miner's law, or simply Miner's rule [12, 13], is one of the best known in the technical literature. This is a linear damage accumulation rule, i.e., it estimates that the order of application of the variable amplitude loading blocks does not change the component fatigue resistance, as long as the total damage produced by such blocks is the same at the end. According to this law, the order of application of the load blocks with variable amplitude does not change the fatigue resistance or the fatigue life of the material as long as the fatigue damage per each block is the same. In this setting, it is important to verify Miner's law applicability evaluating its performance in classical fretting fatigue tests subject to loadings with variable amplitude. Although there are a few works evaluating fretting fatigue response under variable amplitude loading conditions, most of them rely on the construction of fatigue resistance curves for further comparison with variable amplitude loading conditions. In this case, even when Miner's rule is considered, simple uniaxial fatigue approximations are adopted. In this setting, a brief review of previous works in this field is here presented.

In the early 1980s Kantimathil and Alic [14] reported fretting fatigue tests conducted on the 7075-T7351 experiencing variable loading. Specimens were subjected to constant amplitude loading conditions followed by tensile overloads applied at each 1000 cycles. Compressive overloads were also assessed. For the constant amplitude loading cycles, different load ratios were considered. From their results, they have observed that the influence of the overloads were negligible for constant amplitude cycles with high maximum bulk stresses. However, for lower maximum values of the bulk stress in the constant amplitude cycles, overloads seemed to have a beneficial effect in terms of fatigue resistance, which may be explained by crack growth retardation due to plastic deformation at the

crack tip.

Mutoh et al. [15] published a paper in 1987 where they examined the fretting fatigue resistance of a low strength medium carbon steel for two-step variable amplitude loading blocks. Each block consisted of n_1 cycles at a given bulk stress amplitude σ_1 followed by n_2 cycles at σ_2 . In other words, each block consisted of $(n_1 + n_2)$ fretting cycles. Different combinations of n_1 and n_2 per block were considered in their analysis. They concluded that when the block contained a large enough number of cycles and the number of blocks to failure were smaller than 5 or 6, the variable amplitude loading condition lead to life reductions up to 10 times. It was also shown that Miner's linear rule did not always provide good estimates, as it was the case for plain fatigue conditions. Besides, they have highlighted that fretting fatigue life is highly influenced by the number of cycles at high stress levels, where cack growth rates become significant.

Two years later, Mutoh et al. [16] investigated the fretting fatigue resistance of a high strength steel under random loading conditions. Two load spectrum were examined (A and B). In spectrum A, the maximum value of the bulk stress was 45 % greater than its RMS over time, while in spectrum B it was 85 % greater. Overall speaking, random loading conditions reduced fretting fatigue lives by a factor of 1.5. In addition, Miner's rule led to satisfactory life estimates but being generally nonconservative.

In the late 1990s Troshchenko et al. [17] investigated the fatigue damage accumulation in Al and Ti alloys under variable loading conditions in the presence of stress concentration and fretting conditions. In their analysis, failure is not necessarily assumed to occur when Miner's cumulative damage reaches the unity. Then, they reported that damage computations by assuming Miner's linear rule for the fretting fatigue case under variable amplitude loading were equal or exceeded those from smooth specimens. The work was based on the construction of S-N curves considering constant amplitude conditions for a further comparison with tests carried out under variable amplitude programs.

Cortez et al. [18], in the same period, investigated the fretting fatigue behavior of the Ti-6Al-4V under constant and variable amplitude loading. Besides, they also evaluated the influence of the loading frequency on the experiments. For the variable amplitude loading tests, the loading history consisted of 500 high-frequency small amplitude cycles at 200 Hz followed by a single large amplitude cycle at 1 Hz. The maximum load for small and large amplitude cycles were the same. Different positive load ratios were considered in the small amplitude cycles while a load ratio of about 0.1 was observed in the large amplitude cycles. Two main conclusions were drawn concerning the variable amplitude loading tests. Firstly, it was observed that the variable amplitude loading conditions did not present a significant impact on the fretting fatigue resistance of the Ti-6Al-4V assessed. In addition, from the constant amplitude fretting fatigue loading tests, they have used Miner's rule to estimate life at variable loading conditions. In this case, Miner's rule provided reasonably accurate results although slightly optimistic.

Kinyon and Hoepfner [19] in 2000 also presented interesting results concerning fretting fatigue tests under variable amplitude loading. Tests were carried

out on a Ti alloy. Three different amplitudes of bulk stress were considered in their analysis ($\sigma_1 > \sigma_2 > \sigma_3$), where both two and three-step loading blocks were investigated. For the two-step loading tests, the loading sequence consisted of one cycle subjected to σ_1 followed by another cycle subjected to σ_2 . These two cycles with different amplitudes were repeated up to the specimen's failure (Case 1). Similarly, another two-step loading block was considered but at this time replacing σ_2 by σ_3 (Case 2). For the three-step loading set (Case 3), the specimen was subject to one cycle at each stress amplitude σ_1 , σ_2 and σ_3 , where these three blocks were repeated until failure. Throughout fretting fatigue tests performed with constant amplitude loads (σ_1, σ_2 and σ_3), the authors found that the application of Miner's rule provided unsafe life estimates for the Case 1 and conservative predictions for the Cases 2 and 3. At the end, the authors claimed that Miner's rule did not seem appropriate to model fretting fatigue lives.

In the 2000s Kondo et al. [20] investigated the fretting fatigue behaviour under variable amplitude loading conditions for a low alloy steel. In their work, the authors first obtained a fretting fatigue limit diagram (like the modified Goodman line) when considering constant amplitude loadings. Different tests were carried out considering the same contact indentation load but with different fatigue load ratios. At this stage, for fatigue limit conditions under small mean bulk loads, non-propagating cracks were observed. As the mean bulk load was increased in the tests, cracks were not formed at all. In the next, the authors carried fretting fatigue tests considering repeated two-step loadings. In this setting, one of the loading blocks considered fatigue limit conditions by the application of a fully reversed fatigue stress (σ_1), while the other block, with amplitude σ_2 , was set considering positive mean stresses. It is worth noting that, in this case, σ_2 was chosen well below the fatigue limit obtained from the fretting fatigue limit diagram with constant amplitude. Summarizing, it was observed that, even though σ_1 and σ_2 were below the fatigue limit for constant amplitude loading conditions, the repeated two-step loading of σ_1 and σ_2 could lead to failure. At the end of the paper, these authors highlight that care should be taken when using fatigue limit data from constant amplitude fretting fatigue tests once under variable amplitude loading, failure may occur even for stresses below fatigue limit conditions.

Massingham and Irvin [21] in 2006 start their work by highlighting the lack of investigations on fretting fatigue under variable amplitude loading. They have developed a finite element model to assess the influence of overloads followed by the maintenance of constant amplitude loads during the simulations. As the main conclusion, it is verified that in spite of the application of two or more overload cycles, the position of the stick-slip zone boundary as well as shear stress distributions depends only on the largest previous cycle. In other words, the order that the overloads are applied is important in determining whether shear stress distributions are modified, besides, it is the largest previous overload that will dictate the shear stress distribution in subsequent smaller amplitude cycles. The authors also suggest that these changes in stress distribution tends to make linear damage rules act conservatively.

More recently, Gandiolle and Fouvry [22] have conducted experiments and

a numerical study in order to evaluate the crack propagation rate for fretting fatigue under variable loading conditions. Crack length was obtained during the tests by using a potential drop technique. Further, a numerical decoupled approach was used to obtain the crack stress intensity factor, which allowed relating the crack extension with the number of cycles by considering Paris law. Even though they have not focused on the specific effects of considering variable amplitude loads, the strategy permitted the estimate of important parameters such as crack arrest, the crack extension and the number of cycles to failure.

This comprehensive review of the state of the art on variable amplitude fretting fatigue revealed that most of the research carried out up to now was based on the use of (i) S-N curves generated by fretting fatigue tests performed on one actuator fretting fatigue devices (thus bulk and fretting loads are coupled), (ii) the use of Miner's damage rule and (iii) uniaxial fatigue analysis to estimate life. This is obviously a rather simple research approach as it misses the systematic investigation of a number of well know important characteristics of the fretting problem such as the wear, the stress gradient, the multiaxial state of stress, the varying stress ratio, contact nonlinearities, among others parameters. As there is a lack of control of such parameters in these previous works, it has not been possible to draw more firm conclusions even about the applicability of Miner's linear damage rule to fretting fatigue [15, 16, 17, 18, 19]. Although more detailed studies have been proposed more recently [21, 22], they are clearly just a few, which considered a limited range of materials and loading conditions.

In this setting, the aim of this work was to numerically investigate the effect of sequences of variable amplitude shear loadings on contact tractions/stresses and on the development of life estimation methodologies for these more challenging loading histories. In this setting, a finite element (FE) model has been implemented in order to simulate a cylinder on plane contact problem for an aeronautical Al 7075-T651 alloy. High-Low (H-L) and Low-High (L-H) shear amplitude loading sequences under partial slip conditions or under a mix of partial and gross slip conditions are considered in three different case studies. For the case studies where gross slip was involved, the proposed life estimation procedure was enhanced to include the effect of material loss due to wear. As far as the authors are aware, this is the first attempt to investigate the impact of sequences of variable shear amplitude loadings, which provoke a mix of different contact slip regimes (partial and gross), on fretting fatigue life. Also new is the investigation on the role of wear in the life estimation methodology for variable amplitude loading. At last but not least, it should be remarked that another important contribution of this work is the fact that it constitutes the basis for the generation of experimental data (design of tests), which will allow to validate (or not) the different hypothesis considered to construct the life estimation procedure.

2. Multiaxial fatigue life estimation

Several approaches and damage parameters can be applied to problems subjected to fretting conditions. These parameters can be classified conceptually as

critical plane approaches [23, 24, 25], stress invariant approaches [26, 27], fretting specific parameters [28, 29] and continuum damage mechanics approaches [30, 31]. The model used in this study was the Smith-Watson-Topper (SWT) which is a multiaxial strain energy based critical plane approach [24]. This parameter is better suited for materials and loading conditions where cracks propagate perpendicular to the direction of maximum principal stress and strain (Mode I cracks). The SWT criterion can be applied to both low and high cycle fatigue. In addition, this model can also handle non-proportional loading conditions [32]. All those features associated with its simplicity made this parameter one of the most popular in determining fatigue life and planes of crack initiation [33]. The SWT parameter can be defined as:

$$SWT = \sigma_{n,\max} \varepsilon_{n,a} \quad (1)$$

where $\sigma_{n,\max}$ and $\varepsilon_{n,a}$ are the maximum normal stress and the strain amplitude on the material plane that maximizes their product. It also allows estimating the component life by reference to a fully reversed uniaxial test where stress (Basquin) and strain (Coffin Manson) life relations can be combined yielding:

$$\sigma_{n,\max} \varepsilon_{n,a} = \frac{\sigma'_f}{E} (2N_f)^{2b} + \sigma'_f \varepsilon'_f (2N_f)^{b+c} \quad (2)$$

where σ'_f and ε'_f are the fatigue strength and ductility coefficients, respectively, while b and c are the fatigue strength and ductility exponents, respectively.

3. Critical distance approach

The mechanical contact in the fretting problem is a stress raiser and, in this case, it is necessary to consider the effects of the stress gradient caused by the contact between the surfaces. In the 1930s, the development of the Theory of Critical Distance (TCD) was started with the works of [34, 35] in an attempt of predicting fatigue failures in metallic components in the presence of geometric features. Neuber proposed the Line Method (LM) and Peterson the Point Method (PM). Whitney and Nuismer [36] evaluating monotonic loading conditions were capable of defining the critical distance for the PM and LM through a relationship between the Mode I fracture toughness, K_{Ic} , and the tensile strength of smooth specimens. A decade later Tanaka presented a relation with an identical theoretical derivation and equally valid when applied to High Cycle Fatigue (HCF) [37]. Subsequently, several studies were carried out with the objective of proving the feasibility of predicting the fatigue limit resistance by using the TCD for HCF [38, 39, 40].

In general, the TCD define an effective stress, σ_{eff} , which is obtained through an averaging procedure over a volume surrounding the stress raiser. The method assumes that fatigue failures occurs when σ_{eff} exceeds a reference material strength. For 2D analysis, the volume method can be simplified by considering stress averages over an area, line (Area and Line Methods, respectively) or even at a point located at a critical distance, L , from the stress raiser

Figure 1: Schematic representation of the Point Method.

(Point Method) [41]. The PM is used in this work, Figure 1. In this approach, for HCF, the critical distance assumes the following form [39]:

$$L = \frac{1}{2\pi} \left(\frac{\Delta K_{th}}{\Delta \sigma_{-1}} \right)^2 \quad (3)$$

where, ΔK_{th} is the threshold stress intensity factor range and $\Delta \sigma_{-1}$ is the uniaxial plain fatigue limit range both obtained at fully reversed loading configurations.

On the other hand, the relation to estimate the critical distance to static strength of notched members is given by [42, 43]:

$$L_s = \frac{1}{2\pi} \left(\frac{K_{Ic}}{\sigma_r} \right)^2 \quad (4)$$

where the K_{Ic} is the plane strain fracture toughness and σ_r is a reference material constant which may be equal to or greater than the ultimate tensile strength, S_{ut} .

As can be seen in Equations (3) and (4), the values of the critical distances under fatigue and static loading are usually different, which leads us to assume that, the critical distance, L_M , at medium-high cycle fatigue regime depends on the number of cycles to failure, N_f . In this work, as a simplifying procedure, one assumes that $L_M = L$ for any number of cycles.

4. Wear model

In order to model wear by means of material loss, the most commonly used models are the Archard's law [44] and dissipated friction energy [45]. Several authors have published works by using these models to account the material removal due to wear when fretting takes place [46, 45, 47, 48, 49, 50]. Some other were also published out of the fretting scope [51, 52, 53].

In this work, Archard's law is used to model wear and according to this, the volume of material removed by surface wear can be calculated as follows:

$$V = \frac{K}{H} P s \quad (5)$$

where P is the normal load, s is the slip distance, H is the hardness of the material (MPa) and K is a dimensionless constant. In Equation (5), the ratio K/H can be replaced by the specific wear coefficient, κ . McColl et al. [46] developed a local version of the Archard's equation with the objective of using it on a nodal basis in finite element analyses. With their formulation it is possible to calculate the local wear depth through the following relation:

$$dh = \kappa p(x) ds \quad (6)$$

where, dh is the local depth of material removed for a given incremental relative slip ds and p is the contact pressure. For practical reasons, in this formulation, the local wear coefficient κ is assumed to be constant over the fretting cycles and have the same value along all the contact region. Additionally, it can be obtained from measured wear profiles of experimental tests [46].

Therefore, for an incremental implementation of Equation (6) in a FE framework one has:

$$\Delta h_{i,j} = \sum_{k=1}^{n_{inc}} \kappa p(x_j, t_k) \Delta s(x_j, t_k) \Delta N \quad (7)$$

where $\Delta h_{i,j}$ is the wear depth increment for the node j on the contact surface for the i_{th} fretting cycle simulated and n_{inc} is the number of increments of the i_{th} fretting cycle. The contact variables $p(x_j, t_k)$ and $\Delta s(x_j, t_k)$ are the contact pressure and the relative slip increment, respectively, for the node j at the time increment t_k . Note that Equation (7) is multiplied by a factor ΔN . For problems involving high number of cycles such as the fretting problem, it is a common practice to amplify wear computation by an accelerator factor ΔN [46, 47, 54, 55, 49, 50]. In this case, if one wants to consider the total number of cycles, N_t , in the analysis, one has to simulate only $N_t/\Delta N$ fretting cycles. The choice of ΔN must be carried out carefully so that it minimizes computational costs without introduce instabilities to the solution [46].

5. Application to fretting fatigue

Most of the works on fretting fatigue generally consider constant amplitude loadings in the analyses. A typical loading configuration adopted to evaluate fretting fatigue problems is depicted in Figure 2. In this case, firstly a normal load, P , is applied to cylindrical pads ensuring contact conditions. After that, this normal load is held constant while a tangential oscillatory load is applied to pad in phase with an alternate bulk load, F_b , prescribed on the specimen. Depending on the slip regime, i.e. for gross slip conditions, the tangential load, Q , is replaced by a prescribed tangential displacement δ .

The main objectives of this work are (i) to carry out a numerical analysis to design a set of tests which will allow one to study the effects of variable amplitude loading (under partial slip and under mix gross-partial slip regime)

Figure 2: Standard fretting fatigue conditions: (a) contact configuration, (b) loading history.

Figure 3: Schematic representation of the loading configurations: blocks H-L (a), blocks L-H (b).

on fretting fatigue life assessment, and (ii) to verify the effects of variable fretting amplitude loading on fretting fatigue life assessment. In this case, fretting fatigue simulations were performed varying the amplitude of the tangential load/displacement applied to the pad while all other loads were held the same. In order to exemplify that, let us consider the loading configurations depicted in Figure 3. In Figure 3(a) one has a High-Low (H-L) loading sequence, where, for a given number of cycles n_1 and n_2 the amplitudes of the tangential load considered in the analysis are Q_1 and Q_2 , respectively, with $Q_1 > Q_2$. On the other hand, in Figure 3(b), the Low-High (L-H) loading sequence considers first the application of a tangential load of amplitude Q_2 followed by the one of amplitude Q_1 . In this case, the first block amplitude Q_2 is prescribed over n'_1 cycles and this number of cycles is chosen so that the damage generated by the low amplitude block is equal to the one generated in the high amplitude block of the H-L loading sequence. Damage assessments are carried out by means of Miner's rule. Similarly, the number of cycles n'_2 is determined by equating the damage of the high amplitude block in the L-H loading sequence with the one present in the low amplitude block of the H-L loading sequence.

Figure 4: Schematic representation of the three case studies considered in the H-L loading blocks: only partial slip (a), gross slip and partial slip (b), gross slip (including wear effects into the modelling) and partial slip (c).

In this work, besides investigating the effects of variable amplitude loads on fretting fatigue, wear effects by means of material loss were also taken into account in the analyses. However, once the material removal is considerably small under partial slip conditions [56] and apparently does not have great influence on fretting fatigue life estimates [57], here, wear is only considered for gross slip conditions. Figure 4 exemplifies, for the H-L loading sequence, the three different case studies evaluated in this work. In the first type of analysis, Figure 4(a), the H-L loading blocks are applied in partial slip conditions and wear will be discarded in the life estimation methodology for both loading amplitude blocks in this case. In the second case, Figure 4(b), the high block is applied under gross slip regime while the low one remains under partial slip conditions. Again, wear will be neglected in the life estimation procedure for both loading blocks. In Figure 4(c), once more gross and partial slip conditions are considered in the high and low blocks, respectively, however, in this case, wear is considered in the life analysis when gross slip takes place. Note that, in terms of loading conditions, the only thing that changes in each of these analyses is the amplitude of the tangential load Q or displacement δ (gross slip conditions). Following the same reasoning, a similar study was conducted for the L-H loading sequence.

In order to estimate fretting fatigue life, two different strategies were adopted, one for simulations neglecting wear and the other for simulations taking it into account. In both of them, the TCD, by means of the point method, was used once hot spot approaches are not suitable for contact problems, where strong stress gradients are commonly found nearby contact edges. In this setting, when neglecting wear, fatigue damage processes are accounted for by evaluating stresses and strains at a point L vertically distant from the contact edge, Figure 5. In this case, such nonlocal stress and strain information over time are computed along with the SWT multiaxial fatigue criterion and life can be estimated.

On the other hand, when wear effects are incorporated in the life estimation

Figure 5: Procedure for estimating fatigue life when wear is neglected.

Figure 6: Flowchart with the steps for solving the fretting fatigue problem considering wear effects into the life estimation procedure.

Figure 7: Damage accumulation procedure when considering wear.

procedure, the hot-spot point is constantly changing its position due to the material removal and contact stresses redistribution. In this case, life cannot be directly estimated, but increments of Miner's damage rule might be cumulated for each simulated fretting cycle as follows:

$$D_m(\mathbf{x}) = \sum_{i=1}^m \frac{\Delta N}{N_{f,i}(\mathbf{x})} \quad (8)$$

where D_m is the total cumulated damage at the m^{th} simulated fretting cycle, ΔN is the jumping factor (Eq. (7)) considered in the wear computations and $N_{f,i}(\mathbf{x})$ is the estimated life by using any multiaxial fatigue criteria for a given material point with coordinates $\mathbf{x}$. The wear computation strategy adopted in this work is depicted in Figure 6, where a main Python script is in charge of running all the processes, which consist in running each fretting fatigue cycle by means of the Abaqus FE software, perform wear computations with Eq. (7), update contacting surfaces and restart the process if needed. Note that, the jumping factor ΔN considered in the wear calculations makes each fretting cycle simulated to correspond to ΔN wear cycles. As previously explained, wear computations are performed only for gross slip conditions (high block configuration). As can be seen in Figure 6, there are two criteria for terminating the fretting wear simulation, i.e. $N = N_t$ or $D_i = 1$. According to Miner's rule $D_i = 1$ points to material failure. However, as will be seen later, for gross slip conditions, damage computations may reach a plateau, where in this case, the simulation is terminated when a desired number of cycles N_t is reached for the High block. Notice that, in Figure 6, D_0 is the initial damage generated from the low block, or zero if the high amplitude block is the first in loading sequence. In order to update contacting surfaces, a remeshing technique was used. In this work, damages computations were carried out at the centroid of the elements surrounding the contact region, Figure 7. Over the fretting cycles, the position

of the elements centroids are constantly changing due to material loss and mesh modifications, which brings the needing of extrapolating the total cumulated damage from a previous wear step to the current geometry configuration in order to apply Eq. (8). From that, failure is observed when $D_m = 1$ at any point L distant from the contact surface. In this case, the total life experienced by the component is given by $m \times \Delta N$. Once the TCD is here used to account geometric features, damages computations are regarded only for points at least L distant from the contact surface, red dots Figure 7. For more details concerning wear and damage computations the reader is referred to [57].

6. Results and discussions

In this section, three different analyses were conducted to evaluate the fretting fatigue phenomenon under variable shear amplitude loading/displacement. In these three analyses, partial and gross slip conditions were investigated. For some cases the wear modelling was also taken into account. In the next subsections we present the results of our numerical analyses for each one of these investigations. The geometrical model considered in this work is depicted in Figure 8. A pad radius $R = 70$ mm was considered in the analysis. The material adopted for pads and specimens was the aluminum alloy 7075-T651. Its basic material monotonic and cyclic properties are provided in Table 1. According to [58], the stress intensity factor threshold range, ΔK_{th} , and the fully reversed fatigue limit range, $\Delta \sigma_{-1}$, for this aluminium alloy are $3 \text{ MPa}\sqrt{m}$ and 290 MPa , respectively, which yields a critical distance parameter $L = 17 \text{ }\mu\text{m}$. The friction coefficient between the contacting surfaces for a cylinder on plane contact configuration may vary from 0.7 to 0.85, according to the tests carried out by the University of Seville fretting fatigue research team [59, 60]. Thus here we adopted $\mu = 0.75$. The local wear coefficient κ is $1.25 \times 10^{-8} \text{ mm}^2/\text{N}$ according to [61].

Table 1: Mechanical properties of Al7075-T651 [62].

Monotonic properties		
Young's modulus	E	71 GPa
Poisson's modulus	ν	0.33
Yield strength	S_y	503 MPa
Ultimate tensile strength	S_{ut}	572 MPa
Cyclic properties		
Fatigue strength coeff.	σ'_f	1231 MPa
Fatigue ductility coeff.	ϵ'_f	0.263
Fatigue strength exp.	b	-0.122
Fatigue ductility exp.	c	-0.806

As Figure 8 shows, a coarser mesh is used far from the the contact region, whereas, a refined one is considered near the contacting surfaces. In the refined region, linear quadrilateral elements are used with an approximate size of 8.5

Figure 8: FE model, loading and geometric configurations.

μm . Outside the refinement zone, the mesh is formed by triangular linear elements. For all simulations plane strain elements are considered in the analyses. Multi-point constraints are enforced on the upper surface of the pad so that rotation is prevented. Regarding the contact conditions, it was used the Lagrange multiplier approach to define the frictional contact constraints, and the contact nodes located at the specimen were defined as the master ones while the slave nodes were set on the pad.

6.1. 1st analysis: partial slip conditions in both loading sequences

In the analysis of this subsection both H-L and L-H loading sequences were settled under partial slip conditions. Therefore, the effect of surface wear is not accounted for in the life estimation approach here. To carry out the simulations it was considered a normal load $P = 300 \text{ N/mm}$, a bulk fatigue load varying between $F_b = \pm 1250 \text{ N/mm}$, a tangential load varying between $Q = \pm 100 \text{ N/mm}$ in the high block and $Q = \pm 50 \text{ N/mm}$ in the low block.

Figure 9 illustrates the shear stress distribution along the contact surface for each one of the loading blocks. In this case, only the tangential loading history is displayed, however, it is in phase with a bulk load, F_b , and those are prescribed after the application of a static normal load, P . Note that, for the L-H loading sequence, the stress distribution in the high block is not influenced by the first loading block, Figure 9(a). On the other hand, when the low amplitude loading block comes at second, the shear tractions are influenced by the initial high amplitude block, which is not surprising due to the loading history dependency of contact problems. Note as well that, for both cases, only one loading cycle of each loading block is already enough to ensure a stable contact stress profile. In other words, to obtain the stress solutions of each loading block, only one cycle has to be considered.

Once there is no need to perform different loading cycles for each loading block, one can consider the loading history depicted in Figure 10 for evaluating

Figure 9: Shear tractions profile under variable loadings: (a) L-H and (b) H-L loading sequences (partial slip conditions).

Figure 10: Scheme of the loading configuration considered in the FE model in the 1st analysis: (a) H-L and (b) L-H loading sequences.

Figure 11: Life estimation as a function of damage per block of shear loading (partial slip regime only).

the H-L and L-H loading sequences. Denoting d_1 as the damage generated by the first loading block, Figure 11 depicts the estimated life as function of the initial imposed damage d_1 for the H-L and L-H loading sequences. Note that $d_1 = 0$ or 1 means that there is only one loading block. Note as well that the upper abscissa axis denoted by d_2 represents the damage prescribed on the second block, which added to d_1 represents material failure ($d_1 + d_2 = 1$). Damage computations were performed according to the methodology presented in Section 5.

In Figure 11 one can see the influence of the fretting loading history dependency in the analysis. Note that, if there was not such loading history dependency, the H-L and L-H curves would intersect each other for a prescribed damage of 0.5 (i.e. $d_1 = d_2 = 0.5$). One can also see that for the same damage combination in the low and in the high amplitude block, the H-L loading sequence leads to shorter lives compared to the L-H one. This behaviour will become even clearer in the next analysis.

6.2. 2nd analysis: gross and partial slip conditions in the loading sequences

In this subsection, a H-L and a L-H loading sequences are also considered. However, in this case, the high amplitude block is set under gross slip conditions while the low one remains under partial slip conditions. As a first approximation and for the sake of comparison, wear is neglected even in the gross slip phase. To carry out numerical experiments, the loading history depicted in Figure 12 was considered. A normal load $P = 300$ N/mm was used. The oscillatory bulk fatigue load prescribed on the specimen varied between $F_b = \pm 1250$ N/mm. For the low blocks, a tangential load ranging between $Q = \pm 75$ N/mm was chosen, whereas, for the high blocks, a tangential displacement $\delta = \pm 45$ μ m was considered.

Once more, the simulation of only one cycle of each loading block already provides a stable solution. Figure 13 depicts life expected for each loading sequence (i.e. H-L and L-H) as function of Miner's damage parameter d_1 , in the first block (or in the second block regarding the upper abscissa axis). As can be seen, for the H-L shear loading sequence, the larger is the damage in the first cycle, the shorter is the estimated fatigue life. On the other hand, for the L-H loading sequence, the larger is the damage parameter in the first cycle, the longer is the fatigue life expected. Note that in these analyses, wear effects are neglected. Notice as well that, under these circumstances, gross slip conditions yields the most severe stress state. It can also be seen that, for the same damage combination in the low and high loading blocks, the H-L loading sequence leads to predicted lives far below the L-H one, which can be explained by the loading history effect generated by the high amplitude loading block. In the next section, a similar study case is investigated, however, wear effects are taken into account for gross slip regimes.

Figure 12: 1st and 2nd loading sequences analyses: (a) H-L and (b) L-H.

Figure 13: Life estimation varying d_1 (partial and gross slip regimes).

Figure 14: Variation of the specimen contact profile (a) and contact pressure profile (b) considering wear effects.

6.3. 3rd analysis: gross and partial slip conditions in the loading sequences (considering wear)

The analysis conducted in this subsection has the same loading conditions used in the 2nd analysis. However, for both the H-L and L-H loading sequences, the effect of surface wear on the high amplitude block was taken into account. As previously discussed, the wear generated in partial slip regime can be neglected without major consequences in life estimates since the material loss under such conditions is considerably smaller [57].

In order to better understand the wear effects on fatigue damage mechanisms under gross slip conditions, it is here first presented a few results considering only the application of the high amplitude block (loading parameters detailed in Subsection 6.2). In this setting, the idea is to verify the changes in the contacting surfaces profiles, the variation of pressure distribution and the damage accumulation over cycles. Figure 14(a) depicts the specimen contact profile for different number of loading cycles. As can be seen, as wear evolves, the size of the contact zones become larger. As consequence, contact pressure gets smaller once prescribed loads are always the same, Figure 14(b). It can also be seen that the pressure distribution tends to a flat distribution for a high number of cycles.

In Figure 15 one has a comparison between the damage evolution as a function of the number of cycles for simulations considering and neglecting the effects of wear into the life estimation methodology. When neglecting wear, damage computations are carried out at a point L vertically distant from the contact trailing edge (Figure 5). When considering wear, the damage results displayed in Figure 15 were obtained finding the maximum cumulated damage for points L vertically distant from the contact surface. Once there are many points L distant from the contact surface, the point which presents the highest damage

Figure 15: Damage evolution considering and neglecting wear for the high amplitude shear loading block only.

Figure 16: Life estimation varying d_1 (partial slip and gross slip regime with wear).

value is chosen. The jumping factor of $\Delta N = 1000$ was considered in the analysis accounting wear. Such value was chosen after a convergence study regarding both the damage computation and the surfaces worn profile for different number of fretting cycles.

As expected, neglecting wear provides a linear relation between the number of cycles and the cumulated damage. On the other hand, when regarding wear effects by means of material loss, it can be seen that over the first cycles the relation between the cumulated damage and the number of cycles is nonlinear and finds a plateau near 0.51 after nearly 140000 cycles. These results exemplifies the importance of considering wear for gross slip regimes.

Coming back to the investigation of the variable amplitude loading on fretting fatigue, the H-L and L-H loading sequences presented in the last subsection are now evaluated but considering wear for the high blocks. Figure 16 depicts the total estimated life for the H-L and L-H loading sequences as a function of the damage generated by the first block, d_1 , or the second one d_2 .

As can be seen in Figure 16, for the H-L loading sequence, finite life is observed only for a limited range of damage in the first block ($d_1 < 0.51$). In this case, besides limiting the damage evolution, the large material loss in the high block also considerably increases the size of the contact zone. Since the normal load is always the same no matter the loading block, contact stress distribution becomes lower. In this setting, despite the number of cycles in the low block (partial slip conditions), stress distributions do not lead to failure.

A similar behaviour is observed for the L-H loading sequence, where in this case, failure is only observed for $d_1 > 0.49$ (i.e. $d_2 < 0.51$). In this setting, the high material loss introduced by the high cycle (second block) only causes failure if the damage generated by the low cycle (partial slip conditions) is high enough. Such behaviour can be attributed to the removal of severely damaged area introduced by the gross slip regime found in the high loading block.

7. Conclusions

The studies presented in this work show that, for the L-H loading sequence, the first loading block does not influence the stress distribution of the second block. However, for the H-L loading sequence, the shear tractions in the second block are influenced by the high amplitude block due to the loading history dependency in contact problems. For the loading condition in the first analysis, i.e. both loading sequences under partial slip regime, it can be seen that, if only the low amplitude block is considered, life is about 9% larger than the one observed when the low loading cycle is prescribed after applying one high loading cycle. In the second analysis, i.e. loading blocks under partial and gross slip regime without including wear effects in the life estimation procedure, the same behaviour is observed. In this case, the loading history effect decreases life estimates in around 70% when the full low amplitude cycle is compared to the low amplitude cycle prescribed after one high amplitude loading cycle. Note as well that, due to the loading history dependency, the H-L loading sequence leads to life estimates far below the L-H one when the same damage combination in

the low and high loading blocks are regarded. This difference is also noted in the first analysis (only partial slip conditions), but with a subtler difference.

Regarding the third analysis, where the loading blocks are the same as the ones in the second analysis, one can see that, including wear in the investigation significantly changes life estimate results. While when neglecting wear gross slip produces the severest stress state, when it is taken into account the damage generated by the high block (gross slip regime) is limited to a certain value. For the H-L loading sequence, the number of cycles in the first block has to be less than a certain value, otherwise, contact stress distribution becomes lower due to the contact profile changes (Figure 14) and the second block under partial slip condition does not yield failure. Similarly, for the L-H loading sequence, the damage generated by the low amplitude, which is settled under partial slip conditions, has to be high enough, otherwise, the gross slip phase will have time enough to remove severely damage areas and provides infinite life.

To the authors' best knowledge, it is the first time that fretting fatigue cases under variable amplitude loading are assessed in terms of life estimates also including wear effects. This work was aimed to develop a methodology to predict fretting fatigue life under such conditions. Up to this point, it is not possible to measure the accuracy of the present approach due to the lack of experimental data including the literature, however, in a future work to be published soon, an extensive set of fretting fatigue tests reproducing study cases similar to the ones presented here will be carried out. After that, it is expected to answer some open questions such as: (i) Miner's linear rule is capable of dealing with fretting variable amplitude loading? If not, can a nonlinear version of it be more adequate? (ii) Will be the loading history effect observed in the numerical model also verified in the experiments? (iii) Do wear have such a great influence on fatigue lifetime such as verified in the numerical tests? (iv) With the experimental data in hands, can the use of a variable critical distance parameter improve the quality of the results? Therefore, those are some of the points that one expects to shine some light after conducting an extensive experimental campaign to be published soon.

In addition, notice that in our simulations we have always moved from the high amplitude blocks to the low ones starting from a valley (Figures 10a and 12a). However, stress responses would be different if we had started from the high amplitude block peaks (loading history effect of contact problems). In this setting, we have conducted a preliminary numerical analysis considering this aspect for partial slip conditions. This analysis showed that a load history where the low cycle block comes just after the peak of the high one lead to a life increase of the order of 10%. We expect that for gross slip condition, such difference might be increased, and it is something that we will keep in mind for future investigations.

8. Acknowledgements

The authors would like to acknowledge the financial support of TBE (Transmissoras Brasileira de Energia) in the context of the project entitled "Fadiga

de Cabos de Alumínio Liga (CAL) 1120 e 6201: estudo comparativo, efeito de grampos AGS e de emendas pré-formadas”, This project has been funded in the context of the Research and Development Program of the Brazilian National Agency of Electric Energy (ANEEL). This study was also financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

References

- [1] T. Lindley, Fretting fatigue in engineering alloys, *International journal of fatigue* 19 (93) (1997) 39–49.
- [2] C. Ruiz, K. C. Chen, Life assessment of dovetail joints between blades and discs in aero-engines, *Mechanical Engineering Publications*, (1986) 187–194.
- [3] P. A. Withey, Fatigue failure of the de havilland comet i, *Engineering failure analysis* 4 (2) (1997) 147–154.
- [4] J. Araújo, D. Nowell, Mixed high low fretting fatigue of ti6al4v: Tests and modelling, *Tribology international* 42 (9) (2009) 1276–1285.
- [5] C. Azevedo, A. Henriques, A. Pulino Filho, J. Ferreira, J. Araújo, Fretting fatigue in overhead conductors: Rig design and failure analysis of a grosbeak aluminium cable steel reinforced conductor, *Engineering Failure Analysis* 16 (1) (2009) 136–151.
- [6] D. Nowell, D. Dini, D. Hills, Recent developments in the understanding of fretting fatigue, *Engineering Fracture Mechanics* 73 (2) (2006) 207–222.
- [7] R. Rajasekaran, D. Nowell, Fretting fatigue in dovetail blade roots: Experiment and analysis, *Tribology International* 39 (10) (2006) 1277–1285.
- [8] C. Navarro, S. Muñoz, J. Dominguez, On the use of multiaxial fatigue criteria for fretting fatigue life assessment, *International Journal of fatigue* 30 (1) (2008) 32–44.
- [9] A. A. Fadel, D. Rosa, L. Murça, J. Fereira, J. Araújo, Effect of high mean tensile stress on the fretting fatigue life of an ibis steel reinforced aluminium conductor, *International Journal of Fatigue* 42 (2012) 24–34.
- [10] C. Mary, Simulation expérimentale de l’usure du contact aube-disque de compresseur sous sollicitations de fretting, Ph.D. thesis, Ecole Centrale de Lyon (2009).
- [11] A. Cardou, Fretting fatigue under spectrum loading application to overhead electrical conductors: a literature review, *Université Laval - Department of Mechanical Engineering* (2002) 15.
- [12] A. Palmgren, Die lebensdauer von kugellagern, *Zeitschrift des Vereines Duetsher Ingenieure* 68 (4) (1924) 339.
- [13] M. A. Miner, Cumulative damage in fatigue, *Journal of Applied Mechanics* 12 (1945) 159–164.
- [14] A. Kantimathi, J. Alic, The effects of periodic high loads on fretting fatigue, *Journal of Engineering Materials and Technology* 103 (3) (1981) 223–228.

- [15] Y. Mutoh, K. Tanaka, M. Kondoh, Fretting fatigue in jis s45c steel under two-step block loading: Solid-mechanics, strength of materials, JSME international journal 30 (261) (1987) 386–393.
- [16] Y. Mutoh, K. Tanaka, M. Kondoh, Fretting fatigue in sup9 spring steel under random loading, JSME international journal. Ser. 1, Solid mechanics, strength of materials 32 (2) (1989) 274–281.
- [17] V. Troshchenko, V. Dragan, S. Semenyuk, Fatigue damage accumulation in aluminium and titanium alloys subjected to block program loading under conditions of stress concentration and fretting, International journal of fatigue 21 (3) (1999) 271–279.
- [18] R. Cortez, S. Mall, J. R. Calcaterra, Investigation of variable amplitude loading on fretting fatigue behavior of ti-6al-4v, International Journal of Fatigue 21 (7) (1999) 709–717.
- [19] S. E. Kinyon, D. W. Hoepfner, Spectrum load effects on the fretting behavior of ti-6al-4v, in: Fretting Fatigue: Current Technology and Practices, ASTM International, 2000.
- [20] Y. Kondo, C. Sakae, M. Kubota, H. Kitahara, K. Yanagihara, Fretting fatigue under variable loading below fretting fatigue limit, Fatigue & Fracture of Engineering Materials & Structures 29 (3) (2006) 191–199.
- [21] M. Massingham, P. Irving, The effect of variable amplitude loading on stress distribution within a cylindrical contact subjected to fretting fatigue, Tribology international 39 (10) (2006) 1084–1091.
- [22] C. Gandiolle, S. Fouvry, Fretting fatigue crack propagation rate under variable loading conditions, Frattura ed Integrità Strutturale 10 (35) (2016) 232–241.
- [23] W. N. Findley, A theory for the effect of mean stress on fatigue of metals under combined torsion and axial load or bending, no. 6, Engineering Materials Research Laboratory, Division of Engineering, Brown . . . , 1958.
- [24] K. N. Smith, A stress-strain function for the fatigue of metals, Journal of materials 5 (1970) 767–778.
- [25] L. Susmel, P. Lazzarin, A bi-parametric wöhler curve for high cycle multiaxial fatigue assessment, Fatigue & Fracture of Engineering Materials & Structures 25 (1) (2002) 63–78.
- [26] B. Crossland, Effect of large hydrostatic pressures on the torsional fatigue strength of an alloy steel, in: Proc. Int. Conf. on Fatigue of Metals, Vol. 138, Institution of Mechanical Engineers London, 1956, pp. 12–12.
- [27] G. Sines, Failure of materials under combined repeated stresses with superimposed static stresses, Tech. rep., California. Univ., Los Angeles (1955).

- [28] T. Hattori, M. Nakamura, T. Watanabe, Simulation of fretting-fatigue life by using stress-singularity parameters and fracture mechanics, *Tribology international* 36 (2) (2003) 87–97.
- [29] J. Ding, D. Houghton, E. Williams, S. Leen, Simple parameters to predict effect of surface damage on fretting fatigue, *International Journal of Fatigue* 33 (3) (2011) 332–342.
- [30] J. Lemaitre, A continuous damage mechanics model for ductile fracture, *Journal of engineering materials and technology* 107 (1) (1985) 83–89.
- [31] J.-L. Chaboche, Continuum damage mechanics: Part ii—damage growth, crack initiation, and crack growth, *Journal of applied mechanics* 55 (1) (1988) 65–72.
- [32] D. Socie, Multiaxial fatigue damage models, *Journal of Engineering Materials and Technology* 109 (4) (1987) 293–298.
- [33] N. A. Bhatti, M. A. Wahab, Fretting fatigue crack nucleation: A review, *Tribology International* 121 (2018) 121–138.
- [34] H. Neuber, *Forsch ing-wes*, Bd 7 (1936) 271.
- [35] R. Peterson, Methods of correlating data from fatigue tests of stress concentration specimens, *Stephen Timoshenko Anniversary Volume* (1938) 179.
- [36] J. M. Whitney, R. Nuismer, Stress fracture criteria for laminated composites containing stress concentrations, *Journal of composite materials* 8 (3) (1974) 253–265.
- [37] K. Tanaka, Engineering formulae for fatigue strength reduction due to crack-like notches, *International Journal of Fracture* 22 (2) (1983) R39–R46.
- [38] P. Lazzarin, R. Tovo, G. Meneghetti, Fatigue crack initiation and propagation phases near notches in metals with low notch sensitivity, *International Journal of Fatigue* 19 (8-9) (1997) 647–657.
- [39] D. Taylor, Geometrical effects in fatigue: a unifying theoretical model, *International Journal of Fatigue* 21 (5) (1999) 413–420.
- [40] D. Taylor, G. Wang, The validation of some methods of notch fatigue analysis, *Fatigue & fracture of engineering materials & structures* 23 (5) (2000) 387–394.
- [41] J. Araújo, L. Susmel, M. Pires, F. Castro, A multiaxial stress-based critical distance methodology to estimate fretting fatigue life, *Tribology International* 108 (2017) 2–6.
- [42] D. Taylor, The theory of critical distances, *Engineering Fracture Mechanics* 75 (7) (2008) 1696–1705.

- [43] L. Susmel, D. Taylor, On the use of the theory of critical distances to predict static failures in ductile metallic materials containing different geometrical features, *Engineering Fracture Mechanics* 75 (15) (2008) 4410–4421.
- [44] J. Archard, Contact and rubbing of flat surfaces, *Journal of applied physics* 24 (8) (1953) 981–988.
- [45] S. Fouvry, T. Liskiewicz, P. Kapsa, S. Hannel, E. Sauger, An energy description of wear mechanisms and its applications to oscillating sliding contacts, *Wear* 255 (1-6) (2003) 287–298.
- [46] I. McColl, J. Ding, S. Leen, Finite element simulation and experimental validation of fretting wear, *Wear* 256 (11-12) (2004) 1114–1127.
- [47] J. Ding, S. Leen, I. McColl, The effect of slip regime on fretting wear-induced stress evolution, *International journal of fatigue* 26 (5) (2004) 521–531.
- [48] J. Madge, S. Leen, I. McColl, P. Shipway, Contact-evolution based prediction of fretting fatigue life: effect of slip amplitude, *Wear* 262 (9-10) (2007) 1159–1170.
- [49] A. Cruzado, M. Urchegui, X. Gómez, Finite element modeling and experimental validation of fretting wear scars in thin steel wires, *Wear* 289 (2012) 26–38.
- [50] S. Garcin, S. Fouvry, S. Heredia, A fem fretting map modeling: Effect of surface wear on crack nucleation, *Wear* 330 (2015) 145–159.
- [51] V. Hegadekatte, N. Huber, O. Kraft, Finite element based simulation of dry sliding wear, *Modelling and Simulation in Materials Science and Engineering* 13 (1) (2004) 57.
- [52] E. Bortoleto, A. Rovani, V. Seriacopi, F. Profito, D. Zachariadis, I. Machado, A. Sinatora, R. Souza, Experimental and numerical analysis of dry contact in the pin on disc test, *Wear* 301 (1-2) (2013) 19–26.
- [53] H. Lin, Simulation of wear in turbocharger wastegates (2016).
- [54] J. Madge, S. Leen, P. Shipway, The critical role of fretting wear in the analysis of fretting fatigue, *Wear* 263 (1-6) (2007) 542–551.
- [55] A. M. Tobi, J. Ding, G. Bandak, S. Leen, P. Shipway, A study on the interaction between fretting wear and cyclic plasticity for ti–6al–4v, *Wear* 267 (1-4) (2009) 270–282.
- [56] O. Vingsbo, S. Söderberg, On fretting maps, *Wear* 126 (2) (1988) 131–147.
- [57] R. Cardoso, T. Doca, D. Néron, S. Pommier, J. Araújo, Wear numerical assessment for partial slip fretting fatigue conditions, *Tribology International* 136 (2019) 508–523.

- [58] M. Benedetti, V. Fontanari, C. Santus, M. Bandini, Notch fatigue behaviour of shot peened high-strength aluminium alloys: Experiments and predictions using a critical distance method, *International Journal of Fatigue* 32 (10) (2010) 1600–1611.
- [59] V. Martín, J. Vázquez, C. Navarro, J. Domínguez, Fretting-fatigue analysis of shot-peened al 7075-t651 test specimens, *Metals* 9 (5) (2019) 586.
- [60] L. Bohórquez, J. Vázquez, C. Navarro, J. Domínguez, On the prediction of the crack initiation path in fretting fatigue, *Theoretical and Applied Fracture Mechanics* 99 (2019) 140–146.
- [61] G. Jordano, C. Navarro, J. Vázquez, J. Domínguez, Measuring wear in a fretting test with a confocal microscope, in: *Key Engineering Materials*, Vol. 774, Trans Tech Publ, 2018, pp. 461–466.
- [62] J. Vázquez, C. Navarro, J. Domínguez, Experimental results in fretting fatigue with shot and laser peened al 7075-t651 specimens, *International Journal of Fatigue* 40 (2012) 143–153.