ISFF 11TH

8-10 SEPT 25

International Symposium on Fretting Fatigue

UNIVERSITÉ PARIS-SACLAY

Program & Booklet of Abstracts

Espace Simondon
Ecole Normale Supérieure Paris Saclay
4 avenue des Sciences
Gif sur Yvette
France

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Fretting Fatigue Behaviour of Laser Powder Bed Fusion-Produced Ti-6Al-4V: Experimental and Numerical Analysis

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Keywords: Fretting Fatigue; AM; LPBF; Experimental Testing; Numerical Modelling

Abstract

Fretting fatigue is a tribological phenomenon that causes damage at the interface of two contacting surfaces, significantly reducing the fatigue life of components [1-5]. This study investigates the fretting fatigue behaviour of additively manufactured (AM) Ti-6Al-4V using two experimental setups: dovetail joint and bridge-type testing configurations, as shown in Figure 1. Custom-designed test apparatuses were employed to compare the performance of 3D-printed material with its wrought counterpart. Finite element models were developed to analyse stress distribution at the contact interface and predict fatigue crack initiation and propagation. These models utilized Continuum Damage Mechanics (CDM) for crack initiation and the Extended Finite Element Method (XFEM) for crack growth.

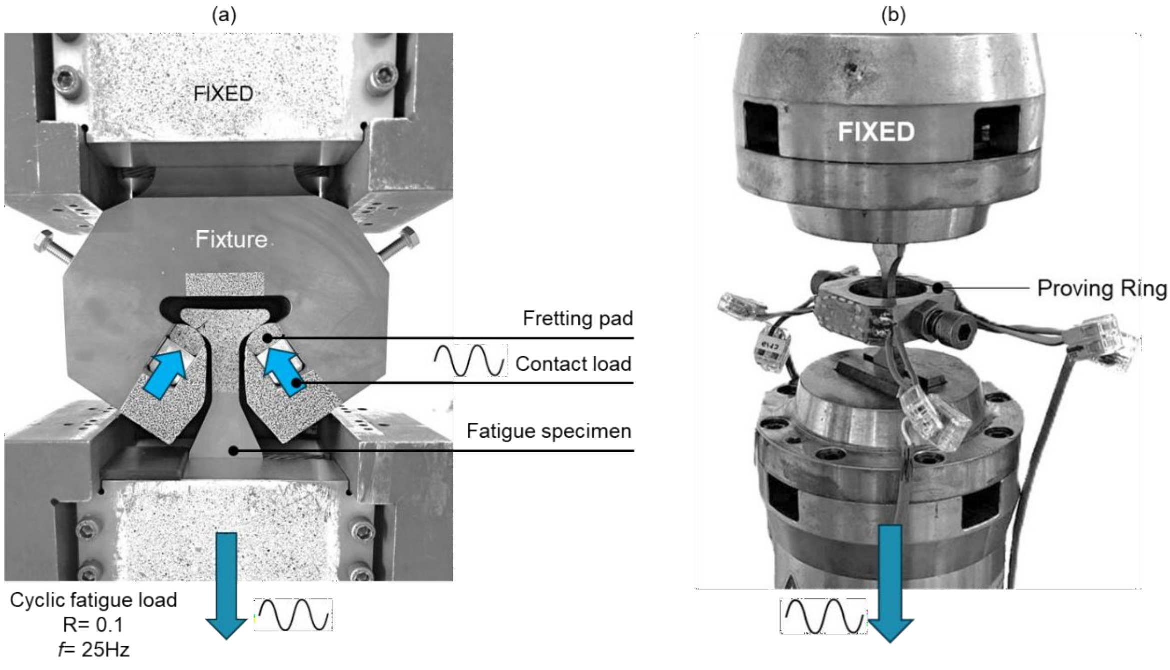

Figure 1: Fretting fatigue test setups: (a) dovetail fixture and (b) bridge-type configuration.

The findings indicate that the fretting fatigue lifetimes of AM-Ti64 align with data reported in the literature. However, the material's performance was constrained by internal voids introduced during the AM process. Lack of fusion defects caused some samples to fail prematurely outside the contact regions due to plain fatigue, as illustrated in Figure 2. Fractographic analysis revealed that critical defects were large and located near the sample edges, creating significant stress concentrations. In AM-Ti64 samples that failed within the contact region, the analysis confirmed slip-stick fretting conditions, which are the most damaging in fretting phenomena. The crack surfaces exhibited multiple initiation points and regions of steady crack growth, suggesting that AM-Ti64 has relatively low resistance to fretting damage and crack initiation but higher resistance to crack propagation.

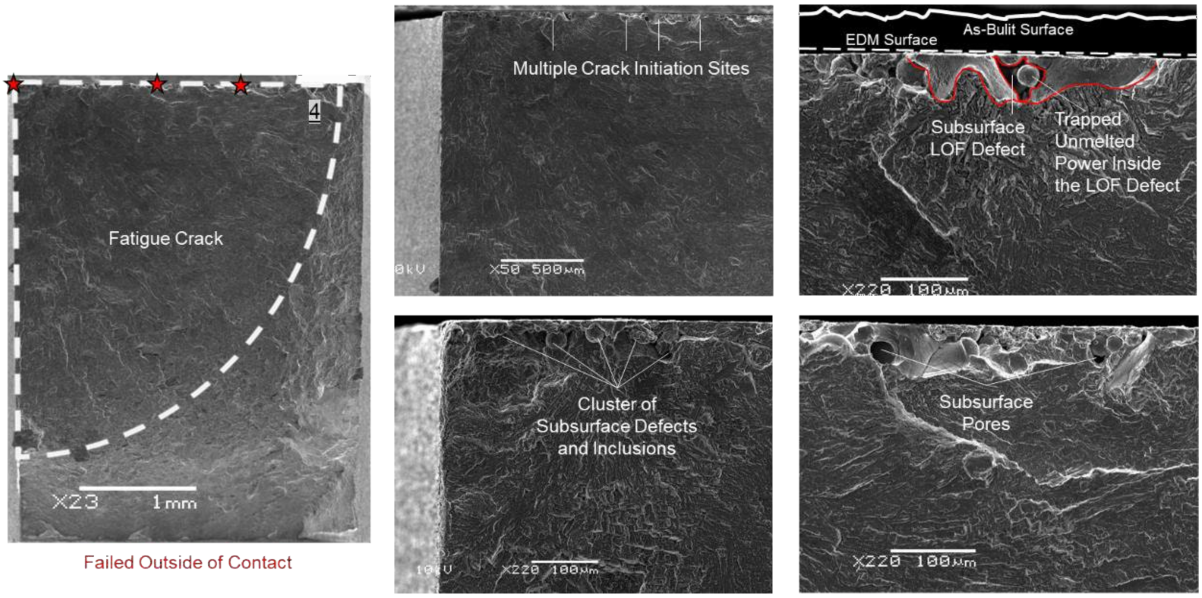

Figure 2: Fracture surface of an AM-Ti64 sample exhibiting failure outside the contact zone.

This study highlights the critical need to mitigate internal defects in safety-critical AM components, as the stress concentrations associated with such defects can far exceed operational stress levels and lead to unexpected failures.

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Fretting fatigue tests and life estimation under out-of-phase and asynchronous contact loads

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Keywords : Fretting Fatigue, Complex loading, Aeronautical alloys, Life prediction

Abstract

This contribution aims to present a mechanical analysis of new fretting fatigue experiments conducted, inspired by the type of loading experienced by aircraft aluminum fuselages during flight. The experiments involved a highly complex loading condition, considering different wave formats and frequencies among the three main loads, namely: the normal load (P), the tangential/fretting load (Q), and the bulk fatigue load (B). Failure analyses revealed a quite distinct crack formation behavior, with a triangular body detached from the specimen. This occurred due to the initiation and further propagation of inclined cracks originated nearly simultaneously from the boundaries of both contact edges (within the slip zones). A numerical model, which combined the theoretical basis of the critical plane multiaxial fatigue approaches with a simple Artificial Neural Network, previously trained with data from different Al alloys and under different loading conditions, successfully predicted fatigue life, yielding conservative results. Comparisons with three different multiaxial models were conducted, demonstrating that the neural network-based model achieved the highest accuracy in predictions.

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Experimental and numerical study of shrink-fitted assemblies under fretting fatigue solicitations: effect of interference and geometry

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Keywords : fretting-fatigue, shrink-fitted assemblies, experimental-numerical coupling, multiaxial fatigue criteria

Abstract

Shrink-fitting is a commonly used process to tightfit mating components such as axles and wheels or sleeves. An important range of applications exists in the railway and maritime industries. Such assemblies are subjected to complex multiaxial fatigue loadings including rotatory bending, compression, and torsion.

This experimental study focuses on a simplified loading case, (i.e. rotary bending), using a specifically designed test bench. The test specimen is a steel shaft with a shrink-fitted bronze sleeve (Fig. 1a). Tests are carried out on an extended range of interference values and sleeve edges filet geometries to obtain fretting-fatigue S-N curves.

Concerning the effect of interference value, no consensus exists in scientific literature concerning this problem. The modification of interference value has a direct impact on contact pressure, and therefore also on local stresses and on sliding amplitude, which are driving factors of fretting solicitations. The given results tend to confirm the benefit effect of increasing the interference value and corresponding contact pressure for the studied assembly.

Regarding the sleeve edges filet geometry problem, previous works showed that modifying the geometry could improve fatigue life by reducing the criticality of tribological damages and contact loadings at the contact borders of the assembly, thus delaying crack nucleation and crack propagation [1]. It was shown a longer fretting fatigue endurance considering r_{fillet} = 10 mm than machining a r_{round} = 3 mm contact sleeve (Fig. 1a, 1b). This investigation extends this research work by investigating the effect of an increase of the radius of the fillet r_{fillet} from 10 to 50 mm. Results presented an asymptotic rising of the fretting fatigue endurance, at least in the finite endurance domain. However, above a r_{fillet} threshold radius, the benefit effect stabilizes, indicating that the larger fretting sliding amplitude promoted by the increase of the r_{fillet} is compensating for the decrease of the local contact pressure.

Damage characterizations confirm these endurance data, underlying significant fretting wear damages and third body layer in the lateral partial slip sliding domains of the sleeve/axle assembly where fretting cracking is operating. By increasing the entrapped debris layer thickness, a rising of r_{fillet} promotes local overpressures which can be

detrimental regarding the fretting fatigue endurance.

All these experimental results have been simulated using Finite Element Analysis, with the aim of improving our understanding of the phenomenon and developing a life prediction model. Interference fitting and bending are considered, as well as the coefficient of friction operating in the interface. Surface wear is also considered to ensure correct modelling of the phenomenon. Multiples tribological and multiaxial fatigue criteria have been implemented as post-treatment to quantify fretting-fatigue damage.

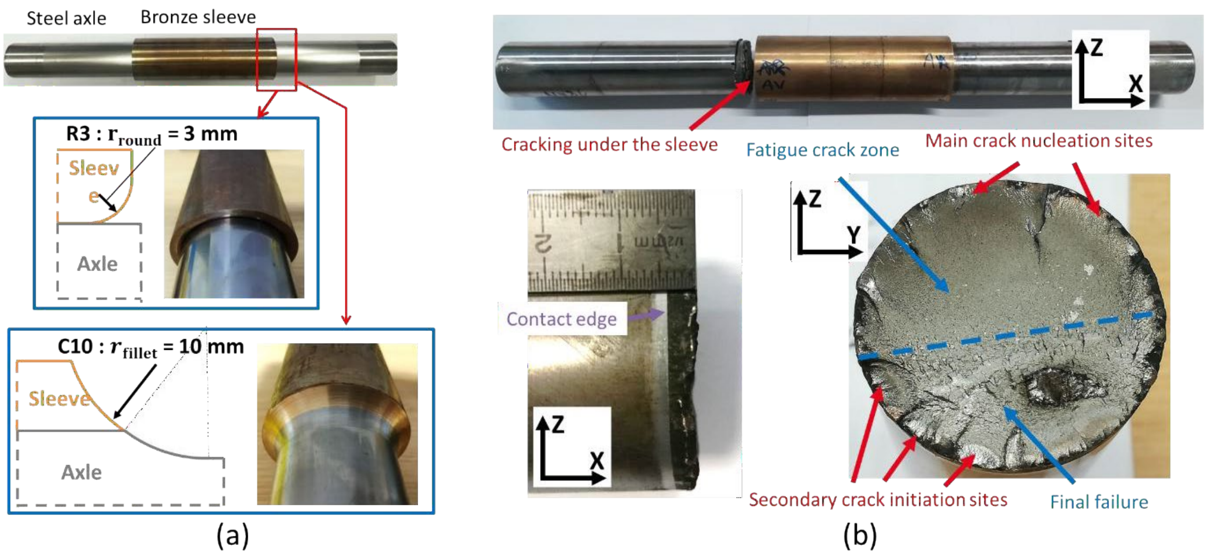

Figure 1: (a) Picture of the specimen the R3 and C10 sleeve geometries (investigation of various r_{fillet} values); (b) Observation of a fully broken R3 specimen (Fretting Fatigue failure).

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Fretting Fatigue: Novel Experiments and Analysis

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Keywords: Fretting Fatigue, Non-proportional Stresses, Critical Plane, Life Predictions

Abstract

This study presents recent novel experiments in fretting fatigue and modeling, utilizing a custom-designed fretting fatigue test machine capable of independently controlling cyclic axial stress and fretting slip amplitude. The experimental setup includes four actuators: two for applying contact pressure, one for cyclic axial fatigue loading, and one for independent slip amplitude control. This configuration allows for the application of non-proportional multiaxial loading under varied contact conditions, enabling evaluation of important fretting fatigue control parameters and challenges for life prediction models.

The current study uses a test configuration featuring flat steel pads in contact with a flat surface cast magnesium alloy specimen with rectangular cross section, a geometry for which no closed- form stress solutions exist. Nonlinear FEA, accounting for both geometric and material nonlinearities, was employed to determine local stress states. A hybrid modeling strategy was developed to reduce the computational burden of full-field FEA by treating the contact edge stresses as stress concentrations, as in notched fatigue analysis. This approach involves defining stress concentration factors for normal and shear stresses at the contact edge, derived from a limited number of FEA simulations, and using them to calculate local stresses from experimental nominal stress histories. Plasticity effects are accounted for using Neuber's rule. The resulting stresses are then analyzed using the Fatemi-Socie (FS) critical plane parameter in its stress-based form suitable for HCF. Stress gradient effects can be considered using TCD.

Contact Load (kN)	Slip Amplitude (μm)	Frequency (Hz)	#Tests
-0.6	5, 30	2, 6	2
-0.5	5, 10, 15, 20, 25	2, 6	16
-0.4	10, 15, 20, 25	2-10	17
-0.3	10, 15	6	2
-0.2	5	6	1

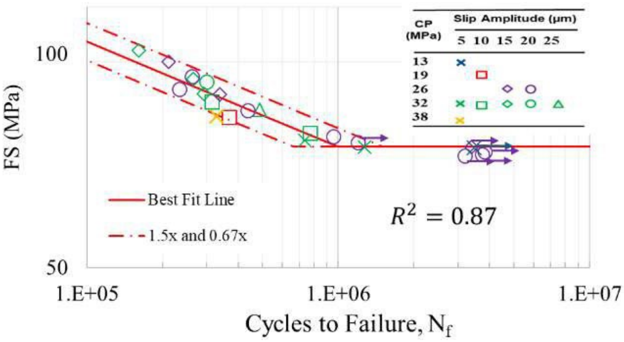

Figure 1: Fretting fatigue test conditions and correlation of data with FS critical plane model

Fretting fatigue tests were conducted with a variety of test conditions shown in the table in Fig. 1 at a cyclic stress amplitude of 41 MPa. The figure illustrates good correlation of fatigue test data using the aforementioned approach, despite the complex non-proportional load paths.

An in-situ Fretting test for X-Ray Tomography

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Keywords : In-Situ Mechanics, Tomography, DVC.

Abstract

Mechanical assemblies are often subjected to vibrations that generate micro-friction at the contacts: fretting. These slight displacements can lead to cracking and/or wear, reducing the service life of the assembly. Numerous models and tests exist to predict contact life, but there is still considerable room for improvement, based on a poor understanding of what happens in the contact. Indeed, most models use a continuous, homogeneous interface, whereas the actual contact area, pressure distribution and friction coefficient depend on the local state of the contact. Access to the evolution of the interface over time, as well as to its damage through wear and cracking, is therefore necessary to further the understanding and simulation of mechanical assemblies. An in-situ tomography test has been designed with this aim. It is instrumented to quantify local information (friction, stiffness, slip) during loading. The final design combines technical and material choices that enable good reconstruction. With this innovative in-situ test, the first displacement fields were obtained for fretting contact by DVC and compared to FE simulation.

Numerical modelling of sphere-to-flat cyclical indentation of polycarbonate: fatigue, fretting wear and fracture

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Keywords: FEM, Fatigue, Fretting Wear, Fracture, Polycarbonate.

Abstract

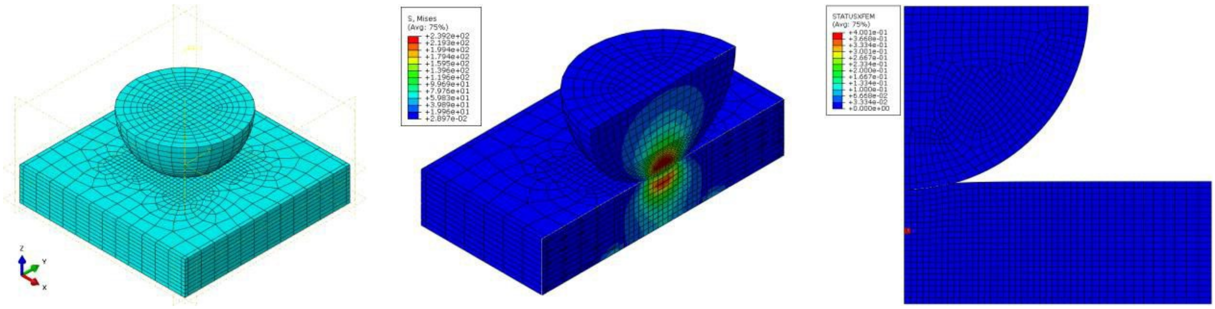
Polycarbonate (PC) is a transparent, high strength and durable thermoplastic, often used as a glass substitute in both industrial application and daily use items. It has been the subject of extensive research [1,2], especially in thermomechanical analysis and monotonic loading conditions [3]. Nevertheless, its performance under finite strains and cyclical loading is still lacking. For instance, the driving factors for nucleation and evolution of crack propagation in contact applications are not yet fully understood. In previous experimental works [4,5], it has been noted that creep, fretting wear and fretting fatigue can be present simultaneously, promoting damage in protective PC coatings. Herein, a numerical framework is proposed for the analysis of the driving conditions for damage accumulation, crack nucleation and fracture of a flat specimen indented by a hemispherical tool. Loading conditions include monotonic normal load for the establishment of inelastic damage; variable normal load for the onset of fatigue damage; and radial displacement leading to fretting wear.

The numerical framework for this study has been implemented in Abaqus® v6.14. It includes a 3D global model and a 2D axisymmetric local model. Both solids are set as deformable. The frictional contact conditions are enforced via the Lagragian method and surface-to-surface segmentation. The indentation tool is modeled as a R3-grade offshore steel while the specimen is modeled as a standard Polycarbonate. The constitutive model adopted for both solids is the Ludwik-Hollomon. A damage law based on traction separation coupled to the XFEM method is assigned to the specimen. For the modeling of the wear phenomena, a dissipated energy method couple with an ALE remeshing method has been employed [6,7].

The parameters for the calibration of the material models are retrieved from previous experimental works [4,5]. The loads are applied in two phases: i) -2kN normal load in a monotonic quasi-static condition; ii) -1.5+-0.5 kN cyclical load for 200,000 cycles. The boundary condition includes a ground restraint on the specimen's bottom ($u_z = 0$) and a XY symmetry in the centerline ($u_x = u_y = 0$).

The finite element model and representative results are depicted in Fig. 1. Partition and structured discretization have been used in the contact zone in order to optimize the mechanical response, see Fig. 1a. The stress distribution (Fig. 1b), after the indentation phase, shows the maximum stress zones for both solids. The nucleation of the first crack can be observed in Fig. 1c. The model is capable to reproduce the experimental results with a maximum relative error equal to 2.2% in the monotonic phase and 3.5% in the cyclical

phase. Results reveal a crack nucleation at the maximal stress zone and a critical damage condition, achieved after approximately 50 thousand cycles of indentation, where the crack starts to grow. The initial crack moves towards the base before also propagating along the XZ plane. Its growth can be used to determine a time to failure (a cross-sectional rupture observed in experiments). Furthermore, the numerical model can be used to investigate additional features such as: hardening rate, effective plastic strain evolution and damage distribution.



a b c

Figure 1: Representative images of the numerical framework – a) discretization of the 3D global model; b) cut-view of the von Mises Stress distribution on the critical zone; c) crack nucleation detected in the 2D local model.

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Asymptotic Representation of Contact Edges with Varying Normal Load

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Keywords : asymptotics, varying normal load, partial slip

Abstract

The applied mechanics problem of solving for the edge of contact partial slip state is central to quantifying fretting fatigue. There are many contacts in engineering applications which have geometries which are almost conformal in nature, but where the edge of the contact is defined by some transition radius. Examples include the fanblade dovetail, firtree connectors, riser locking segments, bolts in shear. Some of these are capable of idealization by a half- plane throughout, whilst others are not, but in every case, the near-edge of contact does display half-plane behavior, a property we will exploit.

Historically, partial slip problems have been solved when the normal load is constant, starting with the original solution by Cattaneo [1] in the 1930's, and with various developments to generalize the contact profile and add in the effect of bulk tension, for about 80 years. At that point we discovered how to solve problems where the normal load varies, and formulated a solution where the normal and shear loads varied harmonically, potentially with a phase shift [2].

In a separate strand of development, asymptotic representations of the conditions at the edge of incomplete contacts were found. These are essentially two of the eigensolutions for a crack tip, and are ; (a) the mode I solution which is square root bounded (the square root singular term has no relevance unless adhesive forces are present), representing the effects of pressure, and (b) the mode II square root singular term which represents the shearing traction in the absence of slipping. Small scale slip is then introduced [3]. Because the mode I solution is both constant and bounded whereas the mode II solution is singular and reversing it is the latter which may be expected to control fatigue crack nucleation. An 'S-N' curve but with stress replaced by ΔK_{II} proved to be a very good correlator of lives and, most importantly, to establish very solidly a threshold for 'no nucleation', i.e. to be a quantity which established the equivalent of an endurance limit (albeit with different dimensions) [4].

In this paper we introduce a sequel to these two developments, i.e. an asymptotic representation of the contact edge state of stress and slip, but where the normal load varies cyclically, as well as the shear load. The solution is appropriate only when the cyclic changes are small in magnitude compared where their respective mean values, but in the majority of practical cases this approximation holds.

The key point is to recognize that when there is a small change in normal load changes (assume an increase) the contact edge will advance by a small amount, and it follows that the change in pressure with respect to a change in contact size is square root singular in nature, and this we designate ΔK_I. The oscillatory problem is therefore defined by mean values, and changes in the locally normal and shear directions defined by (ΔK_I,ΔK_{II}). We recall that near to the contact edge half-plane theory will always apply, and we are able to deduce the changes in contact size, contact pressure and shear traction which occur, using results adapted from those found in [2] for the contact as a whole. It is also possible to find, in closed form the slip zone size and the slip displacements occurring, and the quantities (ΔK_I,ΔK_{II}) may be used to match laboratory test with prototype.

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Modelling of multiple coupled normal and tangential contacts, application to the simulation of axial blade/disk attachments

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Keywords: Multi-contact, semi-analytical method, multi-scale

Abstract

The aim of this work is to extend the calculations used for power transmissions to the technology and design of high-pressure turbine blade-disk attachments. In this context, the use of a mixed method combining semi-analytical formulations with a limited number of finite element computations has significantly reduced computation times compared to conventional methods relying on full finite element modelling. However, the current modelling approach is based on simplifying assumptions aimed at testing the feasibility of the method and estimating the reduction in computation time.

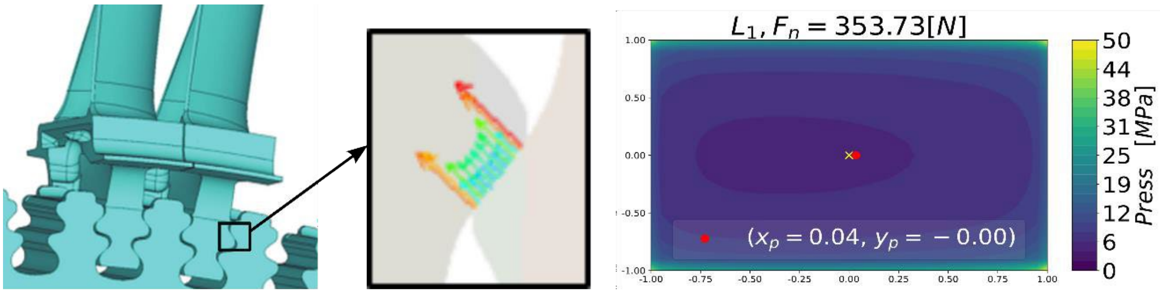
A blade root attachment, due to its specific geometry (cf. Figure 1), involves multiple simultaneous contact zones with various areas of the disk teeth. This configuration requires the simultaneous resolution of multiple contact problems between two bodies for each contact zone, starting from a model initially designed to handle a single contact at a time. To answer this question, we have chosen an approach that decouples the effect of the global structural deformation of the part assembly from the effects of the local deformations of the interface areas due to local contact pressure. This type of approach is often used to calculate load sharing on gears and splines [1].

To compute the local deformation due to contact, we use a scale separation approach between the global scale associated with the attachment and the local scales related to the contact areas. An initial equilibrium is established between the local variables used to control the various contacts calculated upstream and the contact pressures, shear and slip vectors obtained at the output of the semi-analytical (SA) model. This SA model has already been employed in several previous studies, such as the prediction of fretting and wear in blade-disk attachments [2]. Then, a second equilibrium is achieved between the local forces and the applied load in the global frame using an iterative numerical method until global load equilibrium is reached. This numerical method enables us to solve both normal and tangential contact problems.

Due to the combination of thermomechanical loads (centrifugal forces, temperatures, pressures...) experienced by the blade-disk assembly and their evolution over time during the engine operation, the blade undergoes an oscillatory relative movement between the contact surfaces at the blade-disk connection. The numerical method developed will

therefore be evaluated under these load conditions in order to identify the different sliding regimes that may occur during the fretting cycle, as well as the type of damage induced. Lastly, the results from this approach are compared with those obtained from a finite element model to assess the speed up and the accuracy of the simulations.

To account for the effects of structural deformation, the SA model will later be coupled with a model isolating only the effects of global structural deformation. This will provide a structural displacement that will be added to the local displacement to obtain a complete simulation as in [3].



(a) (b) (c)

Figure 1: (a) - geometry of the blade-disk attachments; (b) - zoom on the contact zone; (c) - pressure distribution on the contact zone

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Fretting in an anisotropic contact: a 2D non-local approach for a cubic material

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Keywords : fretting-fatigue, non-local approach, anisotropic media

Abstract

The non-local approach is a methodology for model reduction that has been applied to predict fretting fatigue life in an efficient and geometrically transferable way [1-5]. These advantages make the approach well-suited for industrial applications that require complex finite element assembly models, which do not allow for refined local numerical calculations due to time and energy consumption.

Fretting and fretting fatigue are types of damage known to affect a multitude of mechanical parts and components, from bearings and shafts to overhead electric conductors and blade- disk couplings in jet engines [6]. The latter, like the whole aeronautical industry, is at the forefront of material and mechanical sciences. As a result, it requires the extension of fretting knowledge to account for advanced materials such as light composites and single-crystal alloys with high stress and high-temperature resistance. These materials not only demand precise and controlled manufacturing processes but also exhibit non-isotropic mechanical behavior, which demands more complex formalism to determine stresses, deformations, and displacement fields.

The objective of this work is to extend the non-local approach and review its validity for the contact between two cubic anisotropy parts with similar elastic properties. That means that both in contact parts are made of the same material and have the same crystallographic orientation. Since its first application, the non-local approach in fretting fatigue was based into an analogy between the displacement field around a crack tip in linear elastic fracture mechanics (LEFM) and the displacement field around the contact front in a fretting problem [7, 2]. The anisotropic displacement field of an area of interest around a crack tip [8, 5] is compared to fretting contact to estimate stress intensity factors that can later be related to life prediction criteria. Here, the contact problem is made of a quasi-2D model, meaning that the orientations of study have symmetry around the XY plane (z=0), as Figure 1.

This work lays the foundation for the further extension of the non-local approach, for example the contact between anisotropic against isotropic materials and at the end fully non- similar 3D anisotropic materials (with different behavior properties and with any given orientation). A generalized fretting non-local model will take into account not only direction related stress and stress coupling due to anisotropy [5] but also related to already proposed procedure for dissimilarity between contact parts [4].

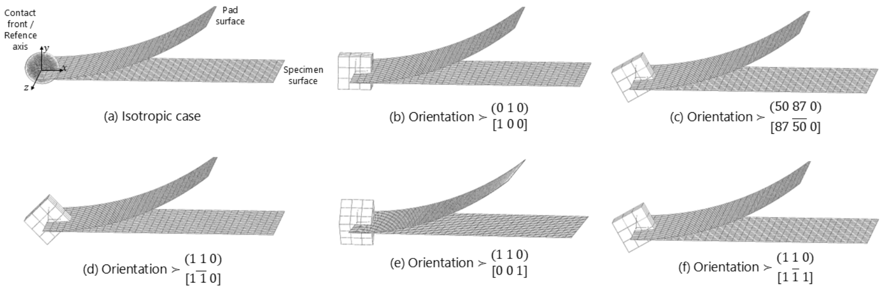

Figure 1: Miller-Bravais crystallographic orientations in relation to contact front, and the normal of contact plane.

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Asymptotic Representation of Contact Edges with Partial Slip

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Keywords : half-plane, asymptotics, partial slip, elasticity

Abstract

The contact between an elastic flat punch with rounded edges and an elastically similar half- plane is a fundamental problem in industrial applications such as gas turbine dovetail roots and locking segments in risers. Existing solutions based on half-plane theory fail to account for the traction-free surfaces of the punch. Whilst half-plane theory assumptions hold well for Hertzian contacts [1], it is a poor representation of rounded contacts with relatively large flat lengths.

To address this limitation, we present a novel nested asymptotic approach [2] that combines two complementary solutions: an outer solution, which models the free surfaces as a three- quarter plane, and an inner solution, based on half-plane theory, to capture local contact behaviour at the rounded edge. This method allows us to analyse geometric coupling effects and determine key contact properties, including the shear traction generated by a normal load.

In more recent work, the calibrations between the outer solution and the nested half-plane solution at the contact edge are found by modelling a small crack collinear with the contact interface of the three-quarter plane using Finite Element Analysis. The stress intensity factor at the 'crack tip' scales the asymptote of the half-plane solution at the contact edge. Setting up the calibrations in this way allows us to find the tractions at the contact edge and the extent of slip for complicated loading histories.

Compared to conventional asymptotic techniques, our approach provides a more accurate representation of the contact geometry [3], offering improved predictive capabilities. This refinement has the potential to enhance the correlation between laboratory fretting fatigue experiments and industrial prototypes.

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A cross-validation approach in neural networks for fretting fatigue prediction on Al 7075 T651

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Keywords: Al7075T651, fretting fatigue, neural networks

Abstract

Fretting fatigue is a material surface damage phenomenon produced when two mechanical elements, that are pressed together, are subjected to time variable bulk loads, generally cyclic. The mismatch of the strains produced between both contacting surfaces leads to relative cyclic displacements between them. This relative displacement, in junction with the friction, produce tangential tractions on the surface which generate high stresses and strains close to the contacting surfaces producing fatigue crack initiation and crack growth [1].

Considering the large number of fatigue tests results published, the lack of accuracy of the models proposed to estimate the fatigue strength and life, the scatter of the tests results, the complexity of the fatigue process, the number of parameters affecting the fatigue behaviour and the importance of the fatigue failures, from the beginning of the century the use of neural networks to estimate the fatigue behaviour of different materials and components under defined fatigue loads became a subject of interest for researchers, and to a lesser extent, also in fretting fatigue [2, 3].

The present work introduces a Feed Forward Network (FFN) designed to estimate the fretting fatigue life of Al 7075-T651 under both cylindrical and spherical contact conditions, thereby accommodating two distinct contact geometries. The network is fully connected, meaning that every neuron in one layer is linked to every neuron in the subsequent layer, ensuring complete information transfer across the network. Additionally, k-fold cross-validation is employed to enhance the model's reliability by substantially reducing the risk of overfitting and maximizing the utility of the available data [4]. Although this methodology has rarely been applied in the field of fatigue or fretting fatigue using ANNs, it has proven effective in improving fatigue life estimation by efficiently leveraging a limited dataset. Furthermore, two different sets of input parameters are evaluated to determine which configuration is best suited for estimating fretting fatigue life under the two distinct contact geometries. One of them is based on loads applied and the geometry of the contact pad and the other one is based on a multiaxial fatigue parameter evaluated at different depths.

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A Computationally Efficient Hybrid Technique for Three-Dimensional Contact Analysis

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Keywords: Contact mechanics, Series solution, Singular Integral Equations, Finite Element Analysis, Hybrid Technique.

Abstract

The load transfer between bodies in physical contact happens over a small area of contact leading to stress concentrations that drive crack initiation and growth, thereby making accurate contact analysis critical. The versatility of finite element (FE) analysis makes it an excellent tool for analyzing three-dimensional (3D) contacts involving complex geometry and loads. However, it requires significant computational effort since the accuracy of results depends on element size and the integration technique used [1]. Using infinite series to solve singular integral equations governing two-dimensional (2D) contact problems requires much lesser computation effort than even 2D FE analysis [2, 3]. However, a large class of contact problems are inherently 3D. In this work, coarse mesh 3D FE analysis is combined with the plane-based series solution method to develop a hybrid technique for 3D contact analysis. The results of this hybrid technique are compared to those of a very detailed 3D FE analysis with fine mesh and full integration, to ascertain its efficacy.

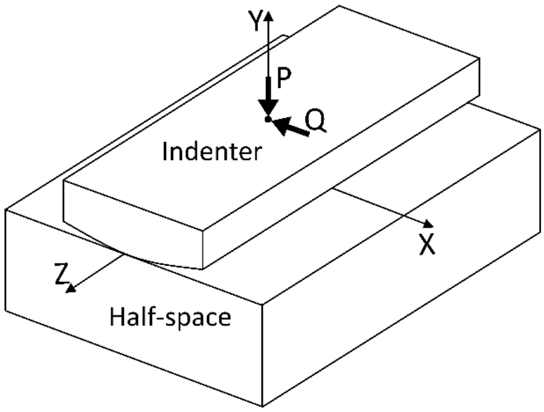
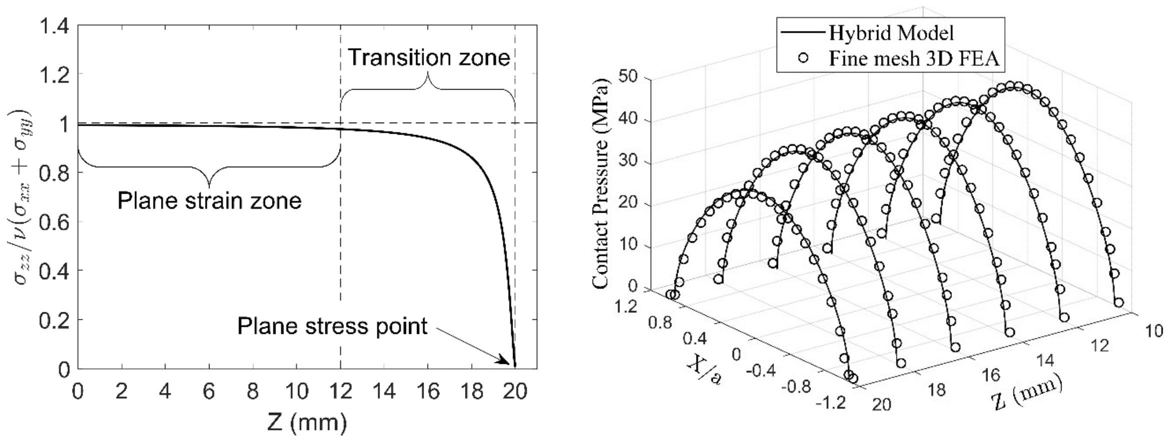


Figure 1: Geometry and loading conditions considered for contact simulation

Three-dimensional full sliding contact between cylindrical indenter and flat half-space (Figure 1) has been considered in this work to demonstrate the effectiveness of the hybrid technique of contact analysis. The half space was taken to be homogeneous and isotropic. Comparisons of contact pressure evaluated using the hybrid technique and 3D FE analysis with fine mesh at various cross-sections along the contact depth are shown in Figure 2 (b). A maximum difference of 3% is observed between the peak contact pressure evaluated using both techniques near the free edge (Z=20 mm). A much better agreement is observed for the cross-sections away from the free edge. The use of coarse mesh 3D FE analysis reduces the total node count of the required FE model in the hybrid technique, thus overall computational effort is reduced significantly. Using a computer with a 16-core 3.4 GHz processor and 64 GB RAM, twenty-two hours were required for a fine mesh analysis after the pre-processing (which itself took an additional three to four hours). However, the hybrid technique took about eighteen minutes for the coarse mesh FE analysis to obtain the net force per unit length at different cross-sections and about 15 to 20 seconds for the MATLAB code to obtain the detailed pressure distribution using these forces.



(a) Plane strain factor

(b) Contact Pressure

Figure 2: (a) State of plane approximation in half-space along contact depth (b) Comparison of contact pressure computed using hybrid technique with a detailed finite element analysis using fine mesh and full integration.

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A nonlocal ANN framework for predicting fretting fatigue life

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Keywords : Fretting Fatigue, Multiaxial Fatigue, Artificial Neural Networks

Abstract

Fretting fatigue (FF) occurs when contacting parts experience both small-amplitude relative slip and bulk fatigue loads. This problem involves multiaxial and non-proportional stress states, as well as steep stress gradients. Recently, a few works have proposed data-driven approaches to estimate fretting fatigue. In Nowell and Nowell [1], for instance, the authors developed an ANN model to predict fretting fatigue life based on contact quantities such as contact peak pressure and contact size, as well as external loading such as the bulk stress and the normalized tangential load (i.e., the tangential load divided by the normal load times the friction coefficient). Despite the successful life predictions of this model, its input parameters do not account for variations in contact geometry and complex loading scenarios, hindering broad generalization. To overcome this issue, Oliveira et al. [2] developed ANN models based on nonlocal stress parameters demonstrating a great generalization capability in predicting fretting fatigue life including different materials, geometries and varied loading conditions. Cardoso et al. [3] also obtained similar results by employing a simpler linear regression machine learning model. However, these models rely on the material's critical distance, which is not always available or accurately estimated, potentially leading to inaccuracies when applying these tools to materials not included in the training phase.

In this context, this work proposes an ANN model based on nonlocal parameters to predict FF lifetime under various conditions, including different loadings, geometries, and aeronautical alloys. This model utilizes simple monotonic material properties and well-stablished multiaxial fatigue parameters as inputs. To account for the stress gradient inherent of contact problems, we present a new nonlocal approach, minimizing the reliance on material-specific parameters, such as the critical distance, which is not always available or accurately estimated. This new nonlocal strategy is based on the highly stressed distance below the contact surface. The results demonstrate that the proposed ANN model is capable of accurately predicting fretting fatigue life. Furthermore, since the approach relies on simple yet representative input parameters, it holds strong potential for future industrial applications.

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Study on the Effect of Grain Orientation on Fretting Fatigue Behavior Using CPFEM

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Keywords: Fretting fatigue; Grain orientation; Deformation incompatibility; scattering phenomenon

Abstract

Fretting fatigue is one of the most critical and hazardous forms of contacting fatigue [1-2], and its behavior exhibits pronounced sensitivity to microstructural characteristics [3-4]. Although the influence of grain features—such as size, orientation, and phase—has been widely studied in steels [5-6], research on aluminum alloys remains limited [7-8]. To the best of the authors' knowledge, no prior publications have systematically analyzed the influence mechanism of grain orientation on fretting fatigue damage in aluminum alloys. Thus, this study investigates the underlying mechanisms by which grain orientation affects the fretting fatigue behavior of aluminum alloys.

The Macro-micro models and parts of simulation results are shown in Figures 1 and 2, respectively. While high stress-strain gradient and stress-strain concentration remain the dominant factors driving fretting fatigue failure, as can be seen in Figure 2, the randomness in local grain orientations induces deformation incompatibilities between adjacent grains. These incompatibilities promote localized stress and strain concentrations, disrupt the intrinsic stress-strain gradient distribution characteristic of fretting fatigue, and ultimately influence both the magnitude and initiation location of critical damage. Comparative analyses conducted under varying grain orientations confirm that grain orientation is a key factor contributing to the scattering phenomenon observed in fretting fatigue behavior.

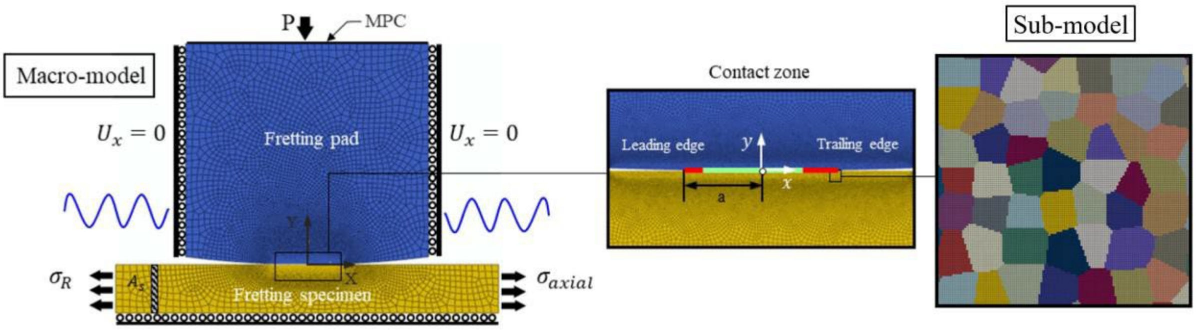

Figure 1: Macro-model of fretting fatigue and its related sub-model based on CPFEM

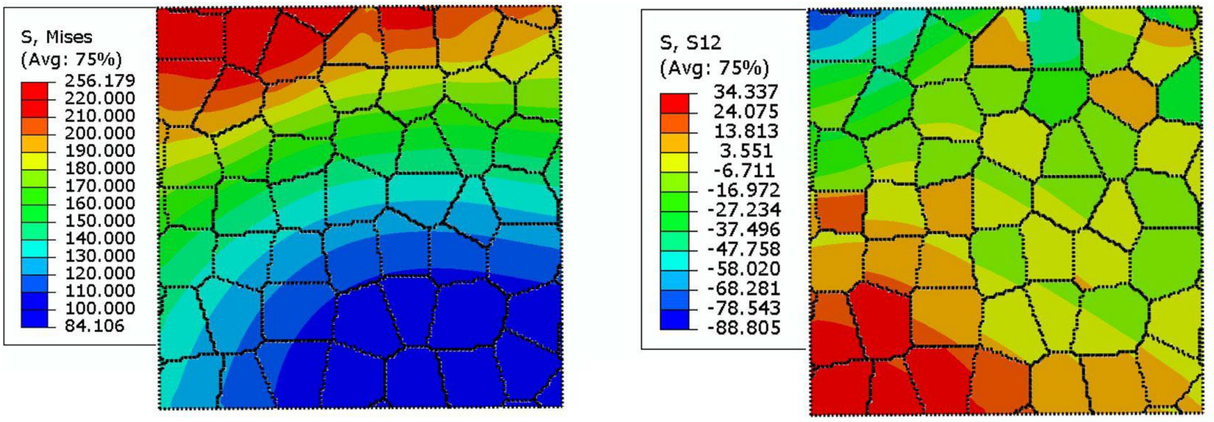

Figure 2: Stress distribution of fretting fatigue behavior

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Length scale effects on the fretting wear of DLC coating systems

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Keywords: Fretting, DLC, multi-scale, nanomechanics

Abstract

Nano-scale fretting of DLCs has been previously explored via a piezo-driven oscillating stage. DLCs are commonly used as protective coatings due to their low friction and low wear. In larger-scale fretting, mechanical properties (H/E) were found to correlate with wear volume and dissipated energy in the contact. Previous accelerated wear tests have required calibration of track length and therefore do not allow for monitoring of fretting regime evolution throughout the test.

A newly developed nano-fretting capability has been implemented on a commercial ultra-low drift nanomechanical test system (NanoTest). This allows for the measurement of real track length in accelerated nano-scale fretting wear experiments in addition to monitoring of on- load depth. Displacement can therefore be controlled through the test to explore dynamic fretting conditions. Experiments have been carried out in elastic and plastic contact conditions with multiple spheroconical diamond probe diameters to explore both fretting wear and full sliding wear (sliding ratios less than one and greater than respectively).

Mechanical properties of the coatings determined via partial load indentations have been used to inform on the tribological response of the coatings. Fretting wear performance across length scales was compared via metrics like dissipated energy, wear scar analysis and frictional response.

Fretting Wear response of a 304L stainless steel contact in pressurized hydrogen up 25 MPa: comparison versus air and Helium

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Keywords: Fretting wear, hydrogen gas, stainless steel, low and high pressures

Abstract

Hydrogen is increasingly recognized as a key solution for achieving carbon neutrality, offering promise in energy storage, transport and applications across various sectors, including automotive, aerospace and heavy industry. This widespread industrial adoption necessitates the development of robust materials capable of enduring high-pressure hydrogen environments. Metals such as stainless steel are commonly used in pipelines, storage tanks, and reactors for hydrogen infrastructure. However, the presence of hydrogen leads to a degradation of the mechanical properties of materials subjected plastic deformations like endured during fretting sliding.

Despite this interest in the hydrogen related industries, there has been limited research conducted in the field of tribology to investigate the wear and friction of materials and surface treatments for friction components exposed to gaseous H_2 environments, such as valves and compression pistons [1], [2], [3]. In this study, an original Micro Fretting Wear rig (MFW) was specifically designed to be inserted into a H_2g chamber previously developed at CDM laboratory for tensile experiments. This high-pressure chamber enables material testing at gas pressures up to 25 MPa (250 bar). This study focused on identifying the friction and wear mechanisms of a sphere/plane homogeneous 304L stainless steel interface in different environments. Hydrogen (H_2) and Helium (He) were used as gas atmospheres and air atmosphere was used as reference (0.1 MPa). A range of hydrogen pressures, from 0.4 MPa up to 25 MPa, were tested. The fretting scar surfaces were meticulously analyzed using SEM, EDX and micro-raman to better interpret the ongoing wear scenario and the dynamics on the surface damage.

Under hydrogen environments and equivalent fretting loading conditions, the coefficient of friction increased compared to air, with severe seizure phenomena predominating during the beginning of the tests Figure 1(a). In a similar fashion, rapid wear happened at the beginning of the tests followed by a smoother kinetics, almost similar to that observed in air. When the hydrogen pressure exceeded a threshold value (i.e. above 0.8 bar), typical "nodule like wear debris" were formed accommodating the contact and reducing the coefficient of friction through a "ball bearing like" phenomenon Figure 1(b). Cross-sections of wear scars were examined after polishing and chemical etching for the different environment. In H_2, a

nanosized grain structure knows as a Tribological Transformed Structure (TTS) was formed in the surface due to the high local stresses and plastic deformation characteristic of fretting wear tests in hydrogen. Hardness analysis in the cross-sections were performed using a nonoindenter to characterize the mechanical behavior of the TTS. The results revealed a significantly high Vickers hardness in the TTS compared to the bulk material was In He gas, the maximum value of the coefficient of friction was higher by 80% than that observed in H_2. The tribological behavior was close to the one typically seen in vacuum, as reported by Iwabuchi er al. [4]. Notably, the absence of nodules like wear debris, which were previously observed on H_2, underscores the critical role of hydrogen in the formation of such debris and the development of a third-body layer.

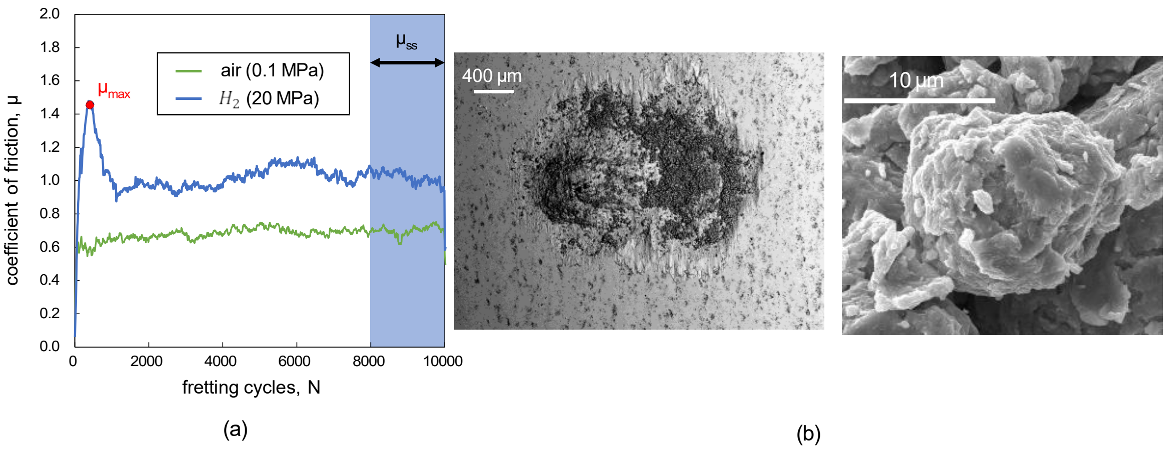

Figure 1: (a) Variation of the friction coefficients μ in air and hydrogen with the test duration (b) SEM image of the wear scar in H_2 at 20 MPa (N = 10 000 cycles, , ,) (b)

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Reciprocating Wear Damage in Steam Turbine Grid Valves: Influence of Coatings and Thermochemical Surface Treatments

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Keywords: Reciprocating wear, Wear volume, Friction coefficient, Coatings, Thermochemical treatments

Abstract

The grid valve is a component of a steam turbine used in extraction turbines to control the flow of pressurized fluid, generally because the extracted steam can be used for other processes, thereby increasing the overall efficiency of the power plant. A typical grid valve architecture consists of a stationary (stator) disk and a rotating disk driven by servomotors or actuators. Flow ducts are machined into both disks, and oblique grooves are added to the mating surface of the stator disk. The valve's opening condition depends on the relative angular position between the rotating and stator disks: the valve is fully closed when the ducts do not overlap, fully open when the ducts are fully aligned, and partially open when there is partial overlap. Under operating conditions, the disks are subjected to a low-amplitude reciprocating relative motion. The pressurized fluid acting on the rotating disk generates a normal force on the mating surfaces, which increases with the pressure differential across the valve. At high differentials, this force may exceed practical actuation limits. To address this, modern grid valves [1] often include a balancing element that reduces the contact load and, consequently, the torque required for actuation. Despite these design improvements, tribological performance remains critical. The disks operate under dry contact, requiring materials with a low coefficient of friction and high wear resistance. These properties are typically achieved through surface treatments or the application of advanced coatings. This study aims to model the contact interface of the grid valve and investigate the friction and tribological behavior arising from the reciprocating motion between the grooved surface of the stator disk and the flat surface of the rotating disk.

The experimental plan involved: two thermochemical treatments (nitriding and carbonitriding); four coatings (Electroless Nickel Plating, Stellite applied by Cold Spray and Laser Cladding, and chromium carbide by High Velocity Oxygen Fuel) applied on 39NiCrMo3 steel; three temperatures (Room Temperature, 24 C, Mid-range Temperature, 120 C, and High Temperature above 500 C); one relative displacement amplitude (500 µm); two frequencies (5 and 50 Hz); two test durations (150 and 250 thousand cycles); and two normal loads (88 and 284 N). The contact surfaces of the specimens were designed to reproduce the interaction between grooved and non-grooved surfaces of the grid valve, using two sliders with matching groove angles relative to the sliding direction. A scale factor was applied between the real and the specimen contact surfaces, preserving the ratio between the contact length (measured along the sliding

direction) and the displacement amplitude [2]. Tests were performed using the test rig described in [3], which was slightly modified to match the required sliding amplitude. In particular, a new set of springs with reduced cross-section was designed and installed, and the shaker was replaced with a more powerful unit. This setup enables a systematic investigation of how coatings, treatments, and loading conditions affect friction and wear in the modelled grid valve contact interface.

Figure 1 shows wear volumes as a function of dissipated energy for five combinations of thermochemical treatments and coatings, tested at mid-range (**Figure 1**-(a)) and high temperatures (**Figure 1**-(b)). At high temperature, wear volumes are generally lower.

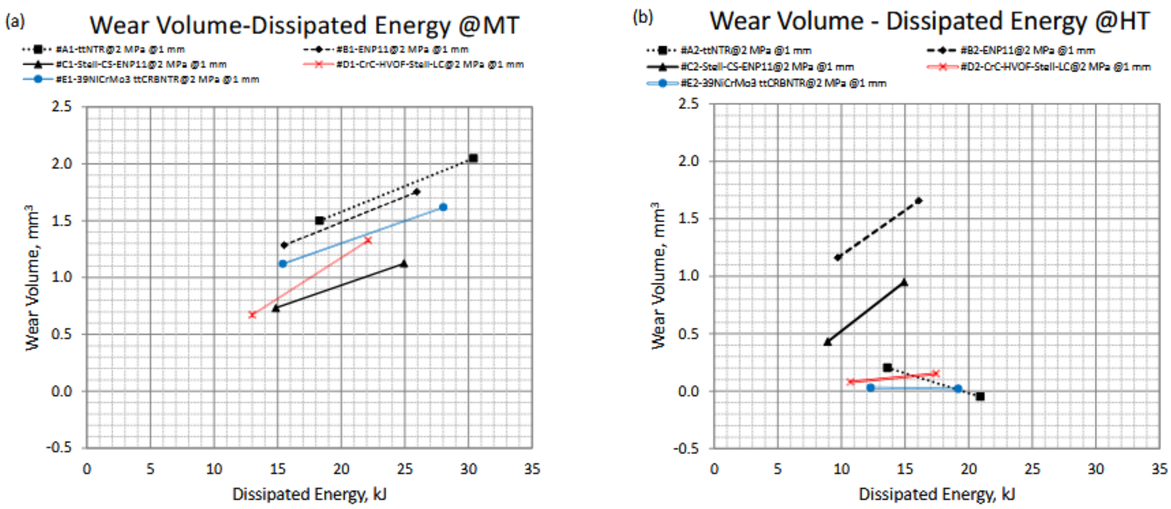

Figure 1: Wear volumes as a function of dissipated energy at Mid-range (a) and High Temperatures (b).

ENP shows similar performance at both temperatures, while other materials respond more sensitively to thermal conditions. Surface treatment selection should account for operating temperature: CrC (HVOF) and Stellite (laser cladding) perform best when used across both temperatures. If different pairings are allowed, ENP and Stellite (cold spray) perform better at mid-range temperature, while carbonitriding performs best at high temperature.

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Influence of Subsurface Defects and Material Anisotropy on the Fretting Fatigue Response of AMed Ti-6Al-4V

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Keywords: Additive manufacturing; fretting fatigue; Voronoi tessellation; subsurface defects.

Abstract

Fretting fatigue behaviour is influenced by external factors, including temperature, corrosion, and lubrication, as well as intrinsic material properties such as surface condition, microstructure, and internal defects like impurities or micro-voids [1-5]. This study focuses on the effects of microstructural inhomogeneity and subsurface defects on the fretting fatigue response of additively manufactured (AM) Ti-6Al-4V (Ti64), a widely used alloy in aerospace and biomedical applications. These factors are inherent to the AM process and significantly impact material performance under fretting conditions. A numerical modelling approach was employed to simulate crack initiation and propagation using continuum damage mechanics (CDM) and the extended finite element method (XFEM). Finite element (FE) models were developed to analyse subsurface defects, with defect characteristics (shape, size, and location) measured from scanning electron microscopy (SEM) images.

The study particularly focuses on critical defects that contribute to fatigue failure outside the contact region. In one approach, only the overall defect size is considered, approximating its shape to evaluate whether a simplified model can still yield meaningful results. These defects are integrated into FE models as irregular voids, serving as stress concentration points. AM Ti-6Al-4V exhibits a lamellar α-phase microstructure within prior β grains, leading to anisotropy and variations in mechanical properties. To model this complexity, Voronoi tessellation was used to replicate the prior β grain structure, validated using electron backscatter diffraction (EBSD) data. A Python script generated Voronoi diagrams in ABAQUS, assigning orthotropic elastic properties and random grain orientations to capture material anisotropy. The plastic properties remained isotropic and were derived from stress-strain curves obtained from tensile tests.

Subsurface defects, identified through fractographic studies, were digitally reconstructed and incorporated into FE models near the contact edges. Defect dimensions (10–50µm) were measured using SEM analysis. High-fidelity meshing with 5µm elements ensured accurate resolution of stress gradients and crack initiation behaviour. Material inhomogeneity was introduced by defining orthotropic elastic properties and assigning random grain orientations to each Voronoi cell. A Python script applied orientations between 0 and 180 degrees to individual cells, effectively capturing the heterogeneity of real AM Ti-6Al-4V.

The results indicate that, although the difference in stress magnitude between homogeneous and inhomogeneous simulations is relatively small, microstructural inhomogeneity significantly influences fatigue life. Additionally, the analysis of internal surface effects reveals that near-surface defects notably increase stress concentration,

leading to crack initiation outside the contact zone, as predicted by FE simulations, as shown in Figure 1. This study highlights the importance of incorporating microstructural variability and defect distributions in fretting fatigue modelling, providing valuable insights for improving the durability of AM components subjected to cyclic loading.

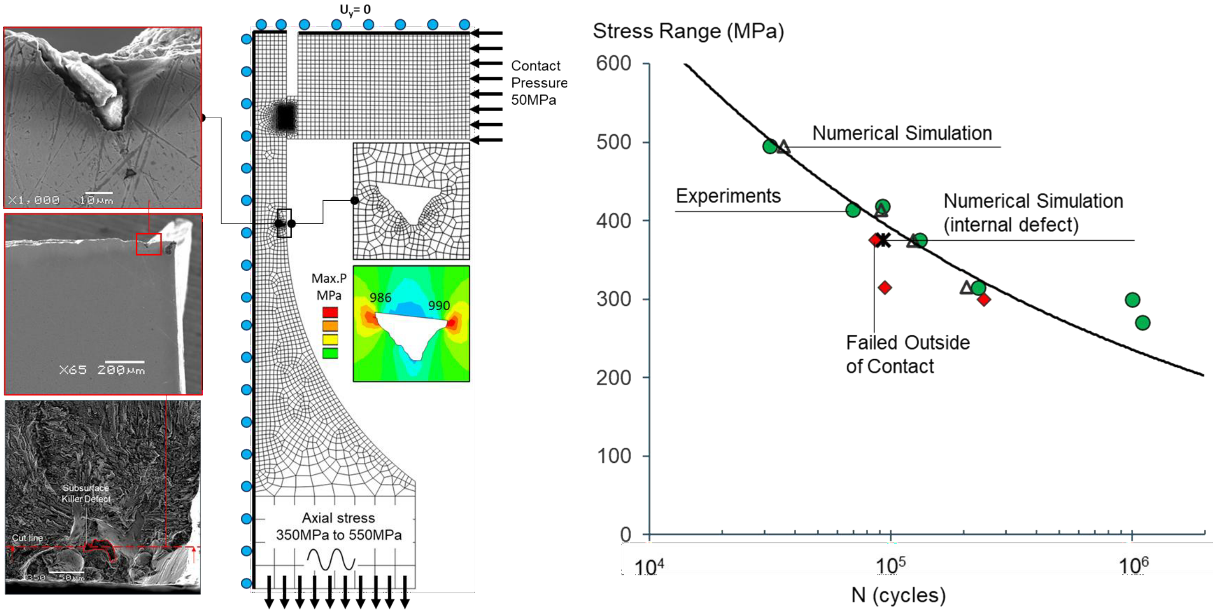

Figure 1: Analysis of internal surface effects shows that near-surface defects significantly amplify stress concentration, causing crack initiation outside the contact zone.

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Digital Twins for Fretting in Submarine Power Cables

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Keywords : fretting, wear, fatigue, machine learning, finite element analysis.

Abstract

Ireland's energy future will rely significantly on offshore renewable sources, with up to 70 GW of ocean energy available within 100 km of its coastline [1]. A key challenge in offshore wind expansion is ensuring reliable power transmission via submarine power cables (SPCs). Dynamic cables for floating offshore wind turbines (FOWTs) are critical infrastructure and form complex systems in which fretting, wear, and fatigue significantly contribute to cable failure [2].

This work presents a preliminary machine learning approach using supervised learning and linear regression to analyse the pre-established global-local methodology and identify fretting wear and fatigue damage patterns in SPC conductors. In this study, a global finite element model is constructed in Flexcom to simulate the FOWT and dynamic cables. The resulting loading conditions are implemented into (i) a simplified SPC sub-element model in Abaqus to assess conductor loading, (ii) a detailed multi-wire conductor model to analyse local inter-wire contact, and (iii) high-resolution frictional contact models that simulate laboratory test configurations to compute fretting wear and fatigue damage [3,4]. Findings indicate that increasing lay angle significantly reduces fretting-fatigue life, with a contact size effect linked to wire diameter.

Building on this methodology, machine learning techniques are introduced to analyse data collected through the global-to-local modelling approach, as illustrated in Figure 1. The machine learning model aims to process extensive datasets to identify fretting failure patterns in SPCs used in FOWTs and to develop a highly efficient and accurate prediction system for fretting-related damage. As an initial step, fretting behaviour is investigated using a simple cylinder-on-flat configuration under various design parameters (e.g. radius, normal load, stroke, bulk stress, and friction) via the software EASY-FRET, developed at the University of Galway. The research follows a step-by-step approach, starting with localised models and progressively incorporating additional layers and training sets into the database, as shown in Figure 2.

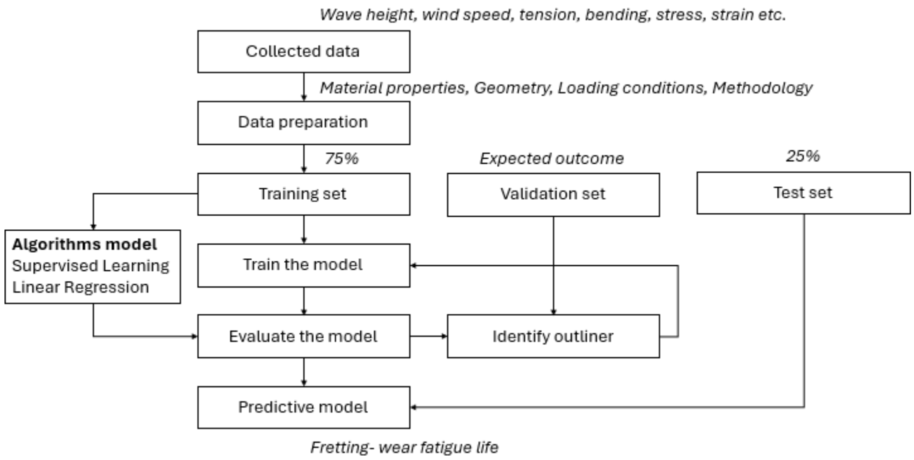

Figure 1: Flowchart of machine learning used for fretting in SPCs.

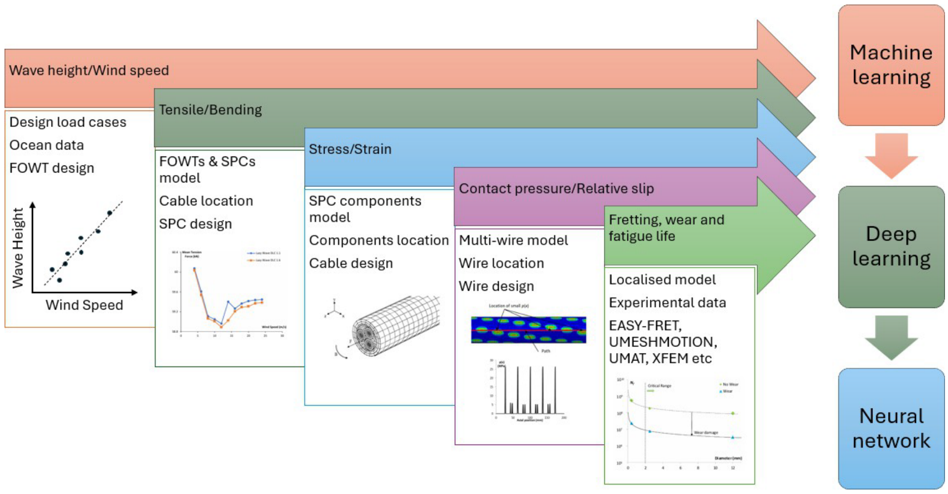

Figure 2: Concept design of the machine learning for fretting in SPCs.

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Fretting Fatigue Modelling: Combining Crack Initiation and Propagation with multiaxial fatigue and Phase-Field

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Keywords : fretting fatigue, phase field, multiaxial fatigue

Abstract

Fretting fatigue is a critical failure mode in mechanical components subjected to repeated small-scale oscillatory motion, which often occurs under multiaxial stress states [1]. This phenomenon, characterised by the simultaneous action of normal and tangential forces at the contact interface, makes accurate prediction of crack initiation and propagation challenging. Despite advances in fatigue modelling, the unique complexity of fretting fatigue requires further exploration of robust numerical tools for reliable life prediction and damage analysis.

This study proposes a hybrid numerical framework that integrates the classical multiaxial fatigue parameter Smith-Watson-Topper (SWT) for crack initiation prediction [2] with the phase-field [3] method for crack propagation analysis. The combination of these approaches offers a comprehensive methodology to address both the early and advanced stages of fretting fatigue failure. While the phase-field method has been employed for general fatigue analysis, its application to fretting fatigue has not been explored before.

To validate the numerical findings, experimental tests were performed on a dovetail connection using aluminum 7075-T6. This material was chosen for its strong mechanical properties, making it suitable for numerical models that rely on elastic behavior. Additionally, the results were benchmarked against established methods.

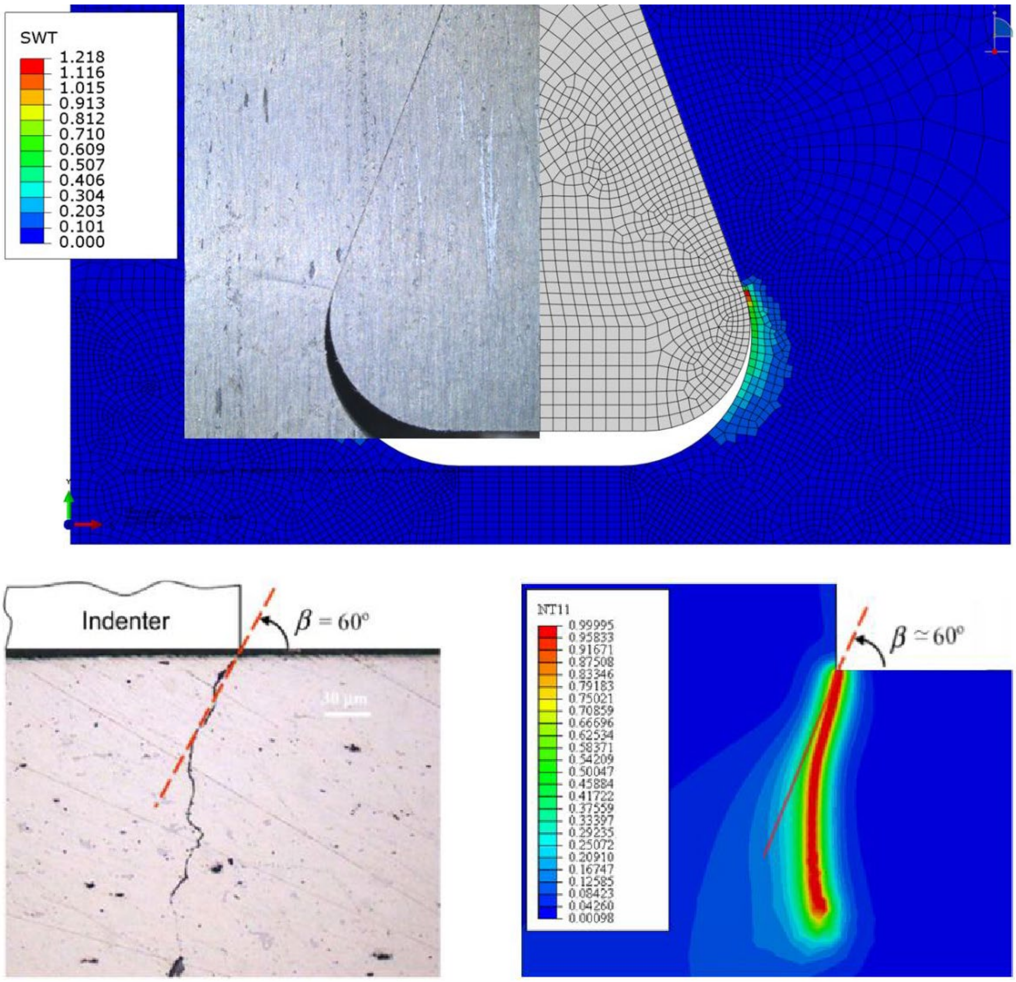

Figure 1: Prediction of crack initiation and propagation in fretting failure: experimental correlation for a dovetail connection and a reference case from the Literature [4].

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On the fatigue life prediction of overhead conductors using neural networks

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Keywords : Neural networks, Fretting Fatigue, Overhead conductors, Life prediction

Abstract

This contribution aims to introduce a data-driven model in conjunction with finite element analysis to predict the fretting fatigue life of overhead conductors. The proposed model is initially trained using fretting fatigue data of two types of aluminum wires and subsequently tested another type of wire data to evaluate its generalization capability across different materials. The second phase involves a more challenging task of predicting the fatigue life of two different overhead conductors, further testing the model's performance in terms of material, loading, and geometry. The estimated fatigue lives fall within the three band, encompassing all accepted wire breaks for the conductors in question. The proposed methodology also is able to accurately estimate the fatigue failure location. This work highlights the generalization capabilities of these models, enabling their easy and precise application in various mechanical scenarios.

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Influence of Finite Friction on Pin Separation and Crack Growth in Deformable Pin Lug Assembly

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Keywords: Interference-fit, Deformable pin, Finite friction, Contact/separation, Crack growth

Abstract

The contact region between the pin and the lug hole is of primary concern in the design of lug joint as it involves heavy load transfer and is also susceptible to stress concentration. Studies on lug joints have addressed stress distribution around the pin-hole, often assuming a rigid pin with smooth interface [1,2]. In this study, a deformable pin is considered and the results obtained are compared with those of a rigid pin. Interfacial friction plays a crucial role in the contact region, as it could influence the stress distribution and consequently the structural integrity. This study primarily focuses on the effect of finite friction on stress distribution and crack nucleation at the interface of pin-lug assembly for interference-fit (Figure 1) involving rigid as well as deformable pins. The lug joint configuration is modeled using commercial FE software ABAQUS and the stress analysis is performed in two steps (Figure 2) involving insertion of interference-fit pin and application of pin load.

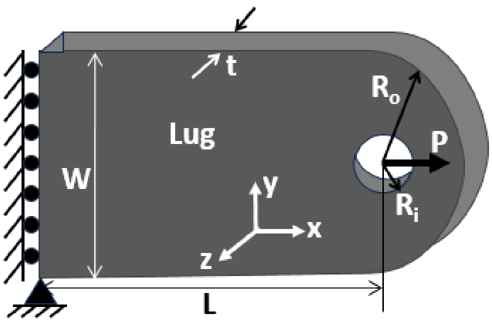

Figure 1: Interference-fit lug joint configuration

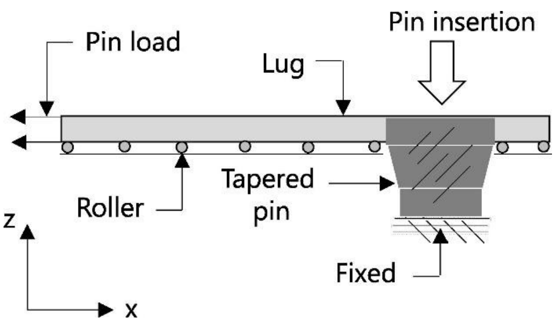

Figure 2: Analysis steps – Pin insertion + Application of pin load

The dimensions of the lug joint indicated by L, W, and t are the length (200mm), width (100mm) and thickness (3mm) of lug respectively. R_o and R_i are the outer radius of the lug and inner radius of the lug-hole wherein $R_o/R_i = 2$. Lug material is Aluminum 2024-T3 (Figure 3) having elastic-plastic material model as per Metallic Material Properties Development and Standardization (MMPDS) document.

The separation behavior of elastic interference-fit pin under increasing axial load is analyzed for different modular ratios corresponding to pin and the lug materials. The results are compared with that of rigid in as shown in Figure 4. The observed variation in pin separation closely aligns with the behavior of a smooth rigid pin up to a certain load, beyond which local

yielding occurs in the deformable pin. The separation observed in steel pin, having a higher modulus relative to the aluminum lug, closely resembles that of rigid pin. However, due to the finite stiffness of the pin material and friction at the interface, the maximum pin separation remains nearly half of that observed in the idealized case. Beyond this threshold, incremental pin separation is accompanied by plastic deformation in the lug.

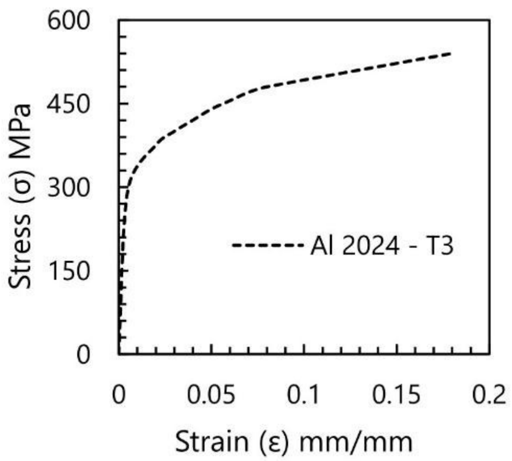

Figure 3: Stress (σ) – strain (ϵ) plot of Aluminum 2024-T3

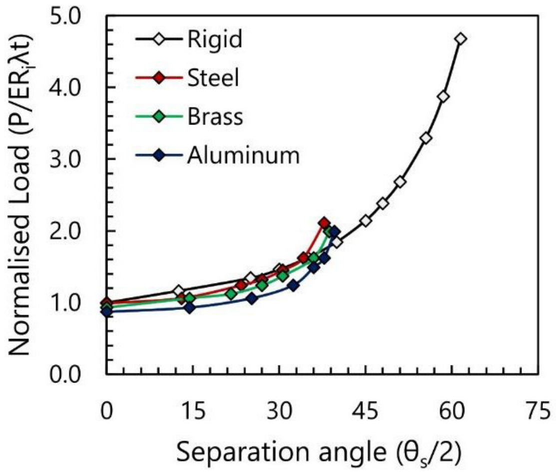

Figure 4: Comparison of separation of deformable pin and rigid pin

The location of crack initiation in case of steel pin with finite friction being different from that of rigid smooth pin case, the crack propagates radially outward and at an angle to the loading direction. Fracture parameters for Mode I and Mode II are evaluated. Crack growth life of steel pin with finite friction is estimated using Paris' law with Elber correction and the results are compared with that of rigid pin. The crack growth life in deformable pin was found to be 10% lesser than that due to the rigid pin.

This research provides insights into the influence of finite friction on stress distribution and crack growth behavior in interference-fit lug joints with deformable pins, contributing to a more comprehensive understanding of their mechanical performance.

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Characterization of fretting damage formation via adhesive process – comparing different running conditions

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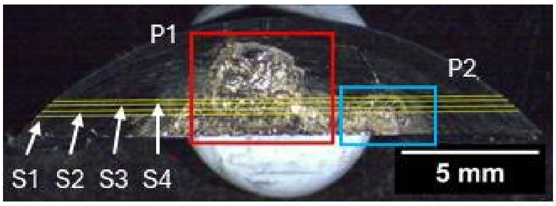
Keywords : fretting wear, fretting fatigue, materials characterization, acoustic emission

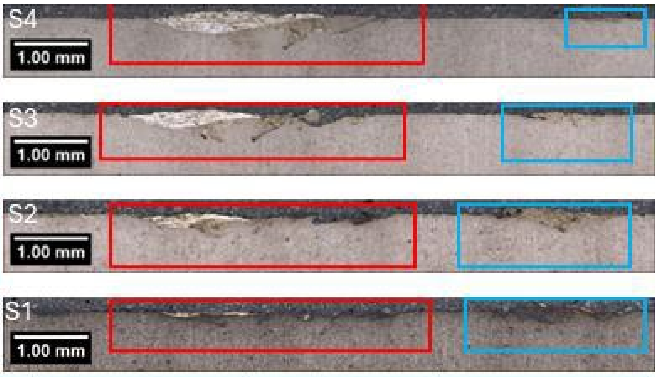
Abstract

Fretting induced damage has been observed to have a predictable evolution in the case of self- mated annular flat-on-flat contacts of quenched and tempered steel (QT) [1]. In gross sliding (GS) conditions the damage evolution can be considered to have four distinct steps. First, the outermost thin oxide layers of the surfaces get torn leading to metal-metal contact and strong adhesion at surface roughness junctions. In the second step, adhesive damage is localized into cold-welded spots where major plastic deformation occurs together with adhesive transfer. Paired fretting fatigue cracks often form at the edges of the 'adhesion spots.' The first steps occur over the first few hundred loading cycles of a GS fretting test and are accompanied by a steep increase in coefficient of friction (COF) up to 1.5. In step three, the adhesion spots start wearing down due to heavy adhesive wear and COF decreases as wear particles cover the contact surfaces inducing a more abrasive wear type. Simultaneously further crack growth takes place. Finally, a steady state is reached where COF stabilizes to 0.7–0.8 and the amount of wear material within the contact stays relatively constant. In partial slip (PS) conditions similar steps can occur depending on factors such as number of loading cycles and the degree of sliding. This experimental investigation aims to clarify the effects of running conditions (sliding amplitude/tangential displacement, number of loading cycles) to the development of the spot like adhesive damage and crack growth and relate the characterization observations to on-line measurements (COF, acoustic emission (AE)). Both PS and GS conditions are considered with sliding amplitudes up to 50 µm. Varied length tests up to $3*10^6$ loading cycles are done to observe damage evolution at different stages.

A systematic materials characterization is required to attain reliable information about fretting damage formation and evolution. After fretting tests, the specimens are ultrasonically cleaned from loose wear debris after which they are imaged with an optical microscope and an optical profilometer. Adhesion spot remnants are identified and measured, and locations are chosen for cross section observations. In figure 1, an example is shown where an area with two large convex adhesion spot remnants has been chosen, and the area has been cut from the specimen. The cross sections from the area of interest are then examined by grinding into the material step-by-step to get an overall view of the subsurface damage. After each grinding and polishing phase optical microscope images are taken and visible cracks and degradation layers are measured (see figure 1). The commonly found fretting induced degradation layers include

the third body layer (TBL), tribologically transformed structure (TTS) and the general deformation layer (GDL).





Adhesion spot	Area [mm²]	Max diameter in sliding direction [mm]	Max. depth/height [μm]
P1	8.47	3.41	240 (convex)
P2	2.93	2.26	100 (convex)

Cross section	Crack length range [μm]	Crack median length [μm]	Crack maximum length by adhesion spot [μm]	TBL maximum depth [μm]	TTS maximum depth [μm]	GDL maximum depth [μm]
S1	77–487	238	402, 487	No TBL	90	274
S2	16–829	200	453, 829	No TBL	210	315
S3	110–744	161	744, 498	No TBL	160	360
S4	25–1213	170	1213, 200	No TBL	149	445

Figure 1: Characterization of cross sections from a gross sliding test (sliding amplitude = 50 μm, normal pressure = 30 MPa, loading frequency = 40 Hz, 10 000 loading cycles).

The goals of this experimental study include clarifying connections between surface and subsurface damage observations and linking characterization data to other data collected during fretting tests. For example, relating the dimensions of the adhesion spot remnants to the lengths of the cracks formed at their edges. Characterization data will be compared to on- line measurement data such as COF and the AE measured close to the fretting contact.

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Fretting fatigue and torsional fretting wear of PC/ABS blends: effect of variable amplitude.

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Keywords: torsional fretting wear, radial fretting fatigue, PC/ABS blends

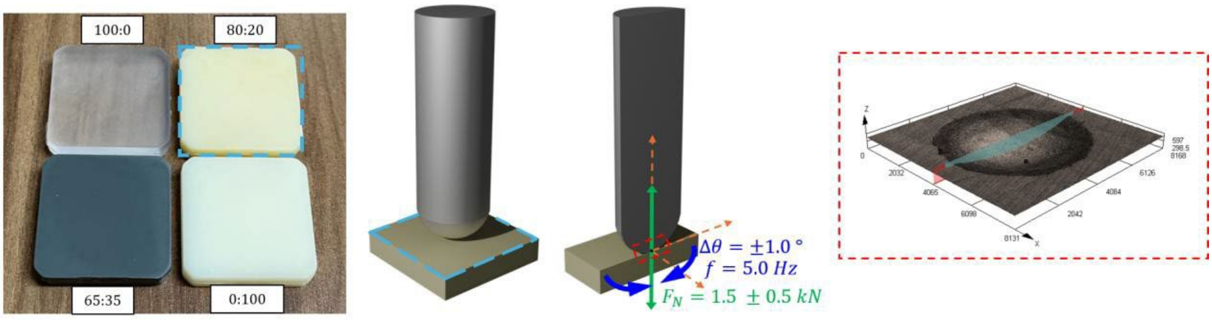
Abstract

Polycarbonate/Acrylonitrile-Butadiene-Styrene (PC/ABS) blends are extensively used in engineering applications due to their advantageous mechanical properties and processability. While previous studies have investigated their basic mechanical and thermal responses [1,2,3,4], a few have addressed their friction and wear behavior under common contact configurations [5,6]. In previous works [7, 8], torsional fretting wear in a constant normal load setting has been investigated. Herein, cyclic compressive normal loads are also considered. This study aims to examine the fatigue performance, and the wear evolution of PC/ABS blends when both failure phenomena are at play. To accomplish this, sphere-to-flat indentation tests in both monotonic and cyclic loading conditions are carried-out.

Prismatic specimens (25 mm in length by 25 mm in width and 5 mm in thickness) are prepared using four PC/ABS compositions: 100:0 (pure PC), 80:20, 65:35 and 0:100 (pure ABS). A metallic counterpart made of R3-grade naval steel is employed as a hemispherical indentation pad (diameter of 15 mm). The boundary and loading conditions are applied using a MTS 809 axial-torsional machine. Tests are carried-out in three testing phases. In phase 1, all flat specimens are subjected to a monotonic normal load of 2 to establish the initial damage created by the indentation. In phase 2, a group of flat specimens are subjected to a cyclical normal load, for 50,000, 100,000 and 200,000 cycles at a frequency to evaluate its fatigue performance. In phase 3, another group of specimens is tested in a multiaxial setting: the same cyclical normal load, , coupled with an in-phase oscillatory torsional motion. Following all tests, the damage marks left on the flat surfaces are inspected using an Olympus LEXT OLS4100 confocal laser microscope. The marks' dimensions are measured to estimate their volume, and their morphological aspects are analyzed and compared. A schematic view of the testing methodology is shown in Fig. 1.

Preliminary results show that the torsional motion resulted in torsional fretting wear (as previously reported by the authors [7, 8]) while the cyclic normal load resulted in both radial fretting fatigue, as described in [9], and radial fretting wear. Moreover, the 100:0 and 65:35 compositions, which previously exhibited the best mechanical resistance to indentation, creep and torsional fretting wear [8], now showed the weakest response to the fatigue load condition, which resulted in fissures or complete rupture of the specimens. As described in [10], cracks initiating at the edge of the contact area are observed for 100:0 and 65:35 specimens, at around 45,000 to 60,000 cycles. 80:20 and 0:100 compositions exhibited no signs of cracking even at the harshest conditions herein tested.

The contributions of this study deepen the understanding of PC/ABS blends mechanical behavior, validate once more the novel testing methodology developed by the authors and may assist engineers in properly selecting the most adequate composition for certain industrial applications.



(a) (b) (c)

Figure 1: Schematics of the testing methodology employed in this study: a) prepared prismatic specimens of each PC/ABS composition (25 mm in length, 25 mm in width and 5 mm in thickness); b) sphere-to-flat contact configuration, employing a R3 graded steel cylindrical tool with hemispherical tip (⌀ 15 mm); c) 3D-view of the damage profile on a 0:100 specimen after 200,000 cycles of oscillatory torsional motion and variable normal load (approx.. 5.95 mm in diameter and 0.42 mm in depth). Adapted from [8].

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Tribological behavior in fretting of Inconel 718 alloy obtained by additive manufacturing

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Keywords : friction, wear, Inconel 718, Laser Metal Deposition

Abstract

In this study, we investigated the tribological behavior of the Inconel 718 alloy produced by additive manufacturing, specifically using Laser Metal Deposition (LMD), under fretting conditions. The research focused on understanding the impact of various laser strategies and fretting parameters on wear resistance. In particular, the effects of sliding amplitude and contact pressure were studied, under gross slip conditions, with Inconel 718 flat in contact with an alumina ball.

Especially, due to the small size of the contact area under the tested conditions, in the same range as the width of the bead in LMD (Figure 1), it was possible to study if there is a difference in wear resistance in the center or in the side of the bead. The results show that, even if there is a slight difference in microstructure and in hardness between the center and the sides of the bead [1], there is no significant difference in friction and wear behavior.

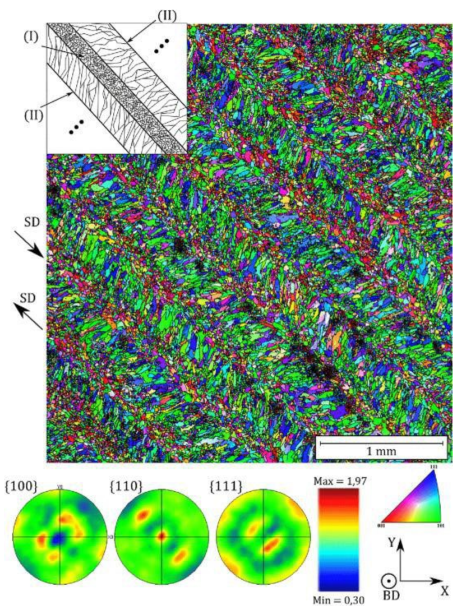

Figure 1: IPF Z (by EBSD technique) showing the top surface of Inconel 718 (obtained with a 45° strategy) and its pole figures, presenting the beads oriented with a 45° angle [1]

The impacts of the scanning strategy and the sliding direction were also studied and the results confirmed that these parameters have no significant influence, as it was observed on large contact under full reciprocating sliding [2].

The results obtained on additively manufactured Inconel 718 were compared to the ones for conventional Inconel 718 (obtained by forging), demonstrating a slightly better behavior of Inconel 718 obtained by LMD at low values of displacement amplitude.

In summary, this experimental study contributes to a deeper understanding of the fretting wear resistance of additively manufactured components. By identifying the effect of different parameters on wear, it provides insights that could be used to optimize the repair and manufacturing of high-value-added parts in industries such as aerospace, where durability and performance are critical.

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Tribologically transformed zones in fretting contacts and the dependence of their formation on the conditions of wear and the resulting rate determining process

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Keywords : Third-body, debris, oxide, transport, diffusion, rate-determining process (RDP)

Abstract

It has been understood for many years that the wear rate in fretting of non-noble metals in air is normally controlled by some combination of the rate of transport of oxygen into the contact to form debris and the rate of transport of debris out of the contact, although it is only in the last five years that coherent models have been developed to describe these [1-3]. It has been argued that the process of fretting wear is made up of the sub-processes of (i) oxygen transport into the contact; (ii) debris formation within the contact; (iii) debris expulsion from the contact. Furthermore, it has been argued that the observed rate of wear will simply be the rate of the slowest of these sub-processes (this being the rate-determining process) [1, 4] and that the rates of the other processes will decrease so that the rates of all three processes are the same (in order to maintain process equilibrium).

If debris egress from the contact is the rate-determining process, then an oxide debris bed (third body layer) exists across the contact, and as such, metal to metal contact (i.e. contact of the first bodies) is prevented. However, if oxygen ingress into the contact is the rate-determining process, then a protective oxide debris bed does not form across the contact, and thus there is contact between the metallic first bodies, which results in deformation, adhesion and transfer between the first bodies themselves, and thus to the formation of a tribologically transformed zone which has implications for the subsequent fatigue behaviour of the material. Figure 1 shows cross-sections through fretting contacts in an S132 steel tested under two different conditions. In Figure 1a, the conditions are such that the oxide debris has acted to protect the first body from contact with the other first body, resulting in a lack of subsurface deformation in the metal. In contrast, in Figure 1b, the conditions are such that the oxide debris was not able to prevent contact between the two first bodies, and thus a highly deformed metallic region has formed, this region generally being termed the tribologically transformed zone (TTZ).

A model has been previously developed which seeks to understand which process is rate- determining in a fretting contact, and as part of this, it considered both the rate of supply of oxygen across the whole fretting contact (limited by its diffusion through the contact) and the rate of demand for oxygen in forming oxide debris at the required rate across the whole contact [1]. In the current work, this model is refined in light of a more recent understanding of the effect of slip amplitude on the rate of fretting wear [5] and is extended to allow behaviour in contacts of different geometries to be compared.

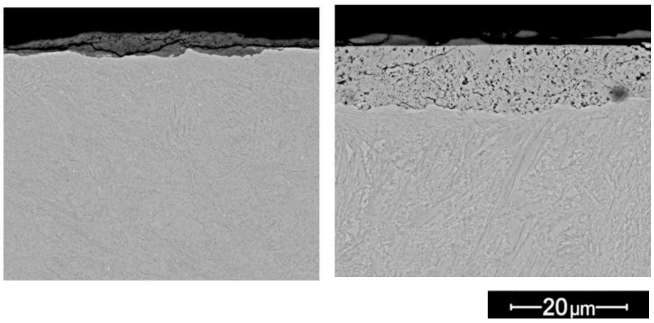

Figure 1 Cross section through two fretting scars in an S132 steel which had been tested in a cylinder-on-flat contact geometry. Test conditions (applied load, fretting frequency, number of cycles) were identical except that (a) had a displacement amplitude of 25 μm and (b) had a displacement amplitude of 50 μm. From [6].

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Fatigue life and crack growth of Inconel 718 superalloy at room and high temperatures under fretting fatigue

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Keywords : fretting fatigue, Inconel 718, high temperature, crack evolution, crack growth rate, life estimation

Abstract

Fretting fatigue is a surface damage phenomenon that occurs in mechanical assemblies subjected to fluctuating forces. This type of failure is a significant issue in the engineering field, particularly in blade-disc connections of gas turbines and compressors. Despite its relevance, fretting fatigue remains a problem not widely known outside the engineering community.

In this study, the fretting fatigue behaviour of Inconel 718 was analysed at both room and high temperatures, 650°C, using 'dog-bone' fretting fatigue specimens with a cylindrical contact pad. Inconel 718 is a nickel-chromium-based superalloy widely used in the aeronautical industry due to its excellent mechanical properties, including resistance to oxidation and corrosion, even at high temperatures. Additionally, the material was heat-treated to enhance its mechanical performance.

Different tests were conducted in the laboratory under varying load levels to obtain the fatigue life curve. The main objective of this work is to analyze fretting fatigue damage, determine the fatigue crack growth rate, and examine crack evolution to compare it with an analytical model. Crack surfaces were inspected using a scanning electron microscope.

The fatigue model used in this study integrates both crack initiation and propagation phases without defining a priori the boundary between them. It is based on a variable crack initiation length approach, where different initiation lengths are considered. In all cases, it is assumed that cracks initiate and propagate completely normal to the fretting specimen surface.

Understanding Hydrogen-Induced Degradation in Fretting Fatigue Strength

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Keywords : Hydrogen, Adhesion, Crack Initiation, Tangential force coefficient

Abstract

Achieving carbon neutrality is a critical global objective, and the use of green hydrogen—hydrogen produced from renewable energy sources—is a key strategy to achieve this goal. However, hydrogen can cause significant degradation in the strength of various metallic materials, a phenomenon known as hydrogen embrittlement. Moreover, hydrogen-related equipment such as joints, valves, and seals often involves contact interfaces where fretting and fretting fatigue can occur. Consequently, understanding the effects of hydrogen on fretting fatigue properties is essential to ensure the safety and reliability of hydrogen equipment.

In this context, the authors have conducted extensive research on the effects of hydrogen on fretting fatigue strength, as well as the underlying mechanisms behind hydrogen-induced reductions in fretting fatigue strength [1–6]. These studies have demonstrated that fretting fatigue strength in hydrogen gas environments is significantly lower than that in non- hydrogen atmospheres, including air.

The primary factor contributing to the reduction in fretting fatigue strength in hydrogen environments is localized adhesion at the contact surfaces [3]. In hydrogen gas environments, the absence of oxygen prevents the formation of oxidative wear debris. Furthermore, the oxide film on the material surface is removed during fretting [5], resulting in direct contact between newly exposed material surfaces. This direct contact leads to localized adhesion, which causes increasing tangential force coefficient and significant stress concentration at the adhered regions, thereby initiating numerous small cracks [3]. These small cracks subsequently serve as the origin of fretting fatigue failure.

To investigate the effect of hydrogen on the tangential force coefficient and crack initiation threshold, the authors previously developed a novel testing method and quantitatively evaluated these parameters [4]. In the present study, the authors further refine this testing method to advance the understanding of hydrogen's effects on fretting fatigue strength of a low-alloy steel and austenitic stainless steel.

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Experimental analysis of fretting fatigue life under multi-level normal load conditions

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Keywords : Fretting Fatigue, Digital Image Correlation, Stress Intensity Factors,

Abstract

Fretting fatigue tests under variable loading are gaining increasing interest. In most tests reported in the literature, in phase, cyclic normal, tangential and fatigue loads [2, 3] are applied (Figure 1). However, this approach inadequately represents real-world scenarios, such as blade-disc interfaces in gas turbine engines, where the characteristic frequencies of shear loads (aeroelastic vibrations of the blades) and of normal and fatigue loads (take off, cruise, landing etc.) are very different. As a matter of fact, when in phase loads are applied, though the contact edge location cyclically varies with the normal loads, the most detrimental loading conditions are always met in the same material points. However, when the normal load frequency is much lower than that of the shear load, the area around the contact edge, which can be damaged by fretting cycles, is not always in the same material points, thus dispersing the potential damage over a larger material area and conversely reducing it in each material point.

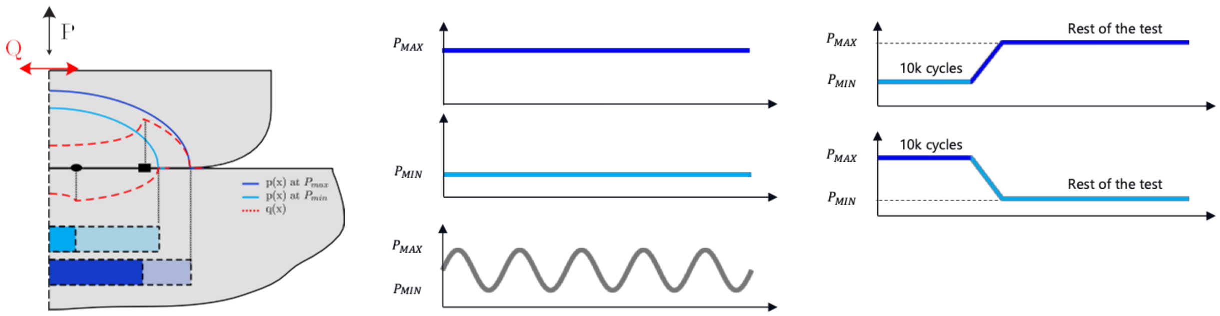

Figure 1: Fretting test under varying normal load: (left) Half-contact width at minimum and maximum pressure levels, and (right) different normal loading scenarios.

The question then arises as to what effect this may have on the fretting-fatigue lifespan. An experimental campaign was conducted in this study to address this issue. Five distinct normal loading conditions P were used in the experiments (Fig.1). Fretting fatigue tests at constant P_{MAX} and constant P_{MIN} were used as a reference. Then, two-level tests were conducted in which the normal load was held constant at the first level for 10,000 shear load cycles, after which the fretting fatigue test continued at the second normal load level—one test transitioning from minimum to maximum load ($P_{MIN,MAX}$) and another from maximum to minimum ($P_{MAX,MIN}$). These tests were compared to an oscillatory cyclic normal load (P_{OSC}) cycling in phase between P_{MIN} and P_{MAX}.

In terms of fatigue life, the constant load conditions revealed that the P_{MIN} test exhibited significantly longer lifespans than the P_{MAX} condition due to lower stress levels. Two-level tests showed that the $P_{MIN,MAX}$ sequence significantly prolonged lifespan compared to constant P_{MAX}, suggesting beneficial effects from the initial lower load phase. Conversely, the $P_{MAX,MIN}$ sequence shortened lifespan relative to constant P_{MIN}, highlighting accelerated failure due to prior damage. The oscillatory loading condition, P_{OSC}, showed lifespans close to those observed in constant P_{OSC}, indicating that cyclic load variability effectively redistributed stress, delaying crack initiation.

A series of observations were conducted to clarify the mechanisms behind the effects of changes in the normal load level on fretting fatigue life, combining observations of contact traces, fracture surfaces, and the distribution of cracks both on the surface and in cross-sections (Fig.2). Together, these observations confirm the role of the displacement of the contact edge and also demonstrate the importance of the crack interactions and their influence on contact behaviour.

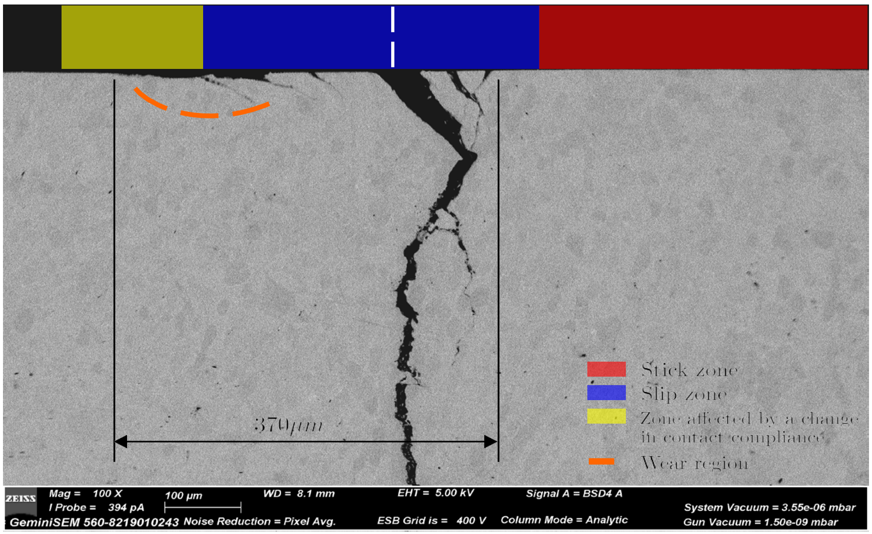

Figure 2: Cross-section SEM image for $P_{'0}$ case.

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Calorimetric Analysis of Fretting Fatigue: Investigating Microplasticity in 35NiCrMo6 Steel

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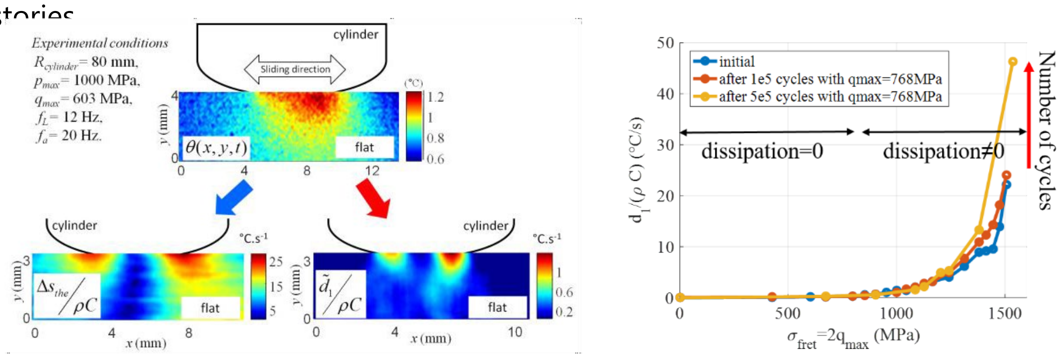
Keywords : Thermography, Fretting Fatigue, Cracking, Damage evolution

Abstract

Fretting damage, particularly in partial slip regimes, severely limits the service life of structural components due to extremely localised cyclic plastic deformation leading to crack initiation. Indeed, partial slip fretting produces multiaxial fatigue loading with a high stress gradient. The conditions for crack initiation therefore depend on the contact configuration, the cyclic responses of the materials and their fatigue properties. On the one hand, determining the risk of fretting cracking in a structural design requires experimental data-intensive methods, and on the other hand, traditional experimental methods for assessing the behaviour of materials under fretting-fatigue are costly in terms of time and materials. Initially appearing in the field of fatigue, alternative experimental methods using the thermal response of materials have been developed to rapidly determine crack initiation conditions under fretting loading [1,2]. They are based on the fact that initiation under cyclic loading depends on the cyclic response of the material: elastic or plastic shakedown and ratcheting [3]. These methods indirectly measure this response by detecting dissipative phenomena [4]. Few studies have explored the use of such methods to monitor the evolution of material behaviour over the long term or as a function of loading history.

The aim of this study is to use an original method for determining heat sources in order to study the evolution of the behaviour of materials under fretting loading. We have developed an original image processing method to separately estimate fields of mean dissipation per cycle d_1 and fields of thermoelastic source amplitude Δs_{the} (Figure 1(a)). In this work, experiments were conducted on 35NiCrMo6 steel in a cylinder-on-flat configuration (radius 80 mm), maintaining macroscopic elastic conditions. We investigated the evolution of dissipative responses with varying shear stress amplitudes and loading histories.



(a) (b)

Figure 1: (a) heat sources (b) dissipation as function of shear stress and number of cycles

Figure 1(b) illustrates the dissipative response of the material as a function of loading history at a maximum contact pressure (p_{max}) of 1,000 MPa. To assess dissipation levels across varying shear stress amplitudes (q_{max}) at relatively constant damage state, we employed a stepped loading approach. The tests involved loading blocks of 3,000 cycles performed at increasing q_{max} values. Between each test, a block of 100,000 cycles was performed at the maximal shear stress (q_{max} = 840 MPa) to accelerate damage accumulation. Analysis of the maximal local intrinsic dissipation as a function of q_{max} revealed a distinct threshold, indicating the onset of localised cyclic microplasticity. This threshold was observed across different p_{max} values and was compared with cracking boundaries determined by conventional methods [4]. While the overall dissipative response was found to be dependent on the material's fatigue damage level, the microplasticity threshold remained independent of stress history. To investigate long-term behaviour, we evaluated dissipation over a 1 million-cycle test at p_{max} = 1000 MPa and q_{max} = 670 MPa. The results show a decrease and stabilisation of maximum dissipation with increasing cycle number (whereas it is often assumed to be constant), even if the distribution of sources remains unchanged (Figure 2 (a)). This indicates a clear evolution in the material's response over extended cyclic loading. These results show the great potential of a calorimetric analysis of fretting tests for a better understanding of damage.

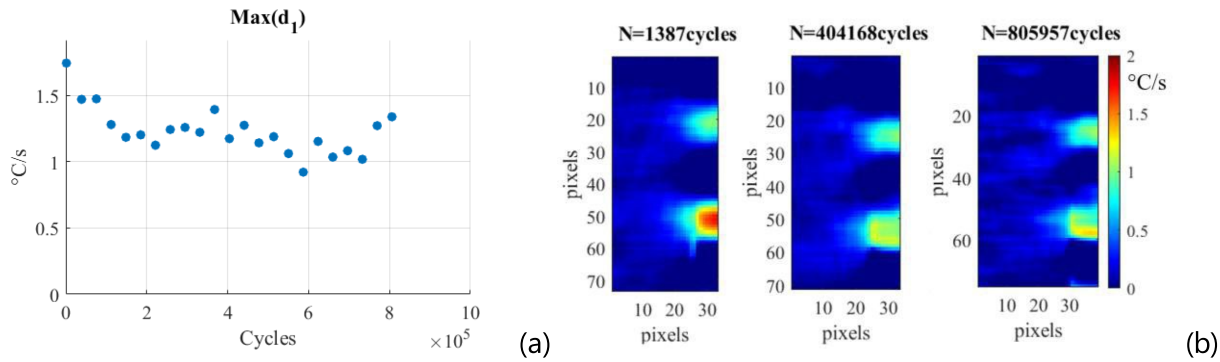


Figure 2: (a) evolution of the maximum dissipation during a test (b) dissipation fields at three different numbers of cycles

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Fretting Fatigue Damage of Steam Turbine Stainless Steel at High Temperature

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Keywords : Fretting fatigue, Stainless steel, Steam environment, High temperature, Fractographic analysis.

Abstract

Fretting damage occurs when two surfaces are in contact and subject to oscillatory tangential movement. This damage results in a deterioration of surface quality and frequently produces a substantial decrease in the fatigue strength of the material. The latter is mainly attributed to the addition of alternating frictional stresses, and the continuous destruction of the protective surface film. It has been recognized that fretting fatigue is a serious problem in steam turbines, which operate at elevated temperatures under increasingly severe conditions caused by higher demands in power and efficiency [1-4]. Fretting fatigue of stainless steels has been investigated to establish of process variables on fretting life and to improve fatigue life through surface treatment and modification [5-7].

Tests were conducted to establish the plain- and fretting fatigue strength of stainless steel-403 steam turbine blade in contact with 3.5 NiCrMoV steel rotor. The tests were conducted in air at room temperature and in steam at 300°C. Analysis of the test results showed that the increase in the temperature and the presence of steam environment have insignificant effect on the plain fatigue S-N curve. Only 10% reduction in the fatigue strength was observed. However, the presence of the fretting action, in superheated steam environment resulted in a significant drop in the fatigue strength by more than 70% due to acceleration in both mechanisms of crack initiation and crack propagation.

Fractographic analyses of the fracture surfaces in plain- and fretting-fatigue testing (Fig. 1) of stainless steel-403 has been analyzed to provide information regarding: (a) the state of stress that caused the material fracture, and (b) the crack origin, and the fracture sequencing and progress. Examination of the fretting wear damage indicated that a gross macro-slip occurred at the specimen/pad interface, resulting in delamination-controlled fretting wear process. The fretting damage also prompted the formation of a network of secondary cracks that is oriented in a direction perpendicular to the direction of slip. In the course of this investigation, a special care has been taken to keep the fracture surface undamaged, since the fretting debris may fall into the fatigue crack and may distort the fracture surface and mask the fatigue striations and the origin of the crack [8].

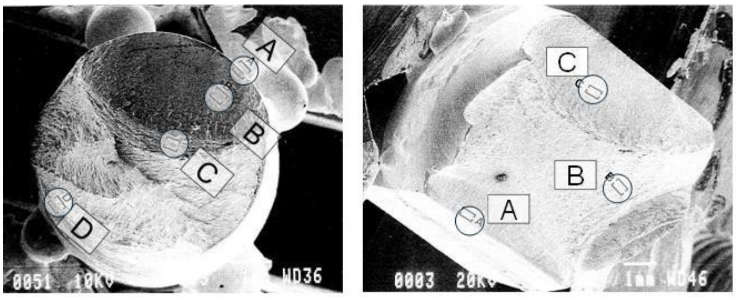

Figure 1: Fractographic analyses of the fracture surfaces in (a) plain fatigue (N= 2.76×10^5 cycles at a stress level of 310 ± 290 MPa), and (b) fretting-fatigue testing (N= 5.34×10^4 cycles at a stress level of 310 ± 255 MPa). Contact pressure p_c = 145 MPa, and frequency f= 80 Hz

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Prediction of the fretting-fatigue endurance of shrink fit lug-bush assemblies: a local Fretting Wear Spot correction

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Keywords : Fretting-fatigue, lug-bush assembly

Abstract

Relative fretting slip at the interface of connection components may occur when the assembly is subjected to fatigue loading [1]. These relative slips can lead to modifications of the surface of the parts in contact through mechanisms such as galling or wear. These surface damages are suspected to reduce the lifespan of these assemblies. The local stresses generated by the presence of a third body at the contact interface are studied through mesoscale numerical modeling.

Shrink fit lug (Ti-6Al-4V) – bush (Maraging 250) assemblies are subjected to uniaxial fatigue loading ($R = 0.1$) until failure (Fig. 1). The use of the SWT fatigue criterion coupled with a model considering a smooth contact interface between the bush and the lug-bore overestimates the fatigue life of the tested connections (Fig. 1a). Fretting damage that forms at the lug-bush interface corresponds to trapped third bodies (referred to as Fretting Wear Spots, FWS) (Fig. 1b). These FWS are generated at the interface in regions of contact where the dissipated frictional energy density is highest. FWS create local over-stresses that promote cracking. To account for the effect of FWS, a first approach consists in modifying the interface geometry by incorporating a geometric indent in the FEA analysis that induces local overpressures (p_{FWS}) (Fig. 1c). A second strategy consists in assuming that the cracking phenomenon is mainly activated by local cyclic shear (q_{FWS}). To simulate the effect of FWS, the local over shear distribution is approximated by introducing local over friction value "μ_{FWS}" so that $q_{FWS} = \mu_{FWS} \times p$ with "p" the pressure profile computed still assuming smooth surface hypothesis. Less computationally demanding, this last approach allows the rapid and efficient integration of the effect of the local discontinuities induced by FWS. Comparison with experimental data shows that both the "geometrical indent" and "μ_{FWS}" approaches provide better predictions of the lifetimes.

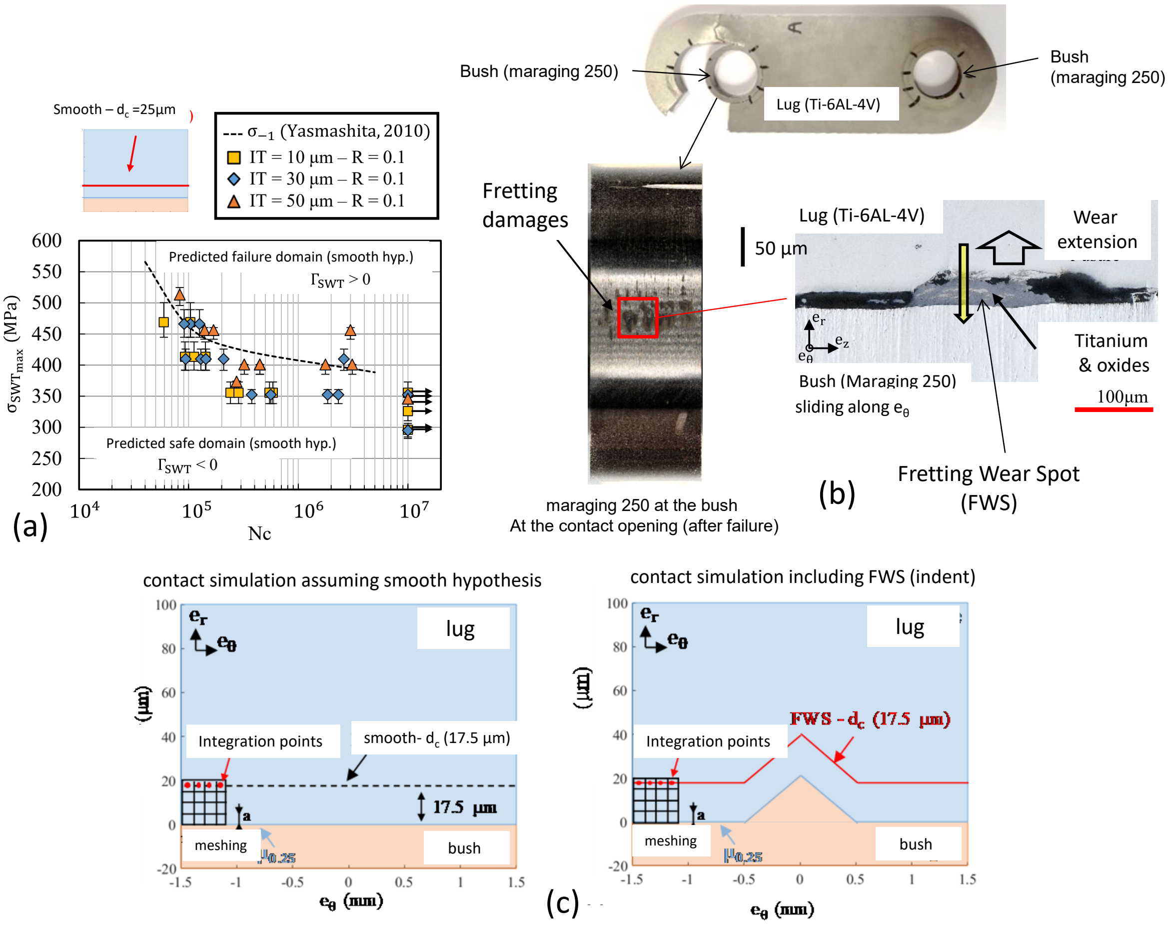

Fig. 1 : (a) Endurance curve; (b) Illustration of FWS ; (c) Simulation of FWS using an geometrical indent.

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Experimental study and modelling of fretting-fatigue-corrosion of galvanized steel in power lines.

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Keywords : Fretting-fatigue-corrosion, galvanized steel, modelling.

Abstract

Electrification and increasing demand are challenging all the Transmission System Operators (TSOs) with a significant increase in demand for electrical energy. Aluminium Conductor Steel Reinforced (ACSR) cables are one of the cable technologies used to transport electricity. They are constituted of galvanised steel strands in the core and aluminium strands around the edges to ensure good mechanical properties and electrical conductivity respectively. The strands are subjected to fatigue loading due to their own weight and the action of the wind. In addition, this assembly allows for slight relative movement between the wires, resulting in fretting within the conductor. The combination of these mechanical loadings, known as fretting-fatigue, induces cracking and wear and is particularly critical compared to fatigue alone. Finally, since the cable is not insulated from the environment, rain and condensation induce the presence of water in the conductor, leading to corrosion. The aim of this study is to characterise the effect of fretting-fatigue-corrosion on the conductor strands near suspension clamps, that are known to be critical zones yielding significant damage. Another objective is to characterize the influence of the aqueous environment on the corrosion products within the contact, and subsequent effect on wear, crack initiation and propagation.

In this context, a fretting-fatigue-corrosion test bench has been developed, allowing independent control of mechanical loads to test a single wire under contact conditions. Fretting-fatigue tests were conducted on steel (Zinc coated)–steel (Zinc coated) contacts in ambient atmosphere at 10Hz, and in water 3.5% NaCl-saturated solution at 10Hz and 2Hz.

The test procedure consists in keeping constant le fatigue loading (σ_a= 175 MPa, σ_{mean}= 175 MPa) and the applied normal force P= 275 N in crossed wire contact (⃠ wire= 2.4 mm, θ=30°) but varying the effective displacement from partial to gross slip (i.e. from δ_{eff}= ±20 to
±300 µm.

The main conclusions of this research work are:

As long as the contact is running under partial slip, the fretting fatigue endurance responses are similar and decrease with the displacement amplitude and the associated increase in the

tangential force amplitude. This suggests that the 3.5% NaCl water is unable to penetrate the interface and that the plain ambient air analysis is quite representative of the application.

However under gross slip condition (i.e. $\delta_{eff} > \delta_{eff,t}$ gross slip transition), when full sliding occurs within the interface, the fretting fatigue endurance tends to increase due to a decrease in the coefficient of friction (lubrication and/or debris layer accommodation) and above due to an increase in contact area induced by surface wear which sharply reduces both pressure shear stress fields. Very different fretting fatigue responses are observed depending on the environmental conditions. Surprisingly, the lowest endurance was observed for contact under ambient air. This can be explained by the high coefficient of friction under dry conditions of around 0.8. The fastest increase in life was observed for the water 3.5% NaCl contact at 10Hz. While the results for samples in water 3.5% NaCl at 2Hz are steel close to ambient air samples. One effect of water is its lubricating behaviour of the contact, which greatly reduces the coefficient of friction (down to 0.4) and thus the mechanical stress. The effect of NaCl is controversial, in this case the most important factor is the frequency, but its effect is difficult to correlate with the corrosion effect. The remaining zinc from the galvanization layer in the interface also seemed to be a relevant factor.

A finite element analysis (FEA) is carried out, including a non-local fatigue crack nucleation approach and surface wear considerations [1], to predict fretting fatigue life under either partial or gross slip conditions thus to capture the decaying effect of corrosion under gross slip sliding.

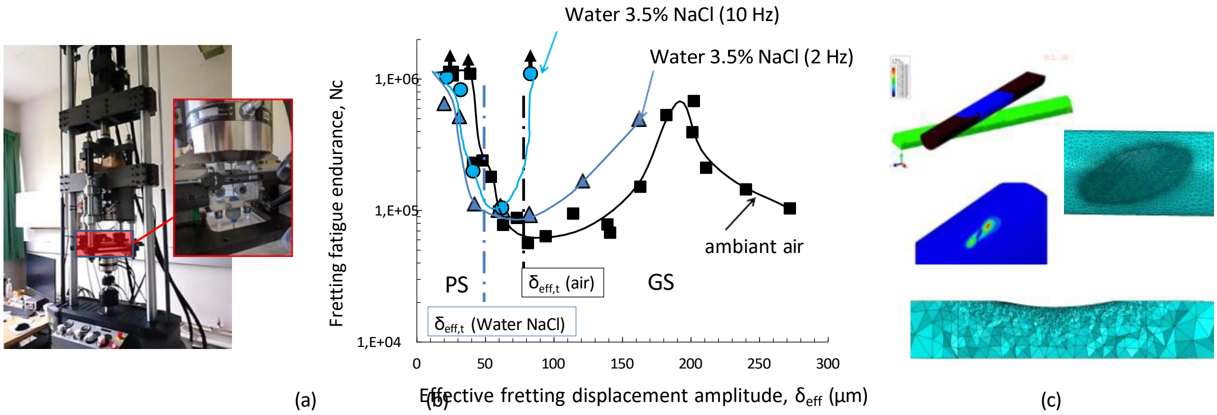

Figure 1 : (a) Fretting fatigue test at Mines Paris under water 3.5% NaCl; (a) Evolution of the fretting fatigue endurance as a function of the applied effective displacement amplitude (loading (σ_a= 175 MPa, σ_{mean}= 525 MPa, P= 275 N); (c) FEA analysis including surface wear in GS.

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Prediction of fretting fatigue failure

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Keywords : Simulation, Fretting damage, Crack propagation, Fretting fatigue failure

Abstract

Fretting fatigues failure consists of two main mechanisms. First the surface cracks are formed at the adhesion spots due to cyclic slip and adhesion. Then the cracks propagate to the structure if the bulk stress amplitude is high enough. A simulation method that considers both mechanisms is presented and applied to a bolted joint fretting experiment. The method is designed for predicting fretting failure of large combustion engines components and is based on macroscale finite element method (FEM). For surface crack formation, contact subroutine for Abaqus is used to simulate spatially variable coefficient of friction (COF) to get more realistic contact response [1]. Fretting tests have shown that there is a limit for stable COF above which fretting damage starts to occur [2]. Based on this information the area where fretting damage and surface cracking occurs can be predicted by simulation. An inhouse tool based on fracture mechanics is used to evaluate how critical the damaged areas are in terms of crack propagation.

The methodology is used to predict failure of a bolted joint fretting experiment [3]. Area where fretting damage is found match well with the simulation. Prediction of total failure is still difficult and needs future investigation and data of fretting induced cracks. Still the simulated critical crack size is logical with the current experimental data.

Figure 1: a) Simulated fretting damage area and critical crack size. b) Fretting scar in the experiment. c) Crack found from the fretting spot.

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Effect of Contact Rotation on Fretting Fatigue Crack Initiation in Total Sliding Conditions.

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Keywords : fretting crack, rotation, wear, modelling.

Abstract

Fretting fatigue is a complex phenomenon that occurs on surfaces in contact under tangential and fatigue loading, leading to significant damage such as microcrack formation and catastrophic failure of mechanical components. This type of fatigue can be divided into two stages: nucleation and propagation, with the former often being the longest phase. Numerical studies have been conducted to understand fretting fatigue, highlighting the importance of considering many factors such as wear, plasticity, and crystal orientation but also boundary conditions.

This study investigates the influence of the boundary condition of rotation in gross slip conditions for both cylinder/plane and plane/plane configurations limiting the study of the crack nucleation. The experimental campaign was conducted under controlled conditions, with displacement amplitudes ranging from 10 to 60 µm for the cylinder/plane configuration and from 25 to 100 µm for the plane/plane configuration, at a frequency of 5 Hz. The normal contact pressures were set at 450 MPa and 600 MPa, respectively [1]. Crack initiation was systematically observed beyond a slip amplitude of 25 µm (displacement amplitude = 45 µm) for the cylinder/plane and 30 µm (displacement amplitude = 70 µm) for the plane/plane contact. To assess the role of rotation, high-resolution digital image correlation (DIC) was used to track the evolution of contact kinematics during fretting cycles, enabling precise measurement of the rotational stiffness and angular displacements.

To analyze the effect of rotation, a finite element (FE) model incorporating a coupled wear-fatigue framework based on the Smith-Watson-Topper (SWT) criterion was used. The simulations accounted for the effect of contact rotation between bodies with same stiffness as experimentally measured. The results indicate that increasing rotation leads to an extension of the slip amplitude range where crack initiation occurs. Specifically, contact rotation induces two major effects: (i) an increase in the local strain amplitude within the SWT criterion, enhancing crack nucleation susceptibility, and (ii) a widening of the contact area, which reduces wear near the crack-prone regions, thereby increasing the domain where crack initiation is possible.

This study provides a refined understanding of the interaction between fretting fatigue and contact rotation, highlighting the necessity of considering rotational effects in predictive models. The proposed numerical framework offers a robust tool for assessing fretting-

induced damage under realistic operating conditions, with implications for the design and durability optimization of mechanical components subjected to cyclic contact loading.

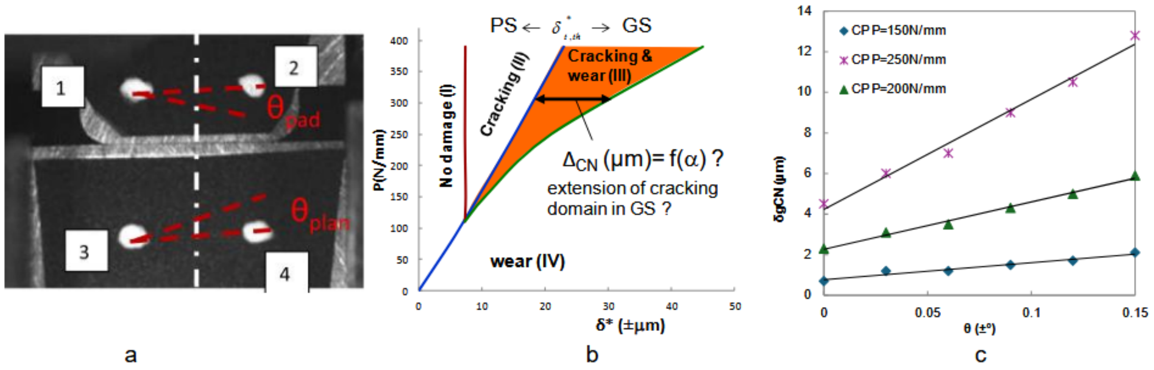

Figure 1 : (a) digital image correlation picture to follow solid rigid displacement; (b) fretting map and sliding amplitude where cracking occurs ; (c) sliding amplitude where crack nucleation occurring as a function of rotation.

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Fretting – Fatigue: State of the art in Helicopter

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Keywords : Helicopter, Test, Materials, Expertise, Stress

Abstract

Fretting is a mechanism that can affect the service life limit of helicopter parts and as a consequence should be taken into account in part substantiation. A state of the art of the way to test, characterize and consider this phenomenon on Airbus helicopters parts will be presented.

This conference will cover the following aspects:

- Overview of parts that can be affected by fretting phenomenon on helicopters

- Mechanical testing methods:

Tribological testing pyramid used will be presented. This pyramid includes:

  - Test benches to characterize fretting maps of different configurations
  - Specific test methods used in Airbus Helicopters to define fatigue limit of different materials and in fretting conditions
  - Technological benches specific for helicopter application

- Material:
  - Behaviors of different materials (steel, titanium, aluminium) in fretting – fatigue conditions used in helicopter applications will be shared
  - Anti-fretting solutions will be discussed

- Expertise:
  - Optical characterization tools to measure wear phenomenon
  - Scanning Electronic Microscopes and associated failure analysis rules

- Stress analysis:
    - Analysis of full-scale tests
    - Stress methodology to consider fretting in part substantiation

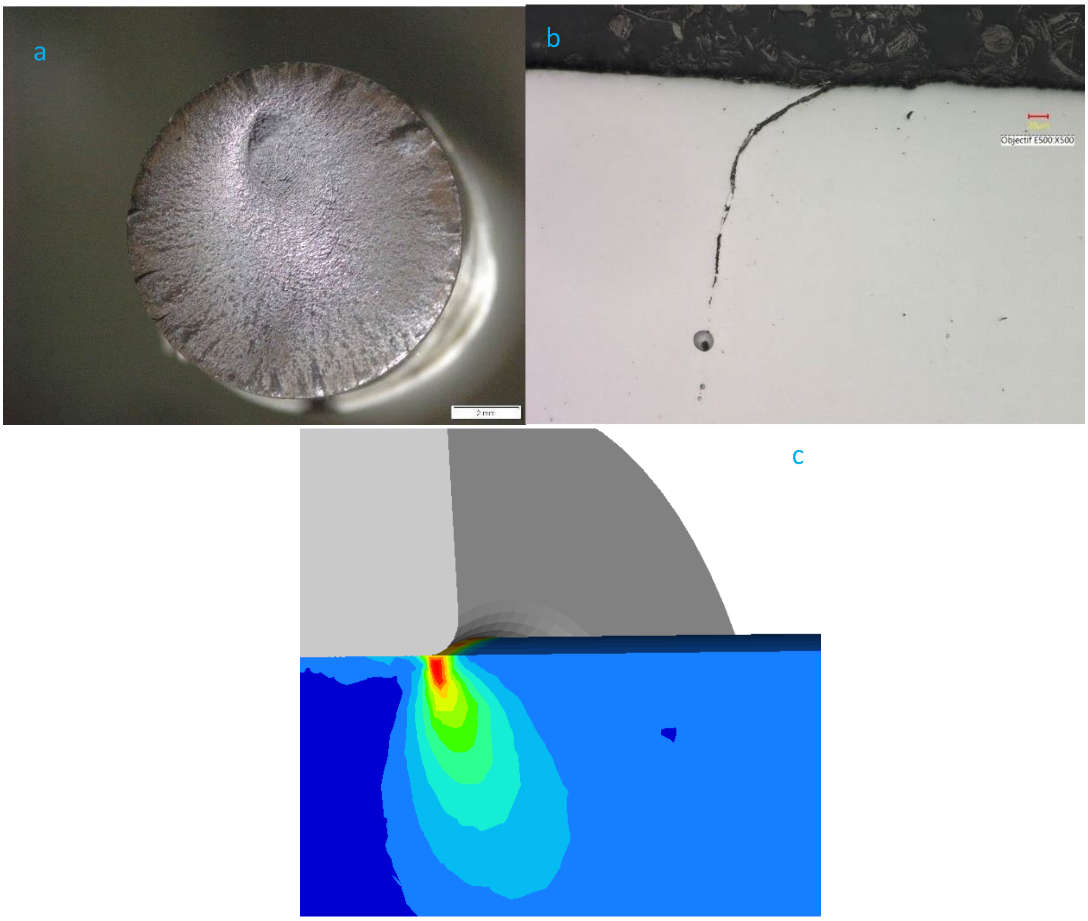

Figure 1: Fretting - Fatigue (a: Fracture surface, b: micrography, c : Finite Element Model)

Finally, this presentation will demonstrate that fretting – fatigue is a phenomenon that gathers different competences: material, testing, expertise and stress analysis.