1. **Introduction**

In engineering, the natural trend is to improve the products towards increased durability and reliability while preserving functionality and, at the same time, limiting costs. In this framework, the knowledge of the material behaviour and its response to the in-service loading is of fundamental importance. It is an everyday experience that fatigue of materials still remains a widespread source of failure in engineering applications. The fatigue damages develop in stages where defects nucleate in initially undamaged regions and then propagate in a stable manner until, if the cracks are not detected in time, catastrophic failure occurs. The understanding of the mechanisms for both defect nucleation and evolution is therefore a key issue. Moreover, from the engineering point of view, clear and straightforward fatigue design methodologies are needed.

In the damage-tolerance approach to fatigue design [1], it is assumed that engineering components contain an initial flaw. The main idea is that the components should be periodically examined for the presence of cracks. If cracks are identified, then the useful fatigue life is defined as the time, usually described in terms of in-service fatigue load cycles or blocks, required for the initial small flaw to grow to a critical size. If fatigue propagation life can be predicted with sufficient precision, then the intervals between expensive and time consuming inspections can be extended without lowering the safety demands. Fracture mechanics offers a solid base for the development of engineering tools based on the damage-tolerance approach. Through fracture mechanics models and knowledge of the in-service loadings, predictions of fatigue propagation lives are possible. The applicability of this approach to fatigue design also relies on the actual possibilities to detect small cracks by non-destructive techniques, such as dye-penetrant, X-ray, ultrasonic or magnetic methods. It is therefore important in fatigue analyses to keep in mind the limitations in crack detection ability of the available techniques. If no cracks are detected, in fact, fatigue propagation lives should be based on the largest crack size that can be missed during inspection.
2. Fretting fatigue

One group of fatigue problems, that has proven to be particularly difficult to approach, has its origin in the contact of mechanical components. The damage phenomenon is named fretting fatigue. Fretting denotes the degradation of material properties due to repeated relative displacements over small amplitude between contacting surfaces, [1]. This sliding process is named slip. Slip is usually confined to a part of the contact, the rest of which is characterized by no relative displacements, denoted as stick. The presence of a stick region implies that the contacting bodies remain fixed and no global relative motion occurs. Cyclic slip is the source for tribological surface transformations, wear and crack nucleation. Classically, three areas can be identified depending on the main global effects connected to the fretting phenomenon. The deterioration of the fretted surfaces is commonly referred to as fretting wear. A rich set of examples of fretting wear cases can be found in [2]. In combination to an aggressive environment, the degradation process is termed fretting corrosion. The detrimental effect on the material fatigue properties is usually denoted fretting fatigue. A detailed and exhaustive description of fretting fatigue, the phenomena and problematic involved, is given by [3].

At very small slip distances, typically less than 50 μm, wear is limited and early initiation of cracks is the predominant phenomenon connected to fretting, see Fig. 1, [4]. Under fretting fatigue conditions, it was observed in laboratory tests that the material fatigue limit can be reduced by as much as 50 to 90% compared to ordinary fatigue, [5]. Moreover, the fatigue growth of the new nucleated small cracks is accelerated by the presence of the high stress concentration at the contact, [6]. The slip phenomenon is also cause of surface and subsurface transformations which locally affect the material characteristics, [7], [8]. A complete fretting fatigue analysis should therefore include a multitude of different aspects, all having a central role. Consequently, the development of engineering tools for fretting fatigue life predictions requires a wide and interdisciplinary experience. It is therefore a complex task.
3. Fretting fatigue in engineering applications

Fretting may occur in structures and multi-component systems with stationary contacts that are subjected to oscillating tangential loads. These loads are typically the result of low-amplitude and high-frequency vibrations. When contacting bodies are subjected to a cyclic tangential load, slip develops at the contact edges, [9]. Slip can also arise in contacts between bodies of different thermal expansion in combination to fluctuating temperatures. Since fretting develops inside contacts, i.e. in regions not easily accessible for inspection and where crack detection is often difficult, it is a particularly dangerous phenomenon. Sometimes, in fact, the evolution of fretting damage is not detected until critical fracture or even catastrophic failure is experienced, [10].

Joints provide typical examples for fretting fatigue occurrence, [11]. In gas turbine applications, such as for instance aircraft jet engines, the dovetail contact between blade roots and discs is a potential location where fretting damages might develop, see Fig. 2. The loss of a blade during service might easily lead to catastrophic consequences. Consequently, fretting fatigue is of great concern for the aerospace industry. Other common examples for fretting fatigue are bolted flanges and riveted panels, where multiple sites prone to fretting fatigue crack initiation could be identified, see Fig. 3. Fig. 4 presents an example of failure due to fretting. Fretting has been reported in numerous
others contact features as press fittings, pin joints, orthopaedic implants, control cables, wire ropes, electrical switches, [10], [11], [12].

Fig. 2. Dovetail joint: (a) sketch of blade root and disc [13] and (b) schematic with possible fretting fatigue crack initiation site.

Fig. 3. Typical critical locations for fretting fatigue crack initiations in (a) bolted flange [11] and (b) riveted panels [12].
4. Fretting experiments

The objective of fretting fatigue experiments is to monitor, under well controlled conditions, the evolution of surface damages and the initiation and propagation of fatigue cracks. Much experimental work has been performed in the last decades, allowing for identification of the key variables and progressively improvement of the fretting fatigue experiments. However, the large number of variables involved in the process and their mutual interaction make it extremely difficult to reach a complete standardization of the experiment procedure, [14].

4.1 Experimental set-ups

The typical experimental set-up in the literature is based on the contact between an indenter and a specimen and contains three main loads: the normal contact forces, \( P \), the tangential contact force, \( Q \), and the bulk stress in the specimen, \( \sigma_{\text{bulk}} \), [3]. A robust experimental configuration, depicted in Fig. 5a, is based on a ordinary fatigue test with two fretting pads of bridge type clamped on a flat specimen, see for example [15], [16]. There are a number of difficulties related to bridge type tests. Due to machining defects or misalignments, the load may be unequally distributed on the feet, [3], and contact conditions can be difficult to characterize. Therefore, the modified half-bridge type configuration in Fig. 5b has been suggested, [3], [17]. Alignment problems are here not as critical as with bridge type indenters and the three forces in the load system can easily be measured during the tests. Both the bridge and half-bridge test type in Fig. 5 use a single actuator. Hence, only the bulk load is actively controlled during these experiments while the tangential force is directly related to the bulk load and in phase with it. In a
further improvement of the set-up in Fig. 5b, two separately controlled actuators were used: the first for $\sigma_{\text{bulk}}$ and the second for $Q$, [3], [18].

Typically, two classes of contact pad geometries are used in experiments: flat and Hertzian. The flat pads include sharp-edged pads [3], [18], characterized by complete contacts, and flat with rounded corner pads [19], characterized by an almost-complete contact. The flat with rounded corner pads are particularly interesting since they reproduce contact stresses similar to those in dovetail joints. The flat pad geometries are very sensitive to misalignment. Also, tilting in the pads may cause local detachment in complete or almost complete contacts, as identified in Paper D. The Hertzian pad typology comprises cylindrical or spherical shapes. The major advantage of these pad geometries is that a well established contact stress state is obtained according to the classic Hertzian theory, [3], [9], [20]. Also, slip can be achieved over a relatively large area, which is a benefit when underlying damage mechanism is studied.

The fretting experiment in Paper A and B is shown in Fig. 6a and contained three separate actuators. The advantage with this set-up is that the three main loads can be independently controlled in time. This allows for a larger variety of different load histories. A single spherical indenter was used in the set-up, see Fig. 6b. The contact geometry was chosen in order to avoid, as much as possible, practical alignment difficulties. It was also convenient because it produced well controlled contact regions and stick-slip boundaries. By choosing a large sphere radius, large contact marks were obtained. Also, as mentioned above, this contact geometry enabled well defined numerical analyses since analytical solution are available in the literature, [21], [22].

Two $\alpha + \beta$ titanium alloys were used in the fretting experiments in Paper A and B: Ti-17 for the specimens and Ti-6-4 for the indenters. The same materials were also employed in the experiments used for the numerical analyses in Paper D. This particular material combination follows that of a compressor stage in a gas turbine. The mechanical properties of the specimen material, Ti-17, are described in the papers.
4.2 Crack detection in fretting experiments

Attia [23] lists various physical quantities that are usually controlled or monitored during fretting experiments. These include bulk load, contact pressure, tangential load, slip, environmental conditions, number of load cycles. From these physical quantities, it is usually not straightforward to detect cracks during fretting experiments. Also, fretting
cracks develop inside the contact and are not directly visible. Periodical removal of the contact to analyse the fretted surface is usually not a good alternative. In fact, there are technical difficulties in positioning the indenter in the same location on the specimen after examination. Also, the surface damage would prevent easy crack detection.

Two non-destructive methods for crack detection are presented in Paper B. The strains in the vicinity of the contact regions are influenced by the presence of fretting cracks. In particular, it was shown that strains at the specimen surface were more and more relieved as the close-by crack became larger, see Fig. 7a. Thus, by monitoring the surface strains with the aid of strain gauges, see Fig. 6b, it was possible to detect a growing fretting crack. Consequently, the time to crack initiation and for crack propagation were experimentally estimated.

As the crack advances through the material, it releases potential energy stored in the material at the crack tip. The energy release produces mechanical waves that travel through the specimen. In the acoustic emission method, [24], these waves are detected by a transducer placed on the specimen, as shown in Fig. 6b. At the experiment start, before crack initiations, only background noise could be detected in the fretting experiments. However, the number of detected mechanical waves increased significantly during crack growth, see Fig. 7b. By acoustic emission measurements, it was therefore possible to identify the initiation and propagation lives in Paper B.
5. Tribological modifications in fretting

In the fretted region, the slip phenomenon leads to inevitable modification of the surface topography, light abrasion and also some plastic flow in a very thin surface layer, [7]. It is observed that these modifications normally cause a significant increase of the coefficient of friction inside the slip region, $\mu_n$, [3]. Experimentally, only the mean value of the coefficient of friction over the whole contact area can be measured, $\mu^\ast$. However, in special cases, it is possible to derive analytical solutions for $\mu_n$ as a function of $\mu^\ast$ if the load history is known, [25], [26]. Through a numerical approach, more complex geometries can also be treated, [27]. In the models, it is assumed that the friction coefficient increases during the first fretting cycles and reaches after a while a steady state value, independent of the normal pressure or slip amplitude.

In Paper A, $\mu_n$ was evaluated in four different ways. For two of these methods, new equations for spherical contacts were derived. The seemingly easy task to determine $\mu_n$ was, in reality, rather complicated. In fact, contact conditions are history dependent and accurate control of the whole test procedure was therefore required. Also, the relations between $\mu_n$ and $\mu^\ast$ for the different methods rely upon very precise experimental estimates of $\mu^\ast$. The friction experiments showed that the increase in the coefficient of
friction was considerable for the material combination Ti-17 against Ti-6-4. It increased in fact from 0.45 in unfretted conditions to 0.83 in the fretting slip zone.

6. Fretting fatigue crack initiation

Several studies have demonstrated that cracks can initiate already at 5–10% of the fretting fatigue life, [5]. This is in opposition to high cycle ordinary fatigue, where crack nucleation covers most of the total life, [1]. Thus, from the engineering point of view, it is essential to identify the key features that influence fretting fatigue crack initiation.

Some empirical macroscopic parameters for fretting fatigue crack initiation are suggested in [28]. The initiation parameter $\sigma \tau \delta$, for example, could be used to explain the location of fretting fatigue crack initiation although its physical interpretation is not clear.

Many attempts have been made to reduce the fretting problem to ordinary fatigue by taking into consideration the non-proportional and multiaxial stress state arising from the complex contact traction distributions. Different multiaxial fatigue criteria have been used, most commonly the Smith-Watson-Topper [29], the Fatemi-Socie [30] and the Dang Van [31]. The criteria were usually evaluated and correlated to experimental findings for nucleation location or total fatigue life. In some works good agreement was found [32], [33], [34]. However, it was realized that the criteria were overly conservative due to the high stress gradients present in fretting contacts, [25]. When the criteria were averaged over a critical volume, better agreement with the experimental results could be found, [25], [35]. The critical volume appeared to well correlate with the grain size of the tested material.

In Paper A, five multiaxial fatigue criteria were applied to the fretting experiments performed in the set-up in Fig. 6. The criteria were McDiarmid [36], Findley [37], Dang Van, Fatemi-Socie and Smith-Watson-Topper. Experimentally, it was found that initiation sites for the main fretting cracks were located inside the slip region and were spread along the hoop direction, see Fig. 8a. The average radial position was at 90% of the contact radius. Conversely, as shown in Fig. 8b, the criteria always identified as most critical some point along the symmetry plane, $\theta = 0$ in Fig. 8b and $x$-axis in Fig. 8a. Also, most important, all of the examined criteria predicted non-conservative estimates of
the fretting fatigue limit. The Findley criterion predicted the lowest value for the fretting fatigue limit expressed in terms of the tangential load amplitude, $Q_{\text{lim}} = 2.07$ kN. However, large cracks were observed at values for $Q$ as low as 1.415 kN. Thus, fretting fatigue crack initiation could not completely be described by general multiaxial fatigue criteria evaluated with nominal macroscopic stresses and strains. Analysis of the fretted areas showed a much rougher surface in the slip zone, see Fig. 9. A rough surface is usually more subjected to fatigue since the pits act as stress raisers, [38]. It can be noted in Fig. 9 that when the indenter and specimen were in contact, pits and asperities fitted into the mating surface. Thus pit-asperity interactions in the fretting induced surface roughness were indicated in Paper A as important for the crack nucleation.

![Fig. 8.](image)

Fig. 8. (a) Experimental initiation sites of main fretting cracks at the spherical contact surface for different load levels, Paper A. (b) Multiaxial criteria values for fretting test with $Q = 2.5$ kN normalized with fatigue limit. The criteria were computed at 90% of the contact radius for various hoop angles, from $\vartheta = 0^\circ$ to $\vartheta = 90^\circ$, x- and y-axis in (a), respectively.
Fatigue crack growth

While fretting drastically reduces the time to crack initiation, the largest part of the fretting fatigue life consists of fatigue crack propagation. Fracture mechanics offers a solid foundation for the study of fatigue crack propagation and, consequently, gives a natural starting point for the development of engineering tools for fretting fatigue crack propagation predictions.

In fatigue, it is common to make a distinction between small and long cracks, [1], even though a well defined separation can not be found. It is usually stated that a crack is long if linear elastic fracture mechanics (LEFM) is able to describe its growth, [39]. The inadequacy of LEFM for the description of the fatigue growth of small cracks is most of all related to the larger influence of microstructurally preferred directions (microstructurally small cracks), the breakdown of the small scale yielding condition (mechanically small cracks) or simply the small crack size (physically small cracks), [1].

In many engineering components, the fatigue crack spends most of its life as a small crack. Also, in some applications, as for example blade roots in dovetail contacts, cracks might already be considered critical before they enter the long crack regime. Thus, it is important to be able to estimate the growth of both long and small cracks. In order to
achieve accurate predictions of fretting fatigue lives, a fatigue growth model was required for the short cracks. Therefore, the investigation in Paper C was performed. The results were thereafter used in Paper D where it was noted that, in shot peened specimens, about 80% of the fretting fatigue crack propagation life was spent growing from an initial 50 μm deep flaw to a 200 μm long crack.

Fig. 10. Schematic illustration of the anomalous small crack fatigue growth behaviour compared to long cracks at the same ΔKI, after [1].

7.1 Short cracks

There is experimental evidence that the fatigue growth of small cracks differs from that of long cracks and that LEFM driving parameters, such as the stress intensity factor range, ΔKI, can not be used to characterize the small crack growth, as depicted in Fig. 10. Most important, Fig. 10 shows that small cracks grow faster than long cracks at the same ΔKI, implying that predictions by LEFM are non-conservative, which is of great concern for the fatigue design methodologies. The direct application of growth data obtained for long cracks to the small cracks can therefore lead to dangerous overestimations of the fatigue growth life in engineering components.

In Paper C, the ordinary fatigue growth of through thickness cracks of approximately 50 μm in length was studied in Ti-17, see Fig. 11a. The cracks were small in just one direction and were therefore defined as short, [40]. The experiments were
conducted in a symmetric four-point bend configuration. Precracking was carried out by loading a sharp through thickness notch in cyclic compression. The notch was thereafter removed to leave the approximately 50 μm long crack. The short crack was then subjected to fatigue loading in tension. The experiments were performed in load control with constant force amplitude and mean value. Thus, the crack tip load increased during crack growth. Fatigue growth continued at a constant $R$ ratio into the long crack regime. The propagation of the short and long cracks was monitored by direct current potential drop measurements. The potential drop method was robust, precise and accurate, even in the short crack regime, see for example Fig. 11b. The measured fatigue crack growth from all the short crack experiments are correlated to the analytical $\Delta K_I = K_{I\text{max}} - K_{I\text{min}}$ in Fig. 12. The figure also includes the linear regression curve for closure free long crack growth data. It was concluded that no anomalous short crack behaviour was observed in the considered material, test procedure and load levels. This conclusion finds support in the literature, where the apparent difference between short and long cracks at low $R$ ratio disappears if crack closure is taken into consideration in the long crack data, [41]. Moreover, LEFM together with closure-free long crack fatigue growth data provided conservative crack growth rates even for the short cracks. Finite element simulations in which non-linear fracture mechanics parameters such as the crack tip opening displacement range, the cyclic $J$-integral and a measure for the cyclic crack tip plastic zone size were computed, confirmed that $\Delta K_I$ was a representative parameter for the short crack growth.
Fig. 11. (a) Short initial through thickness crack in Paper C. (b) Crack length estimates by potential drop for a statically loaded and non-propagating short crack showing the method precision in Paper C.

Fig. 12. Experimental fatigue crack growth rates versus $\Delta K_1$ for the short crack experiments, Paper C. The figure includes the linear regression of the fatigue growth data for closure-free long cracks.
7.2 Long cracks

When the length of the crack is larger than the microstructurally size and the load level is sufficiently low for small scale yielding to be fulfilled, then it is generally agreed that LEFM is applicable. Also, there is no fundamental difference between fretting fatigue and ordinary fatigue, [42], [43]. In reality, modelling the fretting fatigue growth is only an apparently easy task, as the complex fretting loading must be accounted for. Also, most of the models presented in the literature approximate the cracks as two-dimensional edge cracks, [6], [44]. However, real cracks are three-dimensional in nature even when the experimental and contact geometries could be well described by a two-dimensional representation, see Paper D. This complicates the growth analyses considerably.

In Paper B, the fatigue growth of three-dimensional long fretting cracks obtained with the experimental set-up in Fig. 6 was studied. The fretting cracks initiated inside the slip region, as depicted in Fig. 8a, and grew below the contact region and towards the specimen edges, see Fig. 13a. The overall crack shape could be described as a part of ellipsoid, see Fig. 13b.

By assuming that the fretting crack propagated in mode I, it was possible to correlate the growth of the ellipsoidal crack to the growth of an equivalent plane semi-elliptic crack loaded with the same mode I loading. The stress intensity factor $K_1$ along the elliptic crack was computed by the aid of a $K_1$-database. The growth rates on the equivalent crack were determined through a parametrical crack growth description, [45], in terms only of the ellipse semi-axes, $s_1$ and $s_2$, see Fig. 14a. The growth rates were then transferred back to the ellipsoidal configuration that was updated. Fig. 14b compares the measured and numerically computed crack shapes and shows that the numerical procedure well captures the growth of the fretting cracks. The predicted fretting fatigue propagation lives were in good agreement with the experimental estimates obtained from the non-destructive methods in Fig. 7. Thus, LEFM was appropriate for the analysis of long fretting cracks.
Fig. 13. Fretting fatigue cracks obtained with the experiment presented in Fig. 6, Paper B. (a) Top view showing the contact mark on the specimen, fretting scars and the main fretting cracks. (b) Three-dimensional view of a main fretting crack.

Fig. 14. (a) Fretting fatigue growth rates expressed in terms of the problem parameters (crack semi-axes). (b) Comparison between measured and simulated fretting crack shape in Paper B.
8. Palliatives in fretting fatigue: shot peening

During the last decades, increased knowledge on fretting phenomenon has resulted in a number of solutions and palliatives against fretting, [11], [46], [47]. Shot peening is one of the most common techniques for improving fretting life, [10]. In shot peening the contact surfaces are repeatedly exposed to shots of small and hard particles. At each impact the material deforms plastically giving rise to compressive residual stresses in a thin surface layer, [48]. The compressive stresses primarily reduce the fatigue growth rate of small cracks. The crack initiation phase may, in fact, decrease or even disappear due to the increased surface roughness and the introduction of small surface cracks, as reported by [49] and [50]. However, the residual stress state is not always stable and may relax during component operation mainly due to plastic deformations or creep effects, [51]. Relaxation is even possible during cyclic loading at low stress levels, [52]. Relaxation of residual stresses from shot peening was also observed in combination to fretting loading, [8].

From the engineering viewpoint, there is the need to predict reliable and accurate estimates of the fretting fatigue lives. In this framework, since the positive effects of shot peening in terms of increased fretting fatigue life are clear, [5], [11], [16], it is desirable to include residual stresses into the fatigue life models. However, a consequence of the difficulties in quantifying the relaxation of residual stresses, as noted by [53], is that they are usually neglected in life calculations and are solely considered as an additional safety factor.

In Paper D, a fretting fatigue life assessment procedure based on fracture mechanics and incorporating the residual stress state from shot peening was developed. The procedure was used to predict the fretting fatigue experimental lives in [16]. The experimental set-up followed Fig. 5a. The relaxation of residual stresses in shot peened specimens due to fretting was experimentally estimated from X-ray diffraction measurements and numerically simulated by finite element analyses. The computations showed that stress relaxation was locally more significant than the one captured in the measurements. The measurements, in fact, only provided average values of stresses and information on sharp gradients was lost.
The finite element stresses during fretting loading were subsequently used to compute fatigue growth life by the aid of LEFM. Since the residual stresses affected material in a very shallow surface layer, it was important that, in order to include their effects in the life assessment procedure, the initial crack was as small as possible. In the calculations, an initial crack 50 μm deep was used. Results from Paper C were therefore recalled to justify the use of LEFM for this crack size.

Three different fatigue growth numerical models were compared. The first one described the crack as a through thickness edge crack. The second model was based on a parametric fatigue growth procedure that took into consideration the growth behaviour along the whole crack front of a semi-elliptic surface crack. The parametric procedure was the same as in Paper B. The third model was the one implemented in the NASGRO software where crack growth was computed in only two points, in depth and at surface, on a semi-elliptic surface crack. Best agreement between experimental and numerical fatigue lives for both peened and unpeened specimens was achieved with the second model, see Fig. 15. The great advantage of the second model was the ability to include the local behaviour along the crack front.

![Fig. 15. Experimentally found and numerically computed fretting fatigue lives from Paper D. Results for shot peened and unpeened specimens are compared.](image-url)
9. Discussion and conclusions

A new fretting experiment was developed. The experimental set-up proved to be reliable and highly versatile. Various indenter geometries can be used in combination to general load histories. Fretting damages could be reproduced in controlled conditions allowing for direct study of the phenomenon. The non-destructive crack detection procedures furnished promising results. It was possible to detect a growing crack and therefore an approximate estimate for the time to crack initiation. However, no quantitative information of crack size or crack growth rates could be derived.

It was realized that fretting fatigue is more complex than ordinary fatigue. In Paper A, the multiaxial fatigue criteria furnished non-conservative fatigue life estimates when evaluated from stresses and strains based on nominal contact conditions. This conclusion is in conflict with some observations in the literature. A possible reason is that contact regions were here rather large and had therefore not so significant gradient effects. Also, it was realized during the short crack experiments in Paper C that the fatigue properties of the material studied, Ti-17, were much influenced by the surface finish. In fact, during the precracking in compression from the notch, it was indispensable to fine grind the specimen side opposite to the notch to avoid crack initiation in tension on that side. This procedure was for example not needed for reference tests performed in steel specimens. Similarly, the fretting induced roughness in the slip region could be expected to negatively affect the fatigue strength of Ti-17. It is also believed that the fretting induced roughness has in general considerable importance for crack initiation. In fact, it is created by mechanically induced surface transformations in which asperities on one surface fit pits on the mating surface and vice versa. It was therefore suggested that asperity-pit interaction in combination to local slip could be one accelerating factor for crack nucleation in fretting.

Paper B and D showed that life prediction methods based on fracture mechanics furnished very promising results. LEFM, in particular, proved to be reliable even for the fretting case. It could be applied to the three-dimensional cracks and it permitted to incorporate residual stresses from shot-peening in a rather straightforward manner. Clearly, the fracture mechanics based life assessment procedures rely on accurate knowledge of stress state. Thus, a complication in their use is that the complex contact
stick-slip phenomenon should be modelled. In fact, even though the correct estimation of the contact stresses might not be of primary importance for the analysis of long fretting cracks, it is fundamental for the short cracks. Also, elastic-plastic finite elements analyses are necessary in cases where plastic deformations cause considerable redistribution of stresses.

Most of the fretting fatigue life was spent when the crack is small in size. Thus, accurate fatigue life predictions rely on the possibility of modelling the growth of small cracks. It was shown in Paper C that, for the material and load levels investigated, LEFM together with closure-free fatigue growth data provided conservative results for cracks larger than 50 μm. This initial size appeared to be sufficiently small to predict the complete fretting life in Paper D. Hence, in the fretting experiments in [16], the fretting fatigue initiation life was very short, probably due to high contact stress concentrations and to possible presence of defects initiated by shot peening.

The advantage of the fracture mechanics parametric approach in Paper B and D resides in its ability to consider the crack behaviour along the crack front and to describe it through only a few parameters. In Paper D, this approach was proven to be better than methods considering only two points along the crack front which are then treated separately. Clearly, the $K_I$-database was the key that enabled the use of the parametric approach. The database allowed for easy and fast $K_I$ estimates. The available $K_I$-database was however too limited for the load cases used here and a more versatile database was desirable.

Crack closure was a critical point in the fracture mechanics based life prediction methods. The common choice to set $K_{cl} = 0$ furnished non-conservative results in Paper D. Here, due to the residual stresses from shot peen, crack growth was characterized by large negative load ratios, $R$, giving rise to negative closure levels. Conversely, in Paper B, $K_{cl} = 0$ provided conservative or overly conservative results. Thus, since it is desirable to obtain accurate life predictions, it is important to be able to make reliable estimates of closure levels. Unfortunately, this is not easy because crack closure is much dependent on the load history and, in principle, every single load history should be analysed. Moreover, modelling of crack closure is not trivial even with advanced finite element simulation, as shown in Paper C.
10. Suggestions for future work

The mechanisms involved in fretting fatigue crack initiation are still not known in detail. A lot of work has been performed during the last decades and some of the main features have been identified. Nonetheless, additional investigations on the initiation mechanisms are needed. It is now accepted that fretting involves more mechanisms than ordinary fatigue. Knowledge on the evolution of the fretting induced roughness, its dependence on slip and its link to crack nucleation should be developed further. Also, changes in the shallow surface layer, the so called tribologically transformed structure, should be investigated more. A better understanding of these mechanisms would also in turn result in improvements of palliatives for fretting.

Fretting cracks initiate inside the slip region and are subjected to multiaxial loading. The local material microstructure might play a large role in the very first part of fatigue growth. The high contact tractions introduce cyclic plastic deformations in the surface layers. Further investigations on the influence of these factors on the mechanical behaviour of short cracks would represent a crucial step towards improved fretting fatigue lifing procedures. The more insight in the fatigue crack propagation of smaller and smaller cracks is gained, the less the uncertain predictions of crack initiation lives will be needed.

LEFM has proved to be a solid foundation for fatigue growth description in fretting fatigue conditions. An interesting field of investigation would be to check the real boundaries for LEFM validity, for example in the small crack regime. In fact, it is believed that part of the observed short crack behaviour anomalies in the literature actually resided in an incomplete interpretation of the long crack data.

In order to be able to quantify the enhancements in fretting fatigue lives obtained by shot peening, a reliable estimation of the actual residual stress profile in the material is essential. Detailed studies on the mechanisms leading to changes and relaxation of the residual stress state are therefore needed. The attention should be directed towards stress redistribution due to plastic deformations but also stress relaxation due to the creep.
11. Summary of appended papers

**Paper A: A study on fretting friction evolution and fretting fatigue crack initiation for a spherical contact.**

A new design for fretting experiments is presented. The normal and tangential contact loads as well as the specimen bulk stress are separately controlled. The separate control of load systems enables more accurate simulations of the fretting situations in component interfaces. Also, the influence of the salient parameters can be investigated individually. The initial test series comprised a spherical indenter and constant normal load and bulk stress. The evolution of the slip zone coefficient of friction at a spherical fretting contact was evaluated in four different ways. For two of these methods new equations were derived. The importance of a correct coefficient of friction and the advantages of each evaluation method are discussed. The experimental results were evaluated with respect to fretting fatigue crack initiation. Five multi-axial fatigue criteria were evaluated and ranked with respect to their ability to predict fretting fatigue initiation properties. The endurance limits of all criteria were too high as compared to the experimental fretting fatigue endurance level. A qualitative explanation for the discrepancy was found in the surface profile of the slip zone.

**Paper B: Fretting fatigue crack growth for a spherical indenter with constant and cyclic bulk load.**

Fatigue growth of edge cracks subjected to non-proportional fretting loads was investigated experimentally and numerically. The cracks were produced during fretting experiments with a spherical contact between two α+β titanium alloys. Constant normal load was combined with cyclic tangential load and constant or cyclic bulk load. Crack propagation was detected during the experiments by strain gauges on the specimen surface and acoustic emission measurements. A parametric crack growth description procedure was used to model fatigue growth of the three-dimensional fretting cracks that were loaded with multiaxial and non-proportional stresses from the fretting contact. The predicted crack growth lives and crack shapes agreed with the experimental results. A crack path prediction based on the maximum principal value of the stress range tensor $\Delta\sigma_{ij}$ was evaluated.
**Paper C: Fatigue growth of short cracks in Ti-17: experiments and simulations.**

The fatigue behaviour of through thickness short cracks was investigated in Ti-17. Experiments were performed on a symmetric four-point bend set-up. An initial through thickness crack was produced by cyclic compressive load on a sharp notch. The notch and part of the crack were removed leaving an approximately 50 μm short crack. The short crack was subjected to fatigue loading in tension. The experiments were conducted in load control with constant force amplitude and mean values. Fatigue growth of the short cracks was monitored with direct current potential drop measurements. Fatigue growth continued at constant $R$-ratio into the long crack regime. It was found that linear elastic fracture mechanics (LEFM) was applicable if closure-free long crack growth data from constant $K_{\text{Imax}}$ test were used. Then, the standard Paris' relation provided an upper bound for the growth rates of both short and long crack.

The short crack experiments were numerically reproduced in two ways by finite element computations. The first analysis type comprised all three phases of the experimental procedure: precracking, notch removal and fatigue growth. The second analysis type only reproduced the growth of short cracks during fatigue loading in tension. In both cases the material model was elastic-plastic with combined isotropic and kinematic hardening. The agreement between crack tip opening displacement range, cyclic $J$-integral and cyclic plastic zone at the crack tip with $\Delta K$ verified that LEFM could be extended to the present short cracks in Ti-17. Also, the crack size limits described in the literature for LEFM with regards to plastic zone size hold for the present short cracks and cyclic softening material.

**Paper D: Influence of residual stresses from shot peening on fretting fatigue crack growth.**

One method to improve fretting fatigue life is to shot peen the contact surfaces. Experimental results with and without shot peening were evaluated numerically. The residual stresses were measured at different depths below the fretting scar to estimate the amount of stress relaxation after the fretting tests. The measurements were performed on
two peened specimens by X-ray diffraction. An elastic-plastic finite element model was built to simulate the fretting experiments. The computations showed that stress relaxation was locally more significant than the one captured in the measurements. The finite element stresses during fretting load were used with linear elastic fracture mechanics to compute fatigue growth life. Three different fatigue growth numerical models were compared. The first one described the crack as a through thickness edge crack. The second model was based on a parametric fatigue growth procedure that took into consideration the growth behaviour along the whole front of a semi-elliptical surface crack. The third model was the one implemented in the NASGRO software where crack growth was computed in only two points, in depth and at surface, on a semi-elliptical surface crack. The best agreement between experimental and numerical fatigue lives for both peened and unpeened specimens was achieved with the second model.

References


