

FATIGUE DEGRADATION OF MATERIALS AS A TOOL FOR DAMAGE ASSESSMENT

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ABSTRACT

Damage assessment of components or systems is strongly related to the way components fail. Thus, an appropriate understanding of failure degradation of components is necessary. Furthermore, most of the failures are related to fatigue cracks that develop on components under service. This paper is concerned with the fatigue degradation of metallic components. Its emphasis is on the different ways in which the fatigue damaging mechanisms occur, being the main responsible for the failure of components.

This paper has two main sections: one section deals with the fatigue mechanisms and their definition; the second section focuses on the failure analysis of components affected by those mechanisms.

KEYWORDS: damage assessment; failure mechanisms; fatigue; case studies

1. Introduction

Damage prognosis is the prediction in near-real-time of the remaining life of a system given the measurement and assessment of its current damage. A key element in damage prognosis is obviously that of determining the existence and location of damage. The understanding of the basic damaging mechanisms is important in order to determine the possible existence and location of damage, to prevent future occurrence, and/or to improve the performance of the device, component or structure. There are several different categories of physical failures, depending on the classification system. The Failure Analysis and Prevention ASM handbook [1] suggests a convenient way to descriptively categorize and discuss failures. They suggest four categories of failures: distortion and undesired deformation; corrosion; wear; fracture. The first failure category is related to geometry changes (bending, buckling,

swelling or shrinkage). The common causes to distortion failures include temperature-induced phase changes or thermal expansion in metals, fluid absorption of non-metallic, and curing shrinkage such as it may occur in grouts and adhesives. The other three categories of failure, associated with degradation of materials are: corrosion; wear; fracture. Corrosion can be essentially considered as the loss of material due to chemical or electrochemical action [1]. Wear is removal or displacement of surface material due to a relative motion between solid, liquid, or gas [1]. Fracture is generally defined when there is separation of material. There are many causes of fracture. These include brittle fracture, ductile fracture, and fatigue. Though distortion, wear, corrosion, and some kinds of fracture are also of great importance, this paper will consider only part of the fracture failures, namely the fatigue failures.

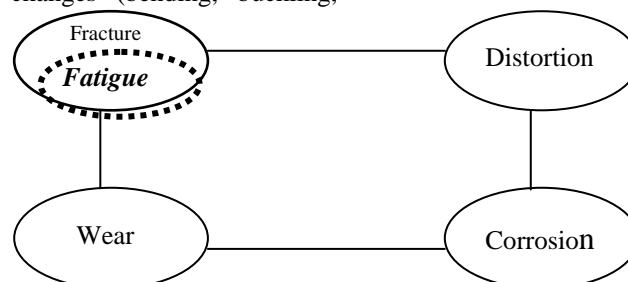


Fig. 1. Basic failure types related to degradation mechanisms [1]



Although fatigue is only a sub-group of the fracture failures, there are several different fatigue failure modes. Some fatigue mechanisms, such as mechanical fatigue or thermal fatigue, are well known. However there are also some failure mechanisms that are traditionally attributed to corrosion or wear but that are mainly related to fatigue mechanisms. In this group is for example cavitation fatigue. It is frequently confused with corrosion fatigue because it happens when a component or at least part of the component is in contact with a liquid. It is assumed that pitting observed in the component is always related to corrosion mechanism. Sometimes cavitation is also confused with wear or abrasion.

Another important aspect to highlight is that it is very frequent that different failure mechanisms act together. Sometimes corrosion precedes fatigue or corrosion acts together with fatigue increasing crack propagation rates. In other cases, such as fretting fatigue, both wear and fatigue act together to nucleate fatigue cracks. Therefore, although in their nature they are different in most fatigue failures it is not possible to isolate one failure type.

The emphasis of this paper is to do a survey of some different fatigue degradation mechanisms and its occurrence on damaged components. Although not all of the mechanisms may be addressed on this paper it is also a purpose to do a classification and categorization of the fatigue failure mechanisms assessed.

The paper is divided in two main sections: the first section intends to give a short definition of each fatigue mechanism. The second section is a description of examples of damaged components with the presented fatigue mechanisms.

2. Fatigue Mechanisms

Basic definitions

The basic feature that underlies all the specific fatigue failure mechanisms is the *existence of repeated or cyclic stresses* at some point of the component [2]. This could be considered the basic definition of fatigue. The cyclic stresses or strains give origin to damage accumulation until it develops into a crack that finally leads to failure of the component.

Keeping in mind the basic assumption for a fatigue failure, different definitions will be provided for the specific fatigue failure mechanisms. The different fatigue failure mechanisms are essentially related to the way those cyclic stresses arise in a specific point of the component, or to the cause of the stresses. Sometimes they are also related to the existence of other concurrent or synergistic damaging mechanisms such as wear or corrosion.

The fatigue failure mechanisms, in this paper, are divided into two classes: the primary mechanisms and the secondary mechanisms, according to the following definition:

Primary mechanisms: mechanisms that are able by themselves to initiate and propagate fatigue cracks;

Secondary mechanisms: mechanisms that are not able by themselves to promote fatigue fracture but may either initiate cracks or help on crack propagation of pre-existing cracks.

A definition for the different fatigue mechanisms, either primary or secondary mechanisms, will be subsequently given. Some schemes of the mechanisms are shown on the damaged components section.

Primary mechanisms

Mechanical fatigue - Mechanical fatigue is the widest definition and is traditionally related to components where external loads are applied for example on the connections/supports. In this definition cyclic stresses flow through the component and concentrate in critical points of the component due to loads/restraints that are applied in other points. If mechanical fatigue occurs at high temperature, another mechanism, of creep, is often active.

Thermal fatigue - Thermal fatigue exists under two different situations: the first is in a singular component due to different temperatures (cyclic) in different areas of the same component; the second situation is, for a component with two dissimilar materials, for a certain temperature (cyclic) in both materials at the same time. In the first situation stresses arise due to the difference in temperature; in the second situation stresses arise through different dilatation coefficients of the same component (with at least two different materials). Due to high temperatures involved in the process and depending on the thermal cycle, shape creep may also be active.

Thermal/mechanical fatigue - Thermal/mechanical fatigue exists when both mechanical and thermal fatigue act at the same time. It is common to have superposed thermal and fatigue cycles. Due to high temperature involved creep is sometimes active in thermal/fatigue situations.

Contact fatigue - Contact fatigue exists when two free bodies are in contact but they are not attached one to another. It occurs mainly when there is a rolling contact. The contact forces are the responsible for the Hertzian stresses and strains in the components. On the contact surface between the free bodies and due to the contact deformation there may exist a very small relative displacement between the bodies. Thus sometimes, another mechanism, the fretting one, may be considered as associated with rolling contact fatigue.

Impact fatigue - Impact fatigue is characterized by the existence of an impact contact. Thus there is a load between the two bodies plus the impact energy due to the prior movement of at least one of the bodies.

Cavitation fatigue - Cavitation fatigue exists when bubbles are created inside a liquid in an under-pressure region and, when those bubbles reach higher pressure zones they implode and the wave pressure that is born from the implosion impacts a solid surface. These waves are responsible for the stresses and strains at the solid bodies.

Creep fatigue - Creep fatigue is a superposition of mechanical fatigue and creep (deformation at high temperature at a constant load). According to the high temperature level and load fatigue cycle, waveform creep may be more or less active but it is almost always present.

Secondary mechanisms

Wear-fatigue - Wear fatigue exists when two bodies are not attached one to another but there is contact and a relative displacement between both components. There are the normal contact forces plus the tangential forces due to the sliding movement between both bodies.

Fretting fatigue - Fretting fatigue is similar to wear fatigue because there is wear between the two bodies due to a relative displacement. The main difference is that the two bodies are commonly connected or attached one to the other for example with screws, and the relative displacement between both components is very small (traditionally between 1 to 100 μm)

Abrasion fatigue - Abrasion fatigue exists when two solid bodies are not in direct contact one to the other but a third body (for example dust) promotes the contact and load transmission between the initial two bodies. The third body (for example dust) may be involved in oil or water. Initially they cause pitting or spalling like on contact fatigue but in cases where a pre-existing crack exists, they may promote crack propagation.

Corrosion fatigue - corrosion fatigue exists when structural metals operate in deleterious environments. This detrimental environment accelerates fatigue crack growth. Even materials immune to SCC - Stress Corrosion Cracking are susceptible to CC – Corrosion Cracking (or corrosion fatigue cracking).

Hydrodynamic fatigue – (trapped water/oil fatigue) - There are at least two different ways in which hydrodynamic fatigue is present. One is when there is load transmission between two rigid bodies by means of a liquid (for example oil) and there is a pre-existing crack. The liquid enters the crack and promotes crack propagation by exerting opening loads on the crack surfaces. The other

situation is when two solid bodies are in direct contact, for example under rolling contact, and there is a pre-existing crack with liquid inside. When one body contacts the other body on the crack position, the crack closes and the liquid is trapped inside the crack. The pressure on the trapped liquid promotes crack propagation.

3. Damaged Components

In this section, examples of most of the fatigue failure mechanisms presented above are shown. Most of them are from failure analysis carried out at Minho University and the components can be seen in the mechanical engineering department. Some schematic representations of the mechanisms are also shown, for their better understanding.

Primary mechanisms

Mechanical fatigue

This is probably the most common fatigue failure and many damaged components can be found, such as the following crankshaft (fig.2). The fatigue failure occurred in a stress concentration on the radius of curvature. This stress concentration is located between where the loads are applied (journals) and the restraints. The stress concentration occurred along the crankshaft due to geometrical constraints. This type of fatigue is what can be defined as mechanical fatigue failures. Different mechanical fatigue failures can be found in literature such as a crankshaft [3] or tooth gears broken by bending [4].



Fig. 2. Crankshaft and engine piston broken by mechanical fatigue [Minho Univ.].

Thermal fatigue

The first situation of thermal fatigue is when, in the same component of the same material, there are different temperatures (cyclic) in different areas of the same component [5]. The brake disk in fig. 3 is an example of thermal fatigue due to different temperatures in a same component. Thermal fatigue cracks develop along the heating front, e.g., parallel to the thermal gradient.

The second situation of thermal fatigue is when a component consists of two dissimilar materials and a certain temperature (cyclic) acting on both materials at the same time. The whole component can be under the same temperature. In this second situation stresses arise through different dilatation coefficients of the same component (with different materials). The material with higher dilatation coefficient tends to be under compression while the material with lower dilatation coefficient will be under tensile stresses. Examples of this second thermal fatigue situation are found, for example, in solder joints [6].

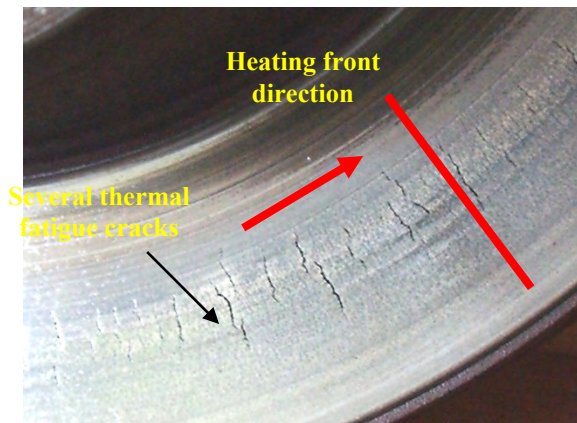


Fig. 3. Brake disk damaged by thermal fatigue [Minho Univ.].

If operating temperatures are high, there may exist creep along with thermal fatigue. Fig. 4 shows a train engine piston with several radial cracks along the piston head. In this case thermal fatigue is related to the stresses in the material induced by thermal gradients in the component. The thermal stresses are due to the 'vertical' distribution of the temperature

along the piston – high temperatures at the top and lower temperatures at the bottom.

There is a homogeneous and regular gradient of temperature on the radial direction along the head of the component. The bowl rim area is the area where temperatures are higher [7]. Thermal deformations under the operating bowl rim temperature are constrained by the surrounding material. This causes large compressive stresses on the total bowl rim circumference that often exceed the yield strength of the material. These compressive stresses at high temperature cause creep at the bowl rim area. After creep relaxation of the high compressive stresses and when the piston gets cold, creep effect gives rise to tensile residual stresses on the bowl rim. These cyclic tensile stresses trigger cracks distributed all around the rim area, as observed in fig. 4.

Thermal/mechanical fatigue

Thermal/mechanical fatigue is a superposition of both mechanical and thermal fatigue. Examples of this situation are, for example, what happens with turbine disks [8-9]. Sometimes, if operating temperatures are high, creep is also active and very complex thermal mechanical fatigue situations exist. Almost all engine components are under thermal cycles (start-up, steady state, and shut down) and mechanical cycles. Therefore, thermal mechanical fatigue arises. An example is another engine piston [7], on fig. 5. On this picture only one crack prevailed and propagated. This is a symptom that mechanical fatigue was the most important mechanism. However thermal fatigue was also active, as the thermal cycles also existed. If thermal fatigue were the most important mechanism, instead of mechanical fatigue, it would be observed several fatigue cracks, as happened with the train engine piston, shown in fig. 4.

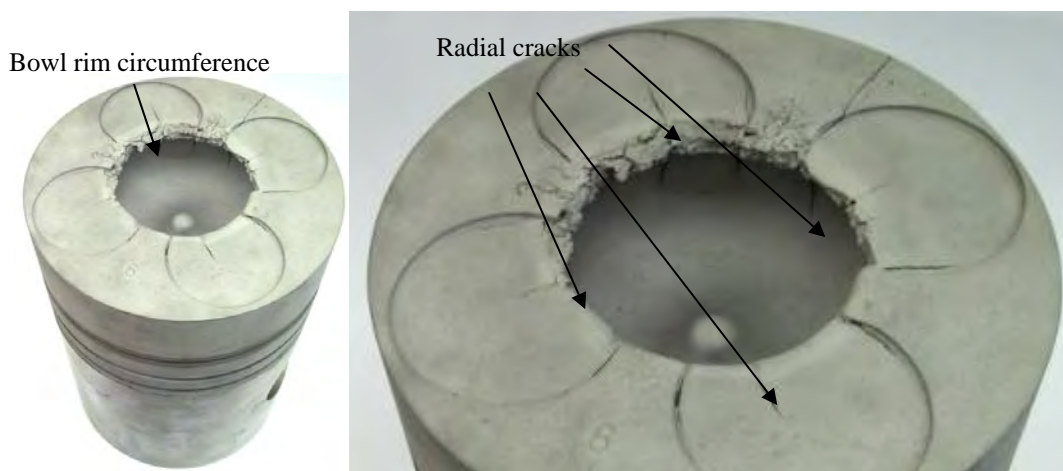


Fig. 4. Train engine piston – piston damaged by thermal fatigue with creep [7, Minho Univ.].



Fig. 5. Engine piston – piston damaged by thermal-mechanical fatigue [10, Minho Univ.].

Contact fatigue

When two free bodies are in contact but not attached one to another, there may exist contact fatigue. Examples are rolling bearings, gears [10], train wheels on railways, etc. On fig. 6 there is a cylinder arm that was in direct contact with the bearing cylinders.

That cyclic rolling contact promoted 'pitting' or 'spalling' of small regions on the cylinder arm.

In fig. 6 can be clearly seen that the area that suffered pitting is the one where the loads were high during the engine cycle. Sometimes fretting is also associated with rolling contact fatigue. As a fact when two free bodies are in contact and there is deformation between them, it is probable that there is also a small relative displacement between the surfaces (this depends on the geometry of the contacting bodies).

Thus, although the fatigue mechanism is known as 'contact fatigue', it is important to consider that most of the times fretting may also play a role on the degradation evolution.

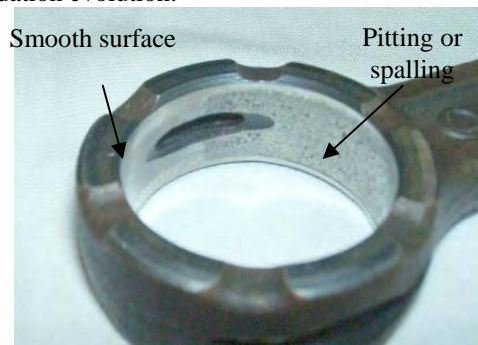


Fig. 6. Cylinder arm damaged by contact fatigue [Minho Univ.].

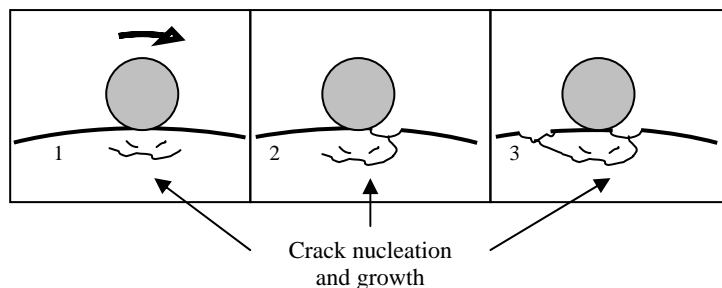


Fig. 7. Schematic damage evolution under contact fatigue.

Impact fatigue - Impact fatigue is characterized by the existence of a contact load between two bodies plus the impact energy due to the movement of at least one of the bodies.

According to [11] it is important to take into account the behaviour of the stress waves due to the impact energy in order to predict the fracture strength of the components.

Traditionally impact fatigue exists in components under the form of vibration but in some cases, such as the one shown on fig. 8, there is impact due to the fact that the valve spring was not strong enough and the valve top component used to lose contact with the cam in one part of the cycle (there was an impact in every cycle).

Therefore, besides the contacting load between the cam and the valve top component there was an impact between both components.

The consequence in terms of fracture morphology is that there are many growing surface cracks. This is due to the impact energy that flows from the contact point through the whole body, as a stress wave, promoting the growth of all existing cracks. Although there are not many studies including impact fatigue, this stress wave effect was observed on small crack growth, by Zhang [12].

In Zhang's study, it is clear that impact fatigue and non impact fatigue have very different crack initiation mechanisms.

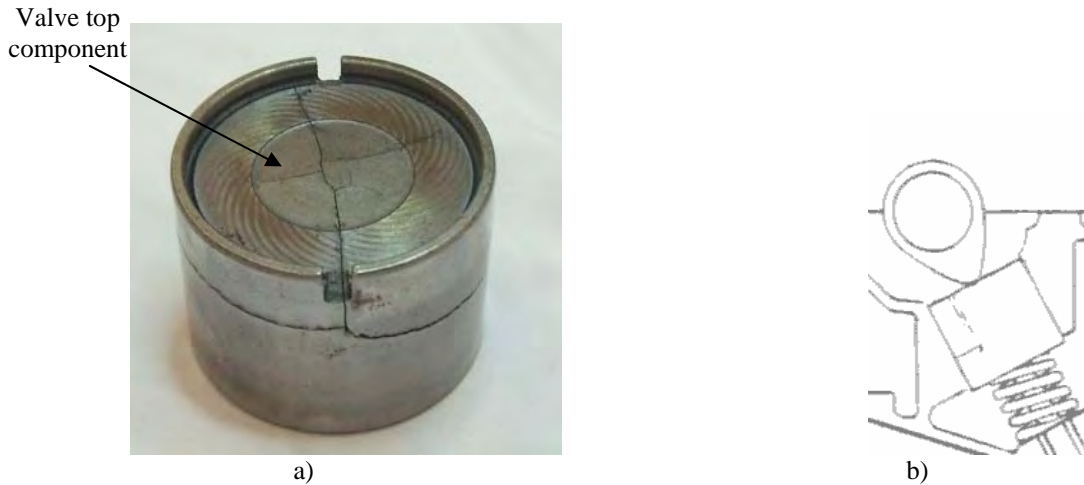


Fig. 8. a) Valve top component damaged by impact fatigue [Minho Univ.];
 b) Working positioning of valve top component.

Cavitation fatigue - Cavitation fatigue exists due to the wave pressure impacts on solid surface. These waves are responsible for the cyclic deformation of the solid bodies. Basically, the bubbles form in low pressure areas and when they reach higher pressure areas, they implode and pressure waves form. These pressure waves flow through the liquid and impact the solid surfaces. Although this mechanism, also called cavitation erosion, as been a matter of controversy, cavitation fatigue is being understood as

a fatigue phenomenon essentially related to cyclic stresses/strains and therefore as a mechanical fatigue phenomenon.

The mechanism is essentially the same as contact fatigue (fig. 7), as described in fig. 9b. It is frequent in diesel cylinder walls due to the vibration of the walls (see fig. 9a), but it is also common in ship propellers, water pumps, injector nozzles [13], and other components that are in contact with liquids.

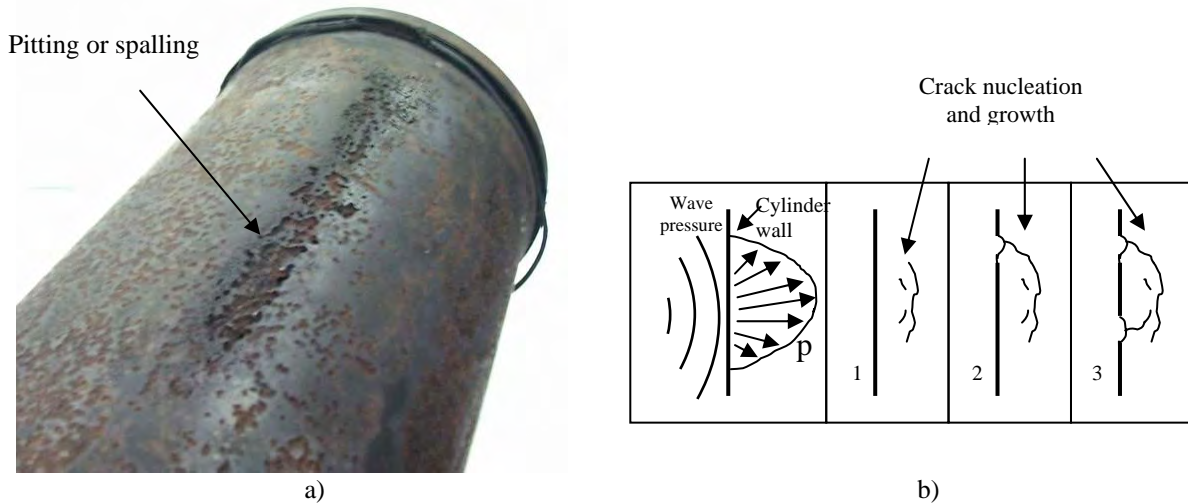


Fig. 9. a) Engine cylinder wall component damaged by cavitation fatigue [Minho Univ.];
 b) Schematic representation of wave pressure damage mechanism (ex: wave pressure against a cylinder wall).

Sometimes cavitation fatigue occurs in situations where there are also thermal cycles and mechanical cycles, such as that of the cylinder walls (fig. 9a). Thus cavitation fatigue is also, sometimes, superposed to thermal-mechanical fatigue [14].

Creep fatigue - Creep fatigue exists when mechanical fatigue operates in a metal component at

high temperature (in plastics there may exist creep fatigue even at room temperature).

Sometimes, when there are thermal cycles with creep, it is also called creep fatigue. Creep fatigue is basically a superposition of mechanical fatigue and high temperature creep [15].

Creep fatigue is common, for example, in power plants or fusion reactors [16].

Due to high temperatures, involved with long hold periods at high temperatures creep is active and promotes crack growth. Due to mechanical cycles, mechanical fatigue is also active promoting also crack growth.

Secondary mechanisms

Wear-fatigue

Wear fatigue exists when there are normal contact forces plus the tangential forces due to the sliding movement between both bodies.

The following crankshaft shows an example [17] of a journal that was in contact with the plain bearing. Besides the normal contact it is clear in the damaged surface (scratched areas) that a sliding contact promoting wear existed between the surfaces. Although the wear was not enough to initiate cracks it is not difficult to admit that, if there were a pre-existing crack, the wear between journal and bearings would help on crack propagation. This is what happened in the crankshaft journal in fig. 10 and the mechanism is schematically described in fig. 11

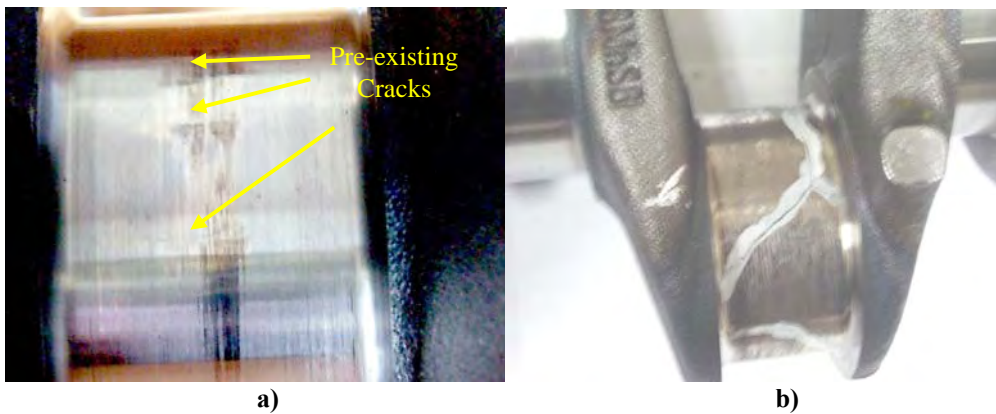


Fig. 10. Crankshaft journal under fatigue wear fatigue [17 - Minho Univ.].
 a) pre-existing cracks; b) after crack propagation.

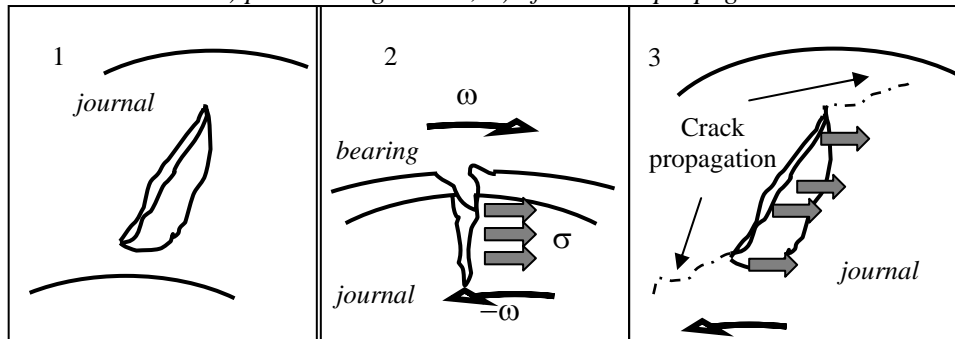


Fig. 11. Schematic damage mechanism under wear fatigue after a pre-existing crack.

Wear fatigue is also considered in situations where the load is transmitted from one body to the other under wear conditions. This is what happens, for example, on cutting tools. The cyclic loads come from the alternating slip and stick of the chips, the vibrations of the machines, and the heavily interrupted cutting process itself. However the cracks grow in places where there is no wear. Thus it is mainly a mechanical fatigue process. Most of the times, during the cutting process, it involves cyclic temperatures. Therefore thermal fatigue may also be active [18].

Fretting fatigue

Fretting fatigue is common in situations where two components are connected or attached one to the

other for example with screws, and a small relative displacement (traditionally between 1 to 100 μm) exists between both components. Fig. 12 shows a suspension component where fretting fatigue accelerated the fatigue damaging in the contact region between the formed component and the screw head. A small relative displacement between both components was responsible for the fretting process. In this case, the failure region was not the most stressed area of the component. Thus it would not be expected that the contact region between the bolt and the component would fail. However, the relative displacement deteriorated that region causing a premature fatigue crack and consequent failure of the component.

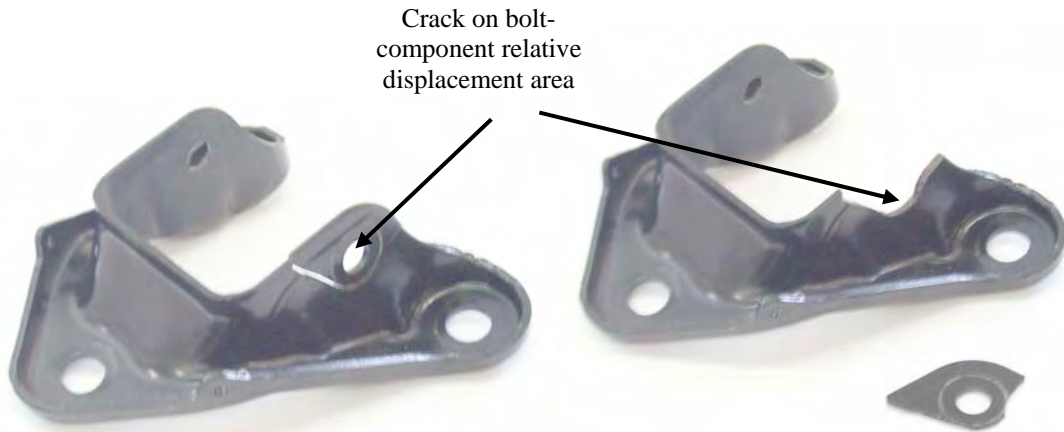


Fig. 12. Suspension component damaged by fretting fatigue [Minho Univ.].

Since structures are composed by individual components that are attached one to the others fretting fatigue failures are very common and occur in many components such as propellers hub-flange assemblies, turbines disc/shaft connections, etc [19].

Abrasion fatigue

Abrasion fatigue is common when load transmission between two solid bodies is made by a third body (for example dust).

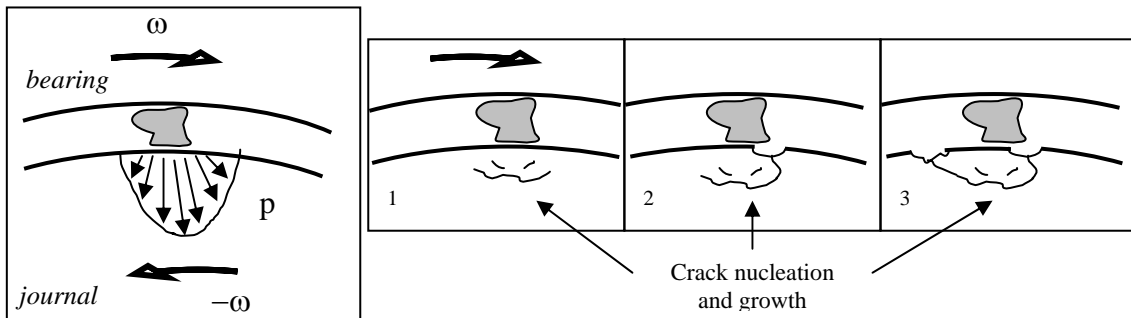


Fig. 13. Schematic damage mechanism under abrasion fatigue.



Fig. 14. Journal bearing damaged by abrasion fatigue [Minho Univ.].

This third body (for example dust) may be involved in oil or water.

This is very common in bearings such as the one on fig. 14. The mechanism is schematically shown in fig. 13. The third body causes pitting or spalling. If by

any reason there is a pre-existing crack the dust particles enter the crack and help in crack propagation. This is schematically exemplified on fig 15. An example of this fatigue mechanism is shown in fig. 10 on the journal crankshaft.

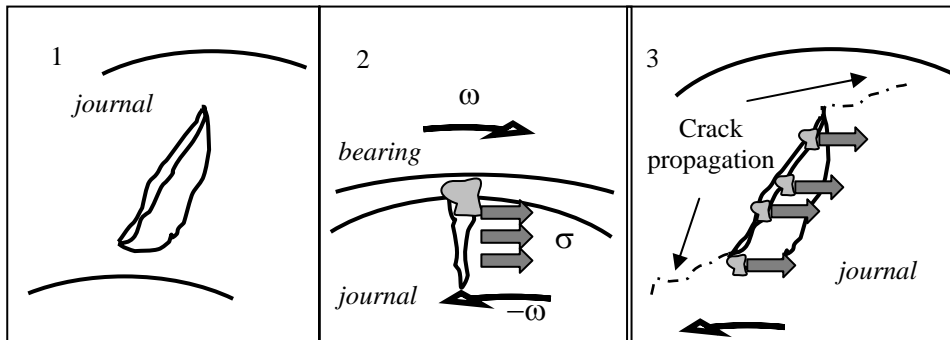


Fig. 15. Schematic damage mechanism under abrasion fatigue after a pre-existing crack.

Corrosion fatigue

Although nowadays it is accepted that the normal environment is very detrimental for fatigue (tests under vacuum put this in evidence) corrosion fatigue is commonly considered a fatigue process under very deleterious environments. Corrosion fatigue is a mechanical fatigue process where the detrimental environment accelerates fatigue crack growth. Corrosion fatigue is not the same as SCC - Stress Corrosion Cracking. SCC occurs even when the

tensile stress level is constant. Corrosion fatigue occurs under fluctuating loads plus a detrimental environment.

Fig. 8 shows connecting rods broken by corrosion fatigue. The effect of the deleterious environment is clearly observed on the fracture morphology. A microscopic analysis shows that in most cases, due to the deleterious environment, crack propagation is mainly intergranular, as it is peculiar in corrosion fatigue [20].

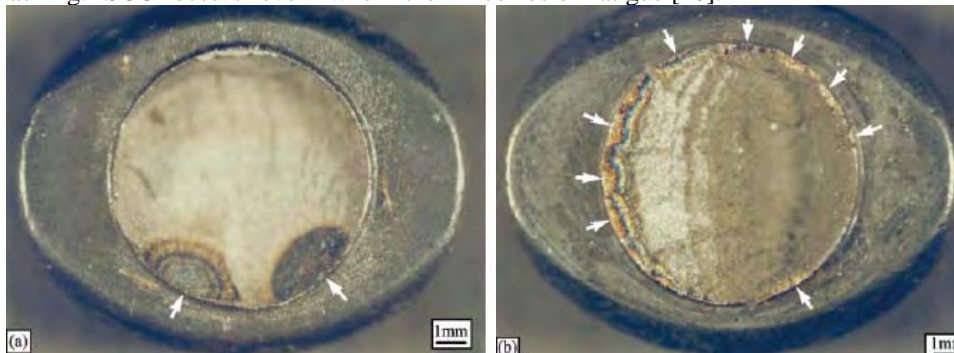


Fig. 16. Connecting rod bolts damaged by corrosion fatigue [21]

Hydrodynamic fatigue (liquid pressure and trapped water/oil fatigue)

The first situation where hydrodynamic fatigue may occur is when two rigid bodies exert load by means of a liquid (for example oil) and there is a pre-existing crack. The liquid inside the crack exerts opening loads on the crack surfaces promoting crack propagation. This situation is schematically presented in fig. 17.

This situation may occur, for example, in journals such as that one in fig. 10a), where some cracks induced by the grinding finishing process exist in the journal.

The oil pressure inside the crack during the normal working process of the plain bearing, promotes crack propagation.

The other situation is common under rolling contact. The crack, originated by contact fatigue, retains some liquid. When one body exerts load on one crack side the crack closes and the liquid is trapped inside the crack.

The pressure on the trapped liquid promotes crack propagation. This may happen, for example, on railway axes.

The train wheels close the cracks on the railway axes accelerating its propagation rate [22].

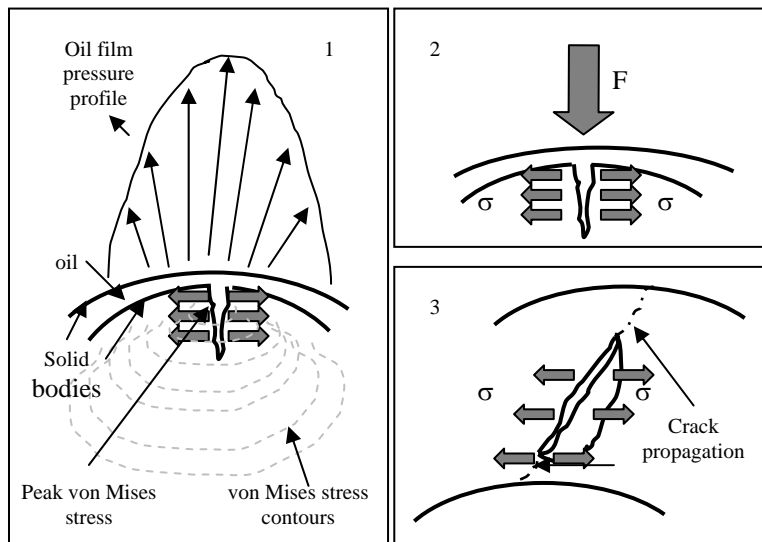


Fig. 17. Schematic damage mechanism under hydrodynamic fatigue.

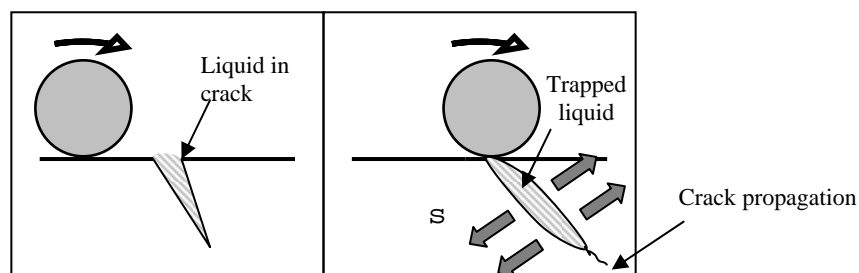


Fig. 18. Schematic damage mechanism under trapped oil/water fatigue.

4. Conclusions

Some different damaging mechanisms were presented in this paper.

All of them may be considered fatigue-damaging mechanisms because all of them are related to cyclic stresses or strains occurring in components that lead to initiation and growth of cracks, causing components failure. Some of the damaged components such as engine cylinder walls, propellers, etc, are sometimes not considered damaged by fatigue because the mechanisms are eventually not well understood.

The reason of this paper is to bring a deeper understanding of the basic fatigue damaging mechanisms in order to better determine the possible existence and location of damage, to prevent future occurrences, and to improve the performance of the component or structure.

The main conclusion of this work is that a better understanding of failure mechanisms may be a tool for damage assessment of structures or components.

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