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Fretting Wear, A Tribological Factor In Catastrophic Failure Of Metallic Surfaces.

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Abstract: *Fretting wear plays a crucial role in many cases where failure is observed. Cyclic motion between contacting surfaces is the essential ingredient in all varieties of fretting wear. It is a surface-to-surface form of wear mainly determined by parameters such as displacement amplitude, normal loading, material properties, number of cycles, humidity, lubrication and a few other less common factors. In this paper, we examine the manner and extent to which certain geometrical forms and engagements are subjected to fretting wear often with cracks initiated in the damaged region and the incidence of catastrophic failure. Methods and equipment used in determining the various parameters affecting fretting as a factor in catastrophic failure are discussed. A series of measures to prevent fretting wear have been treated.*

Keywords: - wear; fretting; corrosion; failure; vibration.

1. INTRODUCTION

Surface material disintegration due to fretting as the ruling wear mechanism leading to severe damage has been an overlooked cause of catastrophic failure in the design of many interacting surfaces. When reciprocating sliding movement occurs at the interface of metallic surfaces at relatively small amplitudes at high frequency, material crumbling related to surface fatigue sometimes follows in a manner often mistakeable with many other forms of failure [1]. *The ASM Handbook on Fatigue and Fracture* defines fretting as: ‘A special wear process that occurs at the contact area between two materials under load and subject to minute relative motion by vibration or some other force.’

Wear is involuntary, gradual removal of material at solid surfaces in relative motion with one another or with a fluid. Wear phenomena are intimately linked to friction processes. In reality, if solid surfaces in relative motion are not separated in some way, wear is expected to ensue in some mode or another.

The most common types of wear are adhesive and abrasive although under specific conditions, surface fatigue, fretting, erosive, corrosive and a score of other varieties may manifest in many industrial applications.

Fretting wear, also known as vibrational wear, chafing, fatigue, wear oxidation, friction oxidation, false brinelling, molecular attrition, fretting fatigue and corrosion is a poorly understood form of fatigue caused by minute oscillating motions between materials in rubbing contact. It ensues whenever low-amplitude vibratory sliding takes place between two surfaces [3].

Fretting is more precisely a contact damage process arising from surface micro-slip associated with small-scale oscillatory motion of clamped structural members and can happen whenever low-amplitude (10-50 μm) vibratory sliding takes place between two surfaces [4]. Examples of vulnerable components are press fits, bolted parts and rolling bearings.

The contact surfaces are worn and, at the same time, affected by cyclic friction stress. Fatigue occurring together with fretting is called fretting fatigue. Fretting is thus a special case of fatigue [5].

The mechanism for fretting fatigue mainly involves three stages; a) crack initiation due to fretting, b) crack propagation under the combined influence of contact loads due to fretting and bulk loads and c) crack propagation under the influence of bulk load only. Ruiz et al developed two criteria for assessing fretting damages on two-dimensional model of a dovetail interface and used them for correlating with fretting fatigue life estimated through experimental results. One criterion, the first one, states that the primary surface damage driving factors are relative slip and contact shear stress at the interface. It considered the frictional work done at the surface as the main cause of surface damage and crack initiation due to fretting. This has been denoted Fretting Damage Parameter (FDP) [7]. Hence the fretting damage parameter which is a function of relative slip (δ) and contact shear stress (δ) at the interface was expressed as:

$$FDP(K_1) = \tau.\delta \ldots\ldots\ldots..(i)$$

Fretting can also combine with many of the other wear processes. Thus, the oscillatory motion causes fatigue wear, which can be enhanced by adhesion. Wear can also be combined with corrosion such as by oxidation and ultimately, the corrosion products can be abrasive. This mainly arises from the fact *that no macroscopic sliding takes place* which often means that wear debris cannot escape but remains trapped between the surfaces. *The contact surfaces are worn and, at the same time, they are affected by cyclic friction stress.*

Thus, while mechanical factors affecting the fretting properties include coefficient of friction, pressing force and an amount of relative slip, fretting, may also occur with no true macroscopic sliding. The surfaces may be in static contact in the central region of contact (stick), where the normal pressure is high, but subject to microslip at the periphery (slip), where the pressure is low and the tangential traction is sufficiently high to overcome the static friction [8]. Fig.1 shows stick and slip zones at such a fretting contact. In this situation, fretting takes place in the microslip region, the fatigue cracks nucleated leading to gross component failure.

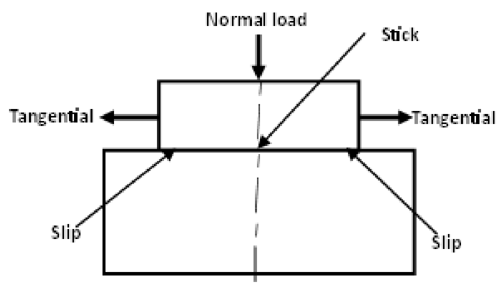

Fig.1: Stick and slip zones at fretting contact.

2. FRETTING WEAR AND ITS MECHANISMS

Cyclic motion between contacting surfaces is the essential ingredient in all types of fretting wear. It is a combination process that requires surfaces to be in contact and be subjected to small amplitude oscillations.

Depending on the material properties of surfaces, adhesive, two-body abrasion and solid particles may produce wear debris. Wear particles detach and get crushed and the wear mechanism changes to a three-body abrasion when the work-hardened debris starts removing metal from the surfaces [9]

For fretting wear to occur, the applied normal load initially causes surface asperities to mutually adhere while the tangential oscillatory motion shears them and generates wear debris which accumulates. Subsequently, the surviving work hardened asperities, now acting on the smoother, softer surfaces, cause them to undergo plastic deformation, creating cavities and cracks and shearing off sheets of particles which also accumulate in depressed portions of the surfaces. Once the particles have accumulated sufficiently to fill the gap between the surfaces, abrasion wear occurs and the wear zone spreads laterally as adhesion, delamination and abrasion wear; the wear debris reaching volumes such that it can no longer be contained in the initial zone, thus escaping into the surrounding valleys [10].

Because the maximum stress is at the center, the geometry becomes curved, microscopic pits form which then merge to become larger and deeper. Ultimately, depending on the displacement of the tangential motion, worm tracks or even large fissures can be generated in one or both surfaces on contact.

Subsequently, the surfaces become work-hardened so that the rate of abrasion wear decreases and so, a fairly constant wear rate takes over, showing that all the relevant wear modes are working together [11].

Thus, the key factor in fretting wear is a mechanically loaded interface, subjected to relatively small oscillatory motion. The relative motion required to produce damage may be quite small, may be of the order of one micrometer, though more often around a few nanometers. Little wear occurs at amplitudes below 100 micrometers (Fig.2). At higher amplitudes however, direct abrasion of the interface by hard particles consisting of oxide or work-hardened particles, initiates a much more serious wear rate [12].

Changes in the normal load generally affect fretting wear. While high normal loads evidently dampen vibration sufficiently to reduce fretting, the resulting increase in contact area produces more surface interaction which tends to outweigh the damping effect. Consequently, increasing load or unit pressure may tend to generate higher wear rates [9].

It has been shown for most friction couples, especially metals, that fretting wear decreases substantially as the relative humidity increases. Wear under humid conditions is always less severe because the moisture contained in the air provides a type of lubricating film between the surfaces. In some cases, involving iron, moisture allows soft iron hydrates FeO (OH)·$n H_2O$ to form instead of the harder, more abrasive magnetite (Fe_3O_4) a magnetic oxide of iron [13].

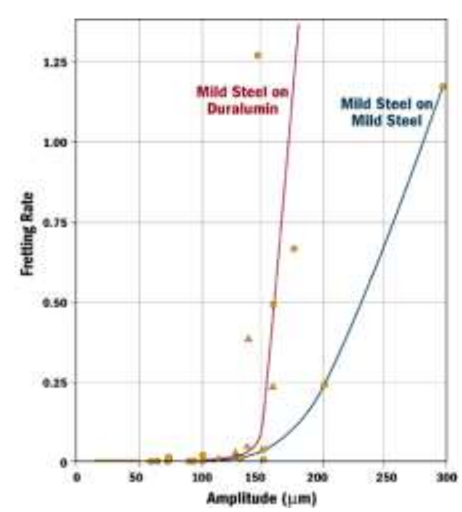

Fig.2: Fretting rate vs slip amplitude (After Fitch E., 1992)

Even under full lubrication conditions, mineral-base oils exposed to the atmosphere contain at least 10 percent air. So, oxygen is present at all wearing interfaces. Wearing surfaces and wear debris commonly show a large amount of oxide, hence the name “fretting corrosion”.

Although in the past, oxidation was thought to be the critical factor behind fretting and in fact, the existence of oxidation products has been a ready means of identifying a fretting process, it has been realized more recently, that fretting occurs even in materials that do not oxidize such as gold and platinum. While oxidation does not cause fretting in most common materials, removing wear debris leaves virgin metal exposed to the atmosphere and oxidation usually follows and in fact it has also been noted that when fretting occurs in an inert environment, the wear rate is considerably less than when conditions cause an oxide film to form and be scraped off [14]

Because the effect of frequency on wear depends on the amplitude of the oscillations, two types of fretting wear may be defined according to the oscillation amplitude: fretting corrosion or wear as earlier analysed and fretting fatigue in which less material is actually removed. Fretting corrosion occurs when two surfaces are in mutual contact and, while nominally at rest, are nevertheless subject to small periodical movements. It manifests itself in pits surrounded by powdery corrosion products [15].

In fretting fatigue, surface cracks initiate and propagate, leading to material removal. The amplitude is small (Fig.2). If the amplitude of slip increases, the fretting fatigue phenomenon can disappear as the wear front begins to advance rapidly enough to remove the initiated cracks before they propagate [16].

Surface hardness plays a key role in fretting fatigue. If both surfaces are hard, asperities will weld, followed by the shearing of junctions, material transfer and wear particle generation. If a hard surface is in contact with a soft surface, fretting fatigue wear will likely occur. The harder of the two surfaces creates sufficient traction to cause plastic deformation of the softer surface and particle release through subsurface void nucleation, crack propagation and subsequent loss of surface material. When one surface is much harder and rougher and is driven by less traction force, the asperities will indent into the opposite surface to cause serious abrasion and wire-like wear debris *[17]*.

Lubricants have a major influence on fretting wear rates. that have smooth surface finishes and close fits Fretting seems to progress more rapidly in friction couples that have smooth surface finishes and close fits. Lubricants do not penetrate wear areas with small clearances characteristic of close fits. In addition, a smooth finish eliminates lubricant-retaining pockets between the asperities in rougher surfaces. Under these conditions with mainly boundary lubrication conditions, continuous interaction of oil wetted surfaces can be achieved. Lubrication is not always successful because the reciprocating action squeezes out the lubricant film and does not allow it to be replenished [18].

In general, the purpose of the lubricant in most fretting situations is to prevent oxygen from reaching the fretting surface and the wear debris. Liquid lubricants with effective metal deactivator additives such as Salpn and Benzotriazole can help to reduce the effect of fretting but will not likely stop it altogether [19].

According to the relative movement of the mating surfaces, fretting has two modes: gross-slip, where relative movement occurs across the entire contact interface and partial stick, where slip occurs near the edge of contact with no slip at the stick zone in the central region, creating mixed fretting *[20]*.

Taking this into account, fretting on metallic surfaces has been attributed to three phases;

Step-1 The initial stage of the surface fretting occurs at the asperity levels. This is mainly adhesion at the surface where disintegration of the material occurs at the extended asperities on the surface.

Step-2 The second stage of fretting wear is by oxidation, generating abrasive wear debris. The gap between the interfaces is small and does not let the debris to escape.

Step-3 The third stage of fretting wear is severe abrasion, leading to the initiation of cracks at the edges of the loaded area. Stresses due to the repeated loading further creates the fretting fatigue [21].

This way, normal and tangential loads engaged at certain frequencies result in microscopic changes of an irreversible nature on the surface and many times ultimately become the reason for rather sudden failure in components otherwise considered in good working condition. The amplitude of load fluctuation, the magnitude of the load and its frequency are the factors that play the leading role in exacerbating subsequent surface and sometime bulk material failure [22].

3. FAILURE DUE TO FRETTING WEAR

Fretting has been found to develop in many shrink fits, bearing seats, bolted parts, splines and dovetail connections.

In bearings, fretting wear may occur when there is relative movement between the bearing ring and shaft or housing because the fit is too loose or due to elasticity even of the order of microns. The small wear particles oxidize and areas of rust appear on the outer surface of the shaft or the bore of the inner ring. The corroded areas act as fracture nodes leading to cracking of the ring and subsequent catastrophic failure. The surface damage caused by fretting wear will act as crack initiation sites. The most severe consequence of fretting is then the reduction in fatigue strength due to the resulting stress concentration when small amplitude movement arises from the cycling stressing of one of the contact surfaces.

Fretting wear normally occurs between surfaces that were not supposed to have movement against each other. This microscopic relative movement, many times, is the result of vibration or elastic deformation of the involved body under load [23].

In fretting wear of metals, debris is commonly in the form of oxide. Wear occurs when such debris is expelled from the contact, the observed wear rate depending upon oxygen transport into the closed contact. The debris oxide formation is the result of the tribological and environmental exposure [24].

Splined couplings on the other hand, are widely used in many industrial fields and one of the most problematic failure modes in these components is fretting wear which manifests because of relative motion between splines [25].

Pressure distribution here depends on both contact geometry and load conditions. Wear is actually found to be more dependent on misalignment than on torque. Thus, wear may cause splined coupling run out; this generally being caused by relative sliding between the engaging teeth due to angular misalignment between the shafts when the shaft and the hub run with an angle between their rotational axes. None the less, they may be exposed to wear damage even when they work in perfectly aligned conditions due to elastic flexibility of their teeth when subjected to strongly variable torque [26].

The interference fit, also known as press fit, is a fastening method where two parts of typically circular cross section are pushed together, one into the other, and kept in place due to pressure p_f between them given as:

$$p_f = \frac{E\delta_d}{2D_f}\left[1 - \left(\frac{D_f}{D_h}\right)^2\right]$$

where

p_f is interference pressure (MPa);
E is the elasticity modulus (MPa);
δ_d is the interference fit level (mm);
D_f is nominal shaft diameter and hub inner diameter (mm) and
D_h hub outer diameter (mm).

Ordinarily, the inner part will have a nominal outer diameter slightly greater than the nominal inner diameter of the outer part, and when pushed or forced together the contact friction forces nominally keep the parts from moving relative to each other. The level of interference thus depends on the negative difference in nominal diameters [27].

Fretting causes considerable reduction in the fatigue strength of an interference fit assembly. The assembly undergoes fretting fatigue at the interface, where both stress concentration and micro-slip take place. Fretting occurs where one of the contacting surfaces is subjected to an alternating stress which results in an alternating strain. This is a typical situation between the hub and the shaft in an interference assembly. The amplitude of the alternating movement is small, probably less than 150 μm and the sliding velocity low (≈5 mm/s). Fretting begins with local welding of rubbing asperities. The alternating movement leads to loosening of these local welds leading to the formation of debris and pitting and subsequent failure of the press fit. [28].

Bolted joints are widely used in mechanical assemblies. Connected parts are brought into contact by bolt preload and transmit tangential loads by dry friction. Under oscillating load, the contact interfaces may undergo relative motion with a small amplitude, which translates to fretting. Substantial change in bolt preload, contact stiffness and friction coefficient due to fretting wear are notable after a fretting wear regime. These significantly affect the dynamic characteristics of joint structures [29].

Referring to threaded assembles in particular, these are widely used in mechanical structures due to their relative ease of assembly and disassembly. After fretting fatigue, self-loosening is the most widespread failure mode for threaded joints subjected to cyclic loading. It may lead to the reduction of structural stiffness or the separation of clamped members [30].

While the rapid self-loosening in the first few hundred loading cycles is caused by the local cyclic plasticity occurring near the roots of the engaged threads, which is quite different from fretting wear, it has been confirmed that fretting wear causes a slow reduction in the clamping force after the early stage of the rapid self-loosening caused by cyclic plastic deformation. The reduction in clamping force is induced by a combination of cyclic plastic deformation and fretting wear prior to the commencement of relative rotation between the nut and the bolt. [31].

The combination of small oscillatory motion, normal pressure and cyclic axial loading develops noticeable stress concentration at the contact zone leading to the accumulation of damage in fretted region that ultimately produces micro cracks and later forms a leading crack that results in failure. It may be very difficult to detect the crack at the initiation phase in bolted joints since damages and cracks are always hidden between the component surfaces [32].

Dovetail joints, on the other hand, will sustain large numbers of vibration cycles during operation and a practical design consideration will therefore be whether these cycles can cause fretting fatigue cracks to initiate and propagate. Micro relative sliding exists on the contact surface of the main primary equipment’s surface structures, giving rise to serious fretting fatigue [33].

MEASUREMET OF FRETTING WEAR

Wear rate measurements are usually performed using either standard or customized friction and wear testing equipment. The same configurations used for friction measurements are also used in wear research. A common measure of wear is the volume of material removed per unit sliding distance [34].

For a system where a volume V_w of material is removed by wear in a sliding distance L, the volume of material worn per unit sliding distance is given as:

$$w = \frac{V_w}{L}$$

Thus, wear rate is expressed in units of area.

The real area of contact of a friction couple A_r, for plastically deforming asperities, may be expressed as:

$$A_r = \frac{F_n}{H}$$

where

F_n is the applied load and

H is the hardness of the softer component in the friction couple.

F_n is the applied load and H is the hardness of the softer component in the friction couple.
Thus, the fraction of the real contact area A_r removed by wear, the wear coefficient K is given as

$$K = \frac{A_w}{A_r} = \frac{V_w/L}{F_n/H}$$

The coefficient K represents the proportion of the plastically deformed volume that is removed by the wear process.
The most effective method to study the behavior of fretting fatigue is a fretting test. This is described in The American Society for Testing and Materials (ASTM) in the "Fretting, Fatigue Test Standard Guide" which elaborates the general types of fretting fatigue tests and provides some suggestions on developing and conducting fretting fatigue test programs. Fretting fatigue tests are designed to determine the effects of mechanical and environmental parameters on the fretting fatigue behavior of metallic materials.

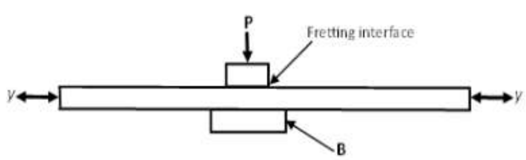

Fig. 2: Experimental Set-up

Figure 2 is a schematic representation of the design concept of the experimental set up for a typical fretting wear experiment which entails applying a normal load P to the fretting pad at the tribologically prepared fretting interface on the test specimen oscillating in the y-y direction at frequencies 0 to 300Hz, amplitudes 0 to 150 µm. to simulate small oscillatory motion between contacting surfaces. The specimen is sustained by the bearing support B against the working force P.

A customized high frequency test equipment after the basic idea is as shown in Fig.3 in which the Ball-on-Flat linearly reciprocating sliding wear, one of the most common laboratory wear testing methods used to determine wear behavior, is realized into standard tooling.

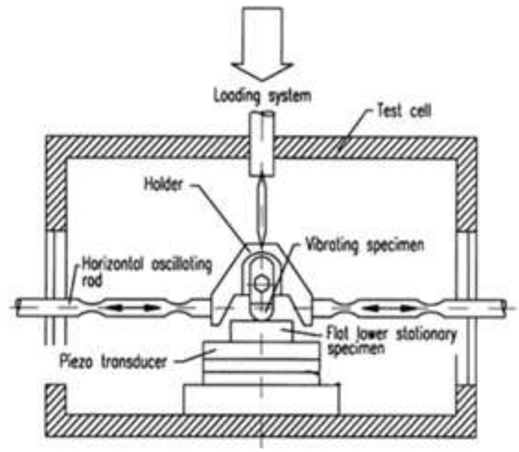

Fig 3: High Frequency Test Device

The volume of the material removed is an important quantifying parameter for wear. There are various methods to measure wear volume. Gravimetric analysis is one of the commonly used methods. But this method fails when the wear volumes are rather small. For all testing conditions, the extent of wear is so small that weighing cannot be effective either. One of the most reliable and accurate methods is the calculation of the wear volume in the three-dimensional surface profiling of the wear scar from a large set of multiple surface profiles [34]. Although this method is very accurate, it is extremely rigorous and time consuming. There are other modern methods like stylus and electron microscopic techniques existing to measure surface topography equally too sophisticated. Empirical equations for total wear volume V have, however, been mastered to largely cover the gap and generally take the form:

$$V = \frac{\pi h_{cap}^2 (3R - h_{cap})}{3} \ldots\ldots\ldots i)$$

Equation i) is used to determine the volume of the wear in the ball-flat sliding system and is based on the assumption that the wear of the flat corresponds to the shape of the worn ball impressed into the flat. The basis for the wear calculation is therefore a ball cap

which is the case of fretting in the true perpendicular direction (Fig.4a), but in the parallel direction the worn surface on the flat is prolonged (Fig.4b), so that the projected area of the worn surface is approximately an ellipse [35].

In this method, use is made of an upper oscillating specimen of standard diameter bearing balls with a high surface finish and a flat lower stationary specimen having a ground surface finish. All samples are ultrasonically cleaned prior to testing usually with a strong solvent like carbon tetrachloride.

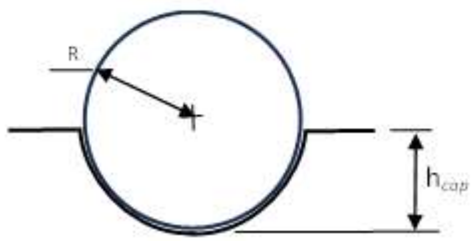

Fig.4(a)

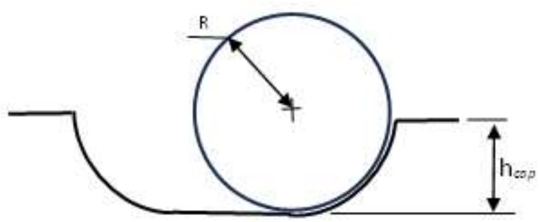

Fig.4(b)

The fretting tests are carried out at room temperature in still air. A normal load and a known frequency of say 200 to 300Hz is used for the tests. The amplitude of oscillation is varied in a stepped manner, say 5, 15, 25, 35 and 50 mm and the tests conducted for preset periods of say l0, 20, 30, 60, 180 min, each test performed on a new specimen. [36].

4. MITIGATION MEASURES

Palliative methods fall into three categories: ones that reduce relative slip or vibration, those that raise the strength by changing the base material as by surface treatment and others that lower the coefficient of friction [37].

Fretting damage can be reduced by decreasing relative slip between the components. This may be achieved by either increasing the contact pressure or separating the surfaces. Increasing contact pressure can change the fretting regime from hydrodynamic and mixed regime to partial slip. This however, may also occasion a sharp increase in local stress and increase the risk of local fatigue damage. It is also not always possible in typical industrial settings. Decreasing slip can include design changes, dampening any vibrations and making certain that all joints are properly tightened especially in highly stressed zones. Also, if the application allows for it, vibrations can be absorbed by rubber while preventing slip zones at the same time.

Design changes can also include pre-stressing of elements in contact especially in dismantlable joints [38].

The increment of preload for example, alleviates thread wear through reducing the relative slip between the threads of the bolt and the nut. Thereby, the anti-loosening ability of bolted joints is improved. The bolted joints using the thread locker exhibit the best anti-loosening ability since the thread locker can inhibit the thread wear through preventing the relative slip and separating the threads of the bolt and the nut *[38]*.

There are also various methods of ensuring that the material in the contact zones acts to minimize fretting damage: this can be achieved by engaging a suitable base metal without treatment. Selecting materials with elevated hardness and fatigue strength can effectively reduce fretting wear and inhibit the initiation and propagation of cracks.

Alternatively, a reduction of friction can be of great influence to fretting wear reduction. A higher value of friction coefficient engenders bigger friction forces and causes a higher shear stress or high strain fatigue on the surface and at the interface, which can intensify fatigue failure or generate delamination cracks. Therefore, in practice, much effort is made to reduce the friction coefficient.

The most efficient way to reduce the friction coefficient is through lubrication. In many instances, however, fluid lubricants may squeeze into crack tips and end up promoting crack propagation.

Lubrication is one of the important methods of preventing fretting damage owing to the remarkable reduction in the coefficient of friction and therefore reduction of the tangential contact force, separate surfaces and wash away debris and also restrict their access to oxygen. In particular, solid lubricant is most efficient in the partial slip regime while grease and particularly oil, are more suitable in the gross slip regime [39].

Some solid lubricant coatings, such as molybdenum disulfide (MoS_2), diamond-like carbon (DLC) or copper nickel indium alloy powder (CuNiIn) coating can easily generate lubricating debris, which forms a third body between contacting surfaces and improves on fretting wear resistance. The decrease in coefficient of friction can also improve the fretting fatigue strength because of the decrease in the alternating tensile shear stresses. It is these high alternating stresses that result in local high strain fatigue and the rapid initiation of fatigue cracks. *[40]*.

A well-considered change in design of the contacting parts is an alternative that is worth the effort. The suppression of fretting by design *optimisation* usually involves the geometrical modification of components and change of the contacting materials. This can sometimes engender unexpected fretting protection effects because the pressure distribution, topological contact mode, contact stiffness of the contact surface may be changed accordingly, thus altering the fretting running regime [41].

Selecting and matching of materials to raise materials pairs with effective mechanical properties that complement to avert fretting wear has produced plausible results. This involves the selection of two materials with different ductilities or 'softness'. A pair of soft and hard metals are proven to have less fretting damage compared to two hard metals since the softer metal 'flows' rather than 'rubs' when in contact. As long as the structural strength needed for the pair to execute their functional role is ensured, the material with better flexibility and larger deformation can effectively absorb relative slip to reduce surface fretting related damage [42].

By using surface hardening treatment or hard coatings on the other hand, fretting wear resistance will be increased accordingly, because an increase in surface hardness will prevent adhesion and abrasive wear during fretting. Most of the surface treatments and surface coatings are effective in increasing the surface hardness which may help to mitigate fretting wear provided that they have good adhesion or bonding strength with the substrate.

The most frequently used method for improving dynamic strength during fretting is shot peening. Shot peening is a cold-working process used to improve product service life by enhancing the mechanical properties of the treated material such as hardness, wear and fatigue resistance in order to prevent crack initiation and propagation. It involves the use of peen in the form of hardened steel balls or glass bead shots entrained in a fast flow of air to impact on the surface with a momentum enough to create plastic deformation [43].

This procedure does not noticeably alter the geometry and can also be done during repair. It plastically deforms metal surface, hardens it and induces pressure-residual stresses [44].

Carburising, nitriding, electroplating as with Cr, Ni etc., and laser cladding are some are renowned heat treatments that accomplish surface hardness using a notably different procedure.

Alternatively, this is achieved by surface treatments such as electrodeposition of soft metals, chemical conversion coatings of phosphate and sulphidised coatings on steels and anodised coatings on aluminium alloys.

There are also several types of advanced surface-modification methods for the mitigation of fretting damage, such as physical and chemical vapour deposition (PVD and CVD), ion implantation, laser treatment and plasma nitriding, etc. [49]

There are times, however, when some of these methods are not very effective in the mitigation of fretting fatigue. The reason is probably that the sharp increase in surface hardness will be accompanied by high residual tensile stresses and decreased toughness in the surface layer, all of which are detrimental to the fretting fatigue strength.

5. CONCLUSIONS

Fretting wear is a consistent source of failure in materials as long as specific measures are not taken to avert the causative factors at the design and construction stages.

Threaded joints will initially experience loosening due to plastic deformation of the threads in the first few hundred cycles undergo fretting wear at a later stage leading to complete loosening resulting in the rotation of the threaded component sometimes necessitating the use of prevailing torque nuts as thread lockers, evidencing fretting wear in this otherwise most popular assembly mechanism.

Dovetail assemblies, interference fits, bearing/shaft fits, splined couplings are combinations of components that are so prone to fretting fatigue damage and require deliberate, tailored remedial measures for individual each case. The exact palliative methods in each case can be subjected to measurement and sometimes calculation utilising empirical and derived formulae.

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