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Some considerations on the mitigation of fretting damage by the application of surface-modification technologies

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Abstract

Fretting is a surface-degradation process due to mechanical and chemical attack by small-amplitude oscillatory movement between two contacting surfaces and it is intimately related to wear, corrosion and fatigue. The introduction of surface treatments or coatings is expected to be an effective strategy against fretting damage. This paper discusses the application of 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. Some coatings are effective in the mitigation of the fretting wear, whereas others are more effective under fretting fatigue conditions. The effects of surface-modification methods on fretting resistance are explained using fretting maps. There are at least five different mechanisms in using surface-modification methods to increase fretting resistance: (1) inducing a residual compressive stress; (2) decreasing the coefficient of friction; (3) increasing the surface hardness; (4) altering the surface chemistry; (5) increasing the surface roughness. Apart from this, the intrinsic properties of the coatings, such as their density and mechanical and chemical properties as well as the adhesion condition with the substrate, also significantly affect the performance of the coatings under fretting conditions. Based on this rationale, a coating-selection method was proposed to select the most appropriate surface treatments or coatings to minimise the probability of fretting damage. Selection of a process is guided primarily by identification of the fretting failure modes, and the ability to adjust and obtain the required surface properties, with a balance between the precise control of the surface properties and the process cost.

Keywords: Surface modification technology; Fretting wear; Fretting fatigue; Coating selection; Fretting mechanisms

1. Introduction

Fretting occurs whenever a small-amplitude oscillatory movement between two contacting surfaces is sustained for a large number of cycles [1]. It can result in two kinds of damage: fretting wear and fretting fatigue [2,3]. The probability of encountering fretting in machines and engineering structures is extremely high [4], e.g., in house-hold appliances, wire ropes, engines, automobiles, aircraft, electrical equipment and even orthopaedic implants [5]. Fretting is a dangerous situation, which often causes seizure, vibration, wear and fracture of the systems. Some of the failures initiated by fretting damage have had tragic consequences, and others have had serious economic consequence [1].

Fretting damage has been reported and investigated for over 50 years. However, it is still one of the modern plagues for industrial machinery [6]. Much research work has been done on the mechanisms of fretting wear and fatigue. Different fretting regimes have been identified and fretting maps or fretting logs have been used successfully to study the fretting behaviour of different materials [7–9]. Understanding of some basic fretting mechanisms has been achieved, allowing the development of different possible palliatives [10–12]. However, up to now, there has been no general agreement about the mechanisms and modelling of fretting. For example, the mechanical, chemical, tribological and electrical processes between two contacting surfaces during fretting have not been fully understood, the reason being that most of the wear models and theories are based on the post-observation of fretting wear damage. Direct or in situ observation of the fretting wear process is supposed to obtain some time-dependent changes and throw more light

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on the real fretting mechanisms. There have been some reports on the direct or in situ observation of fretting wear processes using a sapphire disc to rub against a steel ball [13,14] or using X-ray imaging to observe directly the motion of debris and wear within a contact [15,16]. However, there are still some problems existing for each method and much research is needed on the in situ observation of the fretting fatigue processes.

The methods used to mitigate fretting damage are extremely varied and even contradictory. Which method is to be used depends much on a particular service situation. Generally, there are three basic ways in choosing the preventive measures.

1. *Change in design*. The suppression of fretting by design optimisation usually involves the geometrical modification of components and change of the contacting materials [17]. However, redesigning is not always possible since it is a costly and time-consuming process, and sometimes these measures can cause problems of overloading or decrease in fatigue strength.
2. *Use of lubricants*. Another possible way to provide a useful attenuation of fretting is to use the appropriate lubricants (liquid, grease and solid lubricant) [18]. However, it is generally recognised that because of the very low sliding speed and high pressure occurring in fretting, lubricants are not very effective under fretting conditions [19].
3. *Application of surface engineering*. Since fretting is intimately related to wear, corrosion and fatigue, the introduction of surface treatments or coatings is expected to be an ideal solution to fretting damage [20,21]. It has been reported that some coatings can reduce the volume of fretting wear by a factor of 100 or increase the fretting fatigue life by a factor of about 10 or more [22,23].

Due to the rapid developments in the field of surface engineering, increasing numbers of surface treatments or coatings are becoming available to mitigate fretting damage. However, the deterioration mechanisms of coatings under different fretting conditions are so limited that a modelling design with respect to improving fretting resistance is yet far from being available.

2. Surface engineering to mitigate fretting damage

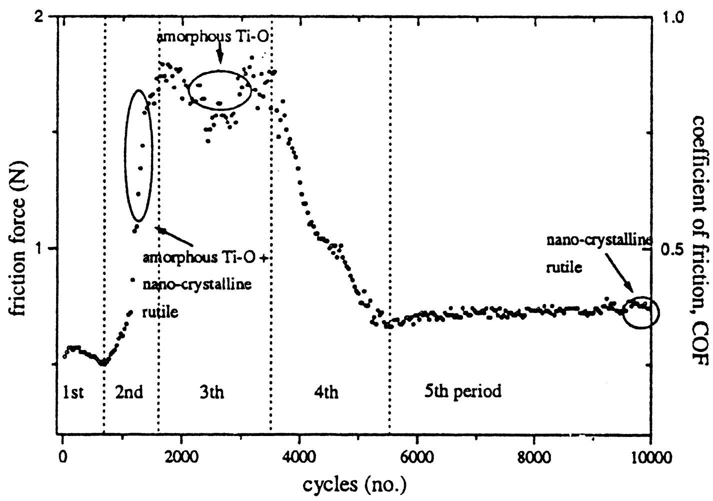
Surface engineering historically ranges from glazing and painting to gas carburizing and electroplating. In recent years, a host of new surface engineering methods have come into existence, partly in response to the shortcomings and environmental problems of the old methods (such as gas carburizing and electroplating), and partly as a result of advances in materials (such as advanced ceramics and composites) and technologies (such as vacuum processing and high-power lasers) [24,25]. This section will focus on the application of some advanced surface-modification methods such as vapour deposition, ion implantation, laser treatment and plasma spraying, etc., in the mitigation of fretting damage.

2.1. PVD and CVD coatings

PVD technology is extremely versatile. Virtually any metal, ceramic, intermetallic or other compound which does not undergo dissociation can be deposited easily onto substrates of virtually any material, even plastics or paper. PVD metal coatings such as gold and silver were used conventionally to prevent the fretting failure [26]. Investigations have shown that under fretting amplitude of 50–100 μm metal coatings such as chromium and zirconium provided durable films [27]. Other metal coating such as cadmium and gold were also found to act as effective films except for their toxicity or cost [28].

At present, a PVD TiN coating is probably one of the most frequently and successfully used PVD coatings for the mitigation of fretting damage [29]. The typical characteristics of the friction and wear behaviour of PVD TiN coatings are shown in Fig. 1. During the running-in period, the coefficient of friction (COF) has a low value (around 0.1). A period of high friction is usually established after around a few thousand cycles, where the coefficient of friction reaches a maximum value. Thereafter, the coefficient of friction remains nearly constant at a value of around 0.2. De Wit et al. [30] investigated the tribo-chemical behaviour of TiN coatings by analysing the fretting debris. Their results indicated that at the beginning of fretting, the debris consisted of both amorphous and nanocrystalline rutile materials with a crystal size of around a few nanometers. During the period of the sharp increase in the coefficient of friction, the debris contained completely amorphous fretting wear debris (which is probably caused by the presence of nitrogen in the tribo-chemical reactions). During the long-term low steady COF period, the debris had a nanocrystalline structure with a crystal size of around 0.5 nm. The amorphous phase transformed into the nanocrystalline phase due to the combined effect of relative humidity, energy input and the continuous oxidation of titanium-oxy-nitride. The significant increase or drop in the coefficient of friction was due to the transformation between the amorphous debris and the nanocrystalline phase. The depth of the fretting scar was found to increase progressively with the test duration as shown in Fig. 1(b), but the width of the fretting scar remained almost constant until the perforation of the TiN coating [31]. Thereafter, the fretting scar expanded mainly in the lateral direction. The degradation of the TiN coating was shown to proceed by oxidative wear.

Slip amplitude, normal load and frequency are three important factors affecting the performance of a PVD TiN coating and their effects can be explained using the role of the debris and the velocity accommodation mechanisms [32]. The normal load has a small influence on the



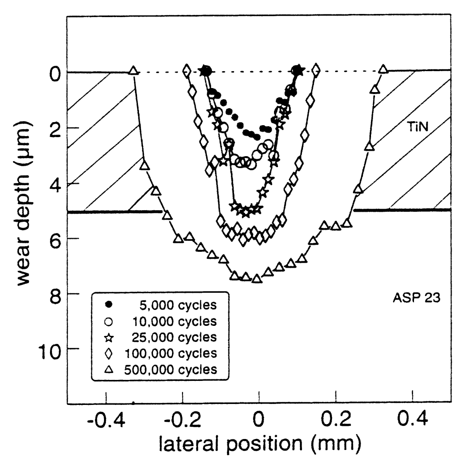


Fig. 1. Showing (a) the evolution of the friction force as a function of the number of fretting cycles during fretting tests on a TiN–corundum tribo-pair [30]; (b) the progress of fretting damage on TiN coatings on nitrided ASP 23 tool steel, where position–depth profiles were obtained by laser profilometry along a track normal to the fretting direction in the centre of the fretting scar [31].

friction and wear behaviour of a TiN coating. With an increase in normal load, the coefficient of friction decreases slightly (probably due to the increase of the oxide debris) and the wear depth is almost constant. A TiN coating is damaged to a greater extent at a relatively large displacement, and wear increases greatly with an increase in the amplitude of slip (see Fig. 2). At low displacement, the central part of the fretting scar is covered by a compacted layer of debris and transferred materials, which acts as a third body separating the two contact surfaces and reducing the wear. At a relatively large amplitude of slip, more debris forms and attempts to escape from the contact interface, acting as abrasive particles and causing an increase in the volume of wear. For a PVD TiN coating, the coefficient of friction increases with an increase in frequency [32] and this effect can be explained with the concept that the formation of oxide debris is a time-dependent process. At a lower reciprocating frequency, the fretting surface and debris are exposed longer to the atmosphere, thus more oxide debris is formed and the coefficient of friction is reduced. The higher the frequency, the less the time for the chemical or oxidation reaction to occur. At the same time, the debris can escape more easily and is ejected far from the contact zone, thus the

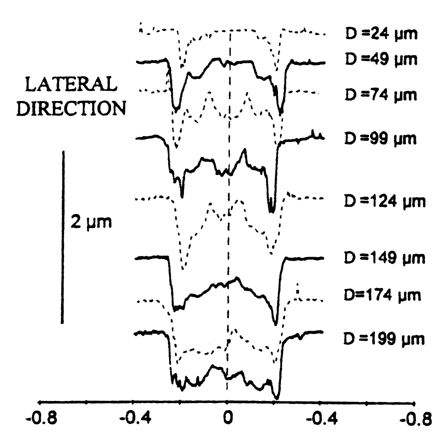


Fig. 2. Effect of the slip amplitude on the fretting wear volume of a PVD TiN coating [32].

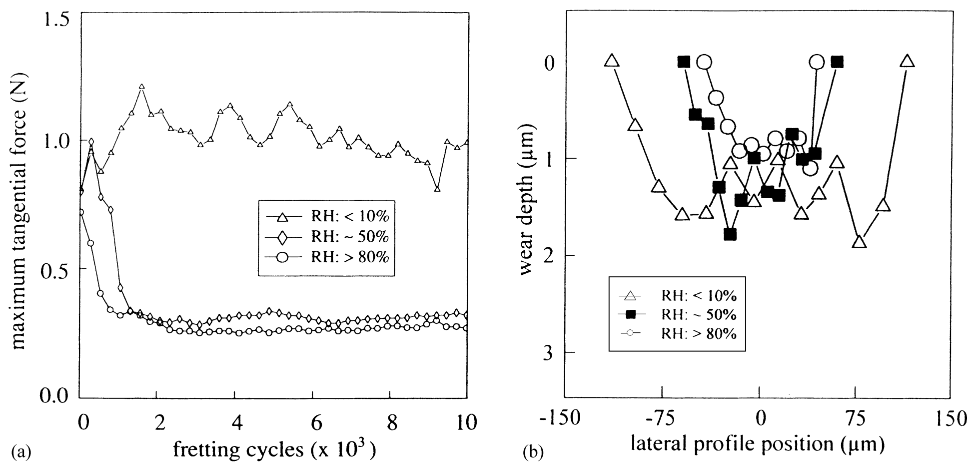


Fig. 3. Effect of the relative humidity on the fretting wear of TiN coating: (a) the evolution of the maximum tangential force with the fretting test duration on a TiN coating under different relative humidities; (b) position–depth profiles of fretting scar induced on a TiN coating by a corundum counterface after 10 000 cycles (normal load: 2 N; amplitude: 100 μm; frequency: 10 Hz) [33].

coefficient of friction increases with an increase in reciprocating frequency.

Relative humidity has a significant effect on the fretting properties of TiN coatings [32,33]. From Fig. 3(a), it can be concluded that fretting at a low relative humidity is characterised by high friction, whilst a transition from high to low friction occurs at medium relative humidity. The volume of fretting wear under high humidity is much lower than that under low humidity (see Fig. 3(b)). The effect of humidity can be explained by the formation of lubricious reaction layers such as TiO_{2-X} in the tribocontact during fretting. The presence of moisture in the test atmosphere seems to promote the formation of such lubricating reaction layers, thus decreasing the coefficient of friction and wear volume [31].

The fretting wear behaviour of a PVD TiN coating in distilled water, sea-water and sodium phosphate solutions has also been investigated [34]. Results have shown that in aqueous environments, the coefficient of friction of a TiN coating was reduced and some additives in aqueous environment, such as Na_3PO_4 or oil-free additives, were suitable to prevent a premature perforation of TiN-coated components during fretting. Studies on the fretting wear behaviour of a TiN coating in inert gases, such as argon [35], have shown that the coefficient of friction of the TiN coating in dry argon was lower than that of the TiN coating in dry air, but the wear depth in dry argon is much larger than that in dry air (see Fig. 4).

Another potential PVD coating used for the mitigation of fretting wear is a diamond-like carbon (DLC) coating [36]. This may be due to the wear debris of DLC coatings, which consists of lubricating, graphite forms of carbon. DLC coatings possess good fretting wear resistance and self-lubricating properties. Under high frequency fretting conditions, the thermal degradation of DLC coatings and partial graphitization of the DLC structure [36] can decrease the coefficient of friction and improve the fretting wear resistance [37]. Humidity is a very important factor in the fretting behaviour of DLC coatings (see Fig. 5) [38]. Under a relatively low humidity (<25%), mechanical wear (abrasive and transfer) is the dominant wear mechanism, and the coefficient of friction and wear volume are much higher, as shown in Fig. 5. At a relatively higher humidity (>25%), the dominant wear mechanism has changed to a combination

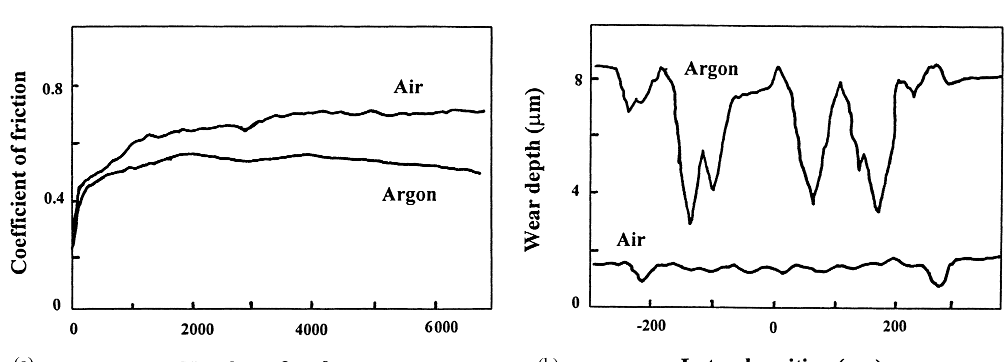


Fig. 4. Effect of argon gas and dry air on the fretting wear of a TiN coating [35]: (a) the coefficient of friction of a TiN coating in dry argon and dry air; (b) the wear depth in dry argon, which is much larger than that in dry air.

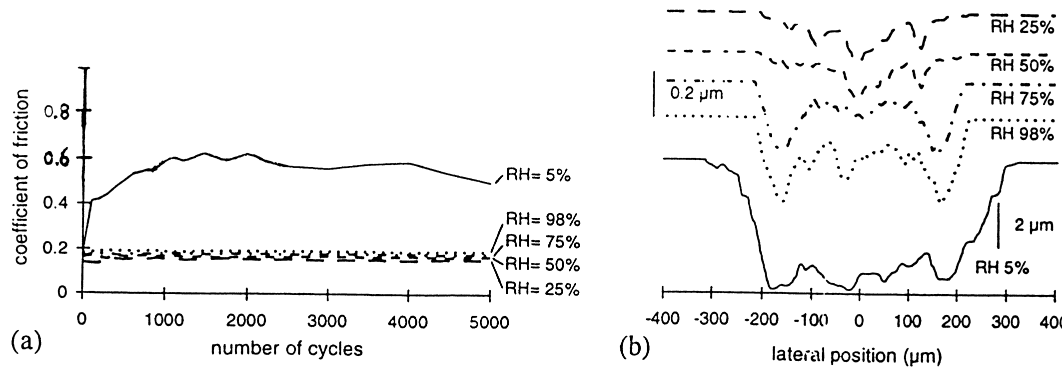


Fig. 5. Showing: (a) the evolution of the coefficient of friction with the test duration, and (b) the wear depth; on a DLC coating against alumina (normal load: 100 N; slip amplitude: 25 μm; frequency: 5 Hz); in a test atmosphere of different relative humidity [38].

of mechanical and tribo-chemical wear (the effect of a natural film of chemisorbed moisture on the DLC coating), thus the coefficient of friction decreases significantly and the wear resistance is relatively high.

De Bruyn et al. [39] have reported the application of a PVD Ti_2N coating in the mitigation of fretting damage, the results indicating that the Ti_2N coating was more effective than a TiN coating. The main problems for PVD coatings or films are their relatively weak adhesion with the substrate and, sometimes, their poor durability during long-term fretting. For some hard and brittle coatings, the fretting debris can cause a severe wear problem.

Chemical vapour deposited (CVD) coatings usually exhibit excellent adhesion but the requirement of high temperature limits their applications to substrates that can withstand these high temperatures [40]. The reported application of CVD coatings or films on the mitigation of fretting damage is mainly limited to diamond and DLC coatings [41]. Fig. 6 shows a comparative fretting wear progress for a PVD TiN coating and different DLC coatings produced by different techniques (CVD, arc ion plating, laser ablating, etc.) [42]. From this figure, it is obvious that CVD DLC coatings, such as PVD DLC coatings, are more resistant to fretting than a PVD TiN coating, although their hardness is not superior. Actually the hardness of the DLC coating is not a dominant factor for friction and wear behaviour, but effects the formation of a lubricating, graphitic form of carbon in contacting surfaces. The fretting wear behaviour of CVD diamond coatings is rather poorly understood [29]. The extremely hard and rough diamond coatings have a significant effect on fretting processes. The COF during the initial period is very high, which is probably due to the rough nature of the diamond coating. After a long time of testing, when a transfer layer occurs on the diamond coating surface, the coefficient of friction shows a low value. Preliminary results have shown that there are two competing mechanisms determining the fretting wear of diamond coatings [43]. The first mechanism is the fracture of diamond asperities and the second is the abrasion of the counterface. If a substantial amount of debris occurs from the counterface, fracture of the diamond asperities is eliminated and no wear is observed on the diamond [37].

At present, PVD and CVD coatings are more frequently used to mitigate the fretting wear resistance rather than to improve fretting fatigue strength. There have been a few studies using PVD and CVD TiN coatings to prevent reduction of the fretting fatigue strength of steel [44]. Preliminary results have shown that both PVD and CVD TiN coatings were effective in improving the fatigue resistance of steel, and that thicker films were more effective because of their wear resistance (see Fig. 7). PVD coatings had advantages over the CVD method because the latter

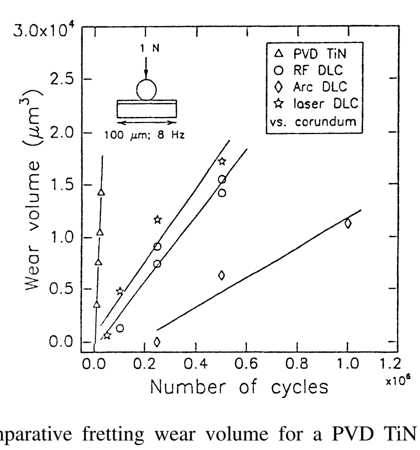


Fig. 6. Comparative fretting wear volume for a PVD TiN coating and different DLC coatings produced by different techniques (CVD, arc ion plating, laser ablating, etc.) [42].

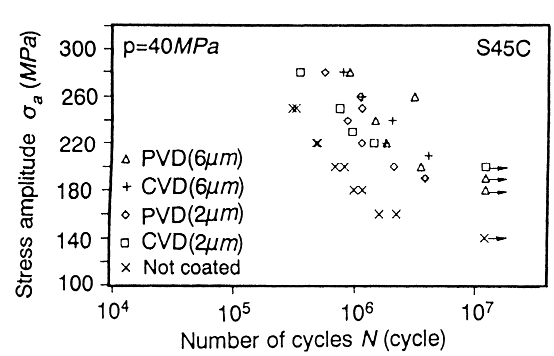


Fig. 7. Fretting fatigue characteristics of different coatings on a S45C steel specimen [44].

decreased the hardness of the substrate in the coating process. However, these conclusions are in need of more experimental support.

2.2. Ion implantation and related treatment

Ion implantation — the process of accelerating high-energy ions bombarding into the near surface region of materials — has been identified as a suitable technique for improving both fretting wear and fretting fatigue resistance [45,46]. Three or more factors are responsible for this improvement. The first is the significant increase in surface hardness, which improves the ability of the material to resist indentation, scoring and deformation [47]. The second is the generated surface residual compressive stress, which is beneficial for the reduction of wear rate and crack formation/propagation [48]. The last is the possible changes in surface chemistry. For instance, nitrogen or carbon ion implantation promotes the formation of nitrides and oxides, or causes the build-up of a carbon layer on the implanted surface, which acts as a solid lubricant between the two contacting surfaces, to reduce adhesion and friction [49]. However, there are some disadvantages in ion implantation, e.g., too shallow a treated depth and line-of-sight problems. How to control the ion beam energy and ion dose during ion implantation is also an important issue [50]. Too high an ion beam energy or ion dose can cause surface damage and high residual stresses, which are harmful to the fretting resistance.

The recent development of ion implantation technologies has moved to plasma source ion implantation (PSII) and ion beam enhanced deposition (IBED) [51]. PSII can eliminate the line-of-sight problem of ion implantation and result in a uniform implantation [52]. Some experiments have demonstrated the effectiveness of PSII in preventing the fretting wear damage of a Ti substrate [53]. Surface modification by PSII alters the surface chemistry, creating a less reactive surface and resulting in a reduction in friction and debris particulates. The examination of wear scars has indicated that after PSII treatment, the dominant wear mechanism of a Ti substrate was changed from the adhesion and ploughing mode to an abrasive–oxidative mode.

Ion beam enhanced deposition (IBED), a simultaneous process combining vapour deposition and ion beam bombardment, is a novel technique for achieving good adhesion of a film–substrate system and high controllability of the film quality [54,55]. The fretting wear behaviour of an IBED chromium nitride (CrN) film was investigated and the results were compared with those for PVD CrN films and a Ti–6Al–4V substrate [56]. Fig. 8 shows the fretting wear volume for these specimens. Both IBED and PVD CrN films decrease the fretting wear volume, but IBED films were superior to PVD CrN films with respect to long-term fretting wear resistance. The hard IBED CrN film with a better adhesion to the substrate can minimise ploughing and sub-surface deformation and hence increase the fretting wear resistance.

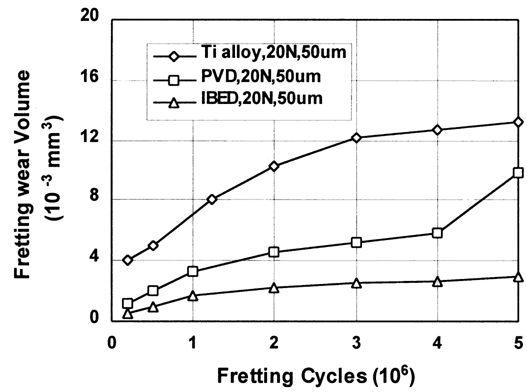


Fig. 8. The fretting wear volumes for an IBED CrN film (1 μm), PVD CrN film (1 μm) and Ti–6Al–4V substrate under the fretting conditions of 20 N and 50 μm [56].

CrN phase in IBED films can improve the anti-corrosive and anti-oxidation resistance of Ti alloy substrate during long-term fretting. Due to the effect of the ion beam bombardment, the hardening depth is much deeper than the film thickness, and the wear resistance will be relatively high even though the film is worn out. For PVD CrN film, if the film is worn out, the wear resistance will be decreased significantly. The concept of the dissipated energy [57,58] has been used to describe and compare the fretting wear resistance of IBED CrN and PVD CrN thin films, and Fig. 9 presenting fretting wear volumes as a function of the total dissipated energy. Although there is a linear relationship between the fretting wear volume and the cumulated dissipated energy for both IBED CrN and PVD CrN films, it appears that PVD films present an energy coefficient that is much higher than the value for the IBED CrN film, indicating the inferiority of the wear resistance of PVD CrN films.

2.3. Laser surface treatments

A localised intense source of heat, such as that of a laser beam, can provide a convenient means of depositing coating material or producing a surface layer of altered microstruc-

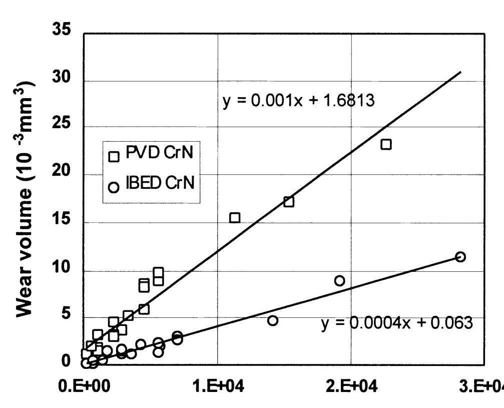


Fig. 9. Evolution of the measured wear volume on IBED CrN and PVD CrN films as a function of the cumulative friction energy [56].

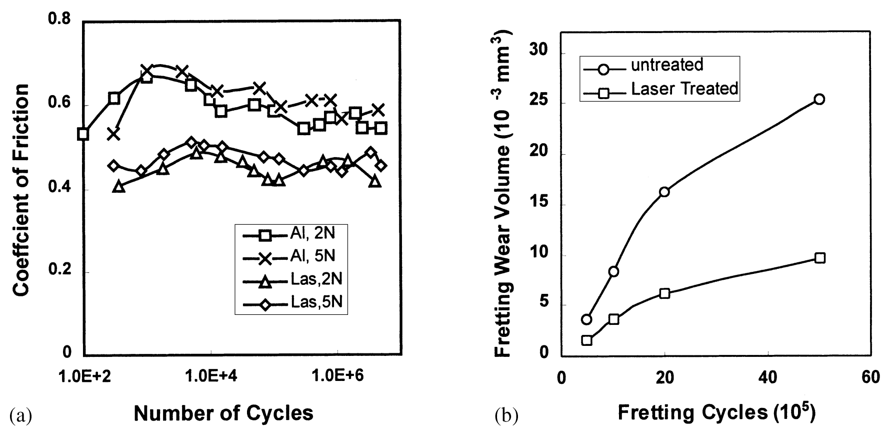


Fig. 10. Fretting wear of aluminum alloys and laser alloyed Al alloys under a slip amplitude of 100 μm [62]: (a) coefficient of friction under different normal loads; (b) fretting wear volume under a normal load of 5 N.

ture. The tribological uses for the laser in surface treatment and coatings include [59]: surface hardening, laser remelting, laser alloying and cladding. It was reported that both laser transformation hardening and laser surface alloying made the fretting wear resistance of 2Cr13 stainless steel increase by 1.81 and 4.48 times compared with the untreated material [60]. Laser alloying of zirconium and chromium films on steel substrates is also suitable to control fretting wear damage [61].

The application of laser alloying with Ni, Cr on the mitigation of the fretting wear of Al 6061 alloy has been reported [62]. Fig. 10(a) shows that after laser alloying, the coefficient of friction of Al alloy decreases. The relatively low coefficient of friction is probably due to the hardening effect of the laser alloyed coating, which can prevent adhesive and abrasive wear during fretting. The fretting wear of aluminium alloys can be reduced by a factor of 3 after laser alloying with Ni and Cr, as shown in Fig. 10(b). This can be attributed to the sharp increase in the surface microhardness of the laser treated coating and a fine microstructure, as well as a decrease in the coefficient of friction. The significant increase in hardness can improve the ability to resist abrasion, adhesion and plastic deformation during fretting. Laser alloying with Ni, Cr can also improve the oxidative and corrosive resistance of Al alloy. In situ observation of the fretting wear process by X-ray imaging has indicated that the wear process is a combination of adhesive, abrasive, oxidation and delamination wear [15]. Adhesive and abrasive wear were observed on the surface of a laser alloyed coating at the beginning of the fretting cycles, but during prolonged fretting, delamination and oxidation were the main wear mechanisms. Results also showed that the laser nitriding of pure titanium with Ni, Cr also improved the fretting wear resistance significantly [63].

So far, the application of laser treatment under fretting conditions is usually focused on fretting wear problems, i.e., under a relatively large fretting amplitude. The reasons may be that after laser treatment, there are often some surface cracks and other defects existing [64] and the surface layer often shows tensile stresses [60]. The rough and hardened surface after laser treatment may cause a concentration of stress and wear in small parts of the coating surface, which can lead to rapid failure during fretting fatigue. The possibility of improvement in fretting resistance depends almost entirely on the optimisation of the laser process parameters [65].

2.4. Thermal sprayed coatings

Thermal spraying covers a wide range of techniques in which coating materials are heated rapidly in a hot gaseous medium and simultaneously projected at high velocity onto a surface to produce a coating. Processes for thermal spraying can be mainly grouped into: arc and flame spraying, plasma spraying, detonation gun and high velocity oxy-fuel (HVOF) spraying [66]. The thermal sprayed metal coatings are conventionally used for the prevention of fretting damage because of the availability of certain oxides in the coatings that can prevent or delay adhesion between two oscillatory surfaces. The laminated structure of coatings also delays fatigue crack propagation from the fretting site [67].

Sprayed molybdenum coatings can increase the fretting fatigue strength of steel by 120% [68], and prevent material loss during fretting at room temperature and high temperature [69]. Molybdenum coatings exhibit good corrosion resistance, which is beneficial for fretting resistance. The favourable fretting characteristics of sprayed Mo coatings are also attributed to the formation of a thin layer of molybdenum oxide on the worn surface. These oxides, such as MoO_2 and MoO_3, appear to spread themselves across the surface acting as a lubricant, to prevent metal contact and retain a low coefficient of friction. Under higher temperature, the oxides become increasingly effective as lubricants on the fretting surfaces, thus decreasing the fretting wear rate and the coefficient of friction. The degree to which they are effective depends on their volume fraction and dispersion in the matrix as well as on the temperature of fretting.

Hard ceramic coatings deposited by spraying can provide high wear resistance but there is limited information on their application in fretting fatigue. Most of these type of coatings have been employed to inhibit fretting wear rather than to improve fretting fatigue strength [70]. Results have shown that a tungsten carbide (WC) coating deposited by the D gun process was beneficial for improving fretting wear resistance [71]. The limitations for the application of sprayed coatings in fretting conditions is probably due to defects in the coatings, such as high porosity, tiny cracks, a coarse lamellae structure and unmelted particles, as well as poor adhesion and cohesion. How to reduce these defects and improve the adhesion properties are important issues regarding the fretting performance of these coatings. Usually, some types of post-spray treatment methods, such as laser treatments, annealing, etc., are recommended [72].

Fretting damage is a severe problem for orthopaedic implants [73]. There are a few reports on the fretting mechanisms and behaviour of plasma sprayed hydroxyapatite (HA) coatings under both unlubricated and lubricated conditions [74,75]. In situ observation by X-ray imaging [16] and SEM observation has indicated that the fretting wear mechanisms of HA coatings under dry conditions were mainly delamination and abrasive wear. The fretting wear resistance of HA coatings was inferior to that of the Ti substrate because of the lamella structure and defects, such as pores, unmelted particles and micro-cracks, in the HA coating, thus particulate debris was generated easily. Under lubricated conditions, bovine albumin can provide effective lubrication during the fretting wear of HA coating, and the porous structure of the as-sprayed coating can retain lubricant, which is good for fretting wear resistance.

Minimising the amount of debris generated by the fretting of a plasma sprayed HA coating would optimise the long-term performance of a device. To solve this problem, hot isostatic pressing (HIP) treatment is used [76]. Fig. 11 shows

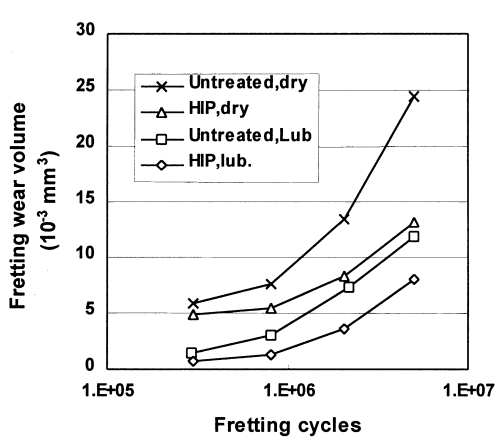


Fig. 11. Effect of hot isostatic pressing (HIP) treatment on the fretting wear behaviour of an HA coating under unlubricated and lubricated conditions under a normal load of 5 N and a slip amplitude of 100 μm [76].

the fretting wear volumes of an HA coating before and after HIP treatment under a normal load of 5 N and a slip amplitude of 100 μm. The wear resistance of the as-sprayed coating has been improved significantly after HIP treatment due to the densification of the microstructure and decrease of defects in the coating, which are helpful to improve the cohesive bond strength of the coatings [77]. The high temperature and high gas pressure during HIP treatment can cause interlamellar diffusion and increase the diffusion bond between the lamellae and between the substrate and coating, which can prevent the formation of fretting debris and improve the fretting wear resistance of HA coatings.

2.5. Duplex surface engineering

Shot-peening has long been considered as one of the best ways to suppress fretting damage [78,79]. The work hardening and roughening of the surface, as well as the generation of compressive stresses have significant effect on the improvement of both fretting wear and fatigue resistance. However, care often has to be taken in order to avoid too much surface damage which will cause the deterioration of fretting fatigue strength. An innovative approach in improving the fretting resistance is to design and develop systems incorporating multilayers and/or duplex treatments, e.g., by depositing of CrN films on a shot-peened Ti–6Al–4V substrate [80]. The fretting wear resistance for untreated Ti–6Al–4V shot-peened Ti–6Al–4V, IBED CrN, and shot-peening + IBED CrN under a normal load of 20 N and a slip amplitude of 50 μm has been studied, the results being shown in Fig. 12 [81]. It is revealed that the duplex treatment by depositing CrN films on a shot-peened surface provides the highest wear resistance and also excellent fretting fatigue resistance compared with the other treatments. This can be attributed to a combination of the benefits of both shot-peening and IBED CrN films. For example, a much harder surface after the deposition of CrN film on a shot-peened surface can improve the abrasive wear resistance, and a CrN phase can improve the anti-corrosive and anti-oxidative resistance of an as-peened specimen.

3. Discussion on mechanisms of surface coatings for the mitigation on fretting damage

From a literature survey, a legion of surface modification methods can be used to mitigate fretting damage. However, the mechanisms for this improvement are quite different. There are at least five different and even contradictory mechanisms for the increase in fretting resistance: (1) to induce a residual compressive stress; (2) to decrease the coefficient of friction; (3) to increase the surface hardness; (4) to alter the surface chemistry; and (5) to increase surface roughness. Table 1 lists the effects of some typical surface modification methods on the above five main mechanisms for the mitigation of fretting damage.

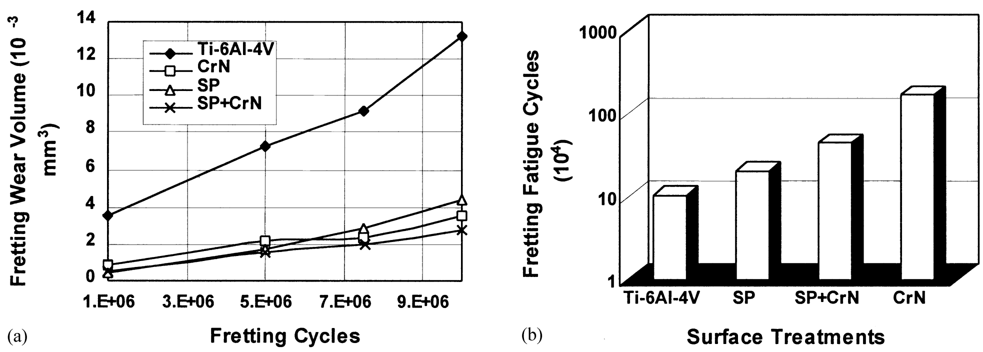


Fig. 12. Showing (a) the maximum fretting wear volume; and (b) the maximum fretting fatigue cycles; for untreated Ti–6Al–4V, shot-peened Ti–6Al–4V, IBED CrN, shot-peening + IBED CrN, under a normal load of 20 N and a slip amplitude of 50 μm [81].

3.1. Compressive residual stress

The induction of compressive residual stresses in the surface layer by surface modification methods is perhaps one of the most important mechanisms for the mitigation of fretting damage, especially for fretting fatigue [82]. The action of the compressive stress is to close-up fretting fatigue cracks at the surface and to prevent their propagation. In addition, the compressive stress will reduce the tensile stress component of the fretting action, which again will reduce the wear rate and the rate of crack propagation [83].

Certain types of surface treatments and coatings are effective in providing the surface with a high compressive residual stress, e.g., shot-peening, ion implantation, carburizing and nitriding, ion beam enhanced deposition, etc. Therefore, they are strongly recommended to be used for the improvement of fretting resistance, especially for fretting fatigue strength. Some types of surface modification methods, such as electroplating Cr and laser treatments, etc., are generally not recommended to be used under fretting fatigue conditions, since these treatments will often induce tensile residual stresses [84,85].

3.2. Coefficient of friction

A higher value of friction force causes higher shear stress (or high strain fatigue) on the surface and at the interface, which can intensify fatigue failures or generate delamination cracks. Therefore, in practice, much effort has been made to reduce the friction force. Some solid lubricated coatings, such as MoS_2, DLC, or CuNiIn coating [56], etc., belong to this category. These films or coatings can easily generate lubricating debris, which forms a third body between contacting surfaces and improves the 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.

3.3. Surface hardness

By using surface hardening treatment or hard coatings, 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

Table 1
Effects of surface modification technologies on fretting damage[a]

Surface modification methods	Decrease the coefficient of friction	Introduce compressive stress	Increase in hardness	Increase in surface roughness	Durability or adhesion	Economy	Mitigation of fretting wear	Mitigation of fretting fatigue
Carburizing	√	√	√	D	√√	√	√	√
Nitriding	√	√√	√√	D	√√	√	√	√
Electroplating (Cr, Ni, etc.)	D	××	√	D	×	√	√	××
Hard anodizing	D	×	√	D	√		√	××
Shot-peening	×	√	√	√√	–	√√	√√	√√
Plasma sprayed coating	D	D	D	√	××	√	D	D
Solid lubricated coatings	√√	D	D	×	D	×	√	√
Ion implantation	√	√√	√	D	√√	×××	√	√
IBED hard films	√	√	√	××	√	××	√√	√√
PVD and CVD hard coatings	√	D	√	×	D	×	√	D
Laser alloying or laser cladding	D	×	√	√	√√	√	√	D

[a] D: depending on conditions; ×: bad effect; √: good effect.

treatment and surface coatings listed in Table 1 are effective in increasing the surface hardness and may also help to mitigate fretting wear provided that they have good adhesion or bonding strength with the substrate. However, 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 stress and decreased toughness in the surface layer, all of which are detrimental to the fretting fatigue strength.

3.4. Altering the surface chemistry

The pivotal role of oxidation during fretting and the significant effect of oxide debris have been realised by many researchers. The altering of the surface chemistry by the formation of an oxide, nitride or carbide layer can help to improve fretting resistance by creating a lubricating effect. Otherwise, when there is no a layer of oxidised (or nitride or carbide) debris to separate the sliding bodies, plastic deformation and adhesion are the only means of accommodating the velocity difference between two counterfaces. For example, during ion implantation with carbon, the presence of a carbon overlayer modifies the usually encountered adhesion interaction between the substrate and the counterface and as a consequence also interacts on the break-in period of fretting wear. For another example, some thermally sprayed Cr, Ni or Mo coatings offer good resistance to fretting damage, and research has shown that the mechanical status of oxides of Cr, Ni and Mo under fretting conditions had a significant effect on fretting wear resistance [86]. The oxide films of Cr_2O_3 or MoO_2 can: (1) avoid metal–metal contact and adhesion; (2) decrease the friction coefficient; and (3) prevent fretting fatigue fracture. However, results also indicated that the formation of some hard oxides could accelerate fretting wear under certain fretting conditions.

3.5. Surface roughness

The effects of surface roughness on fretting resistance are very complicated and even contradictory. A high degree of surface finish accentuates fretting damage, and to minimise the fretting damage, roughening surfaces by different treatments are sometimes adopted, e.g., by shot-peening. A rough surface has a higher plasticity index than a smooth surface [87], so some plastic deformation will occur at the tips of the asperities. Work hardening is likely to prevent these deformed asperities from being completely flattened so that the sharper asperities on a rough surface are able to accumulate more of the tangential movement by elastic deformation. During fretting, a lot of hard oxide debris accumulates on the contact surface and can cause severe abrasion, but on a rough surface, there is a greater chance that wear debris will escape from the contact areas into the adjacent hollows or depressions, instead of ploughing the worn surfaces [88]. However, in some cases, the increase in surface roughness can result in an increase in the coefficient of friction, which is not beneficial for fretting fatigue resistance. A rough surface containing potential stress raisers is very dangerous, especially under fatigue conditions.

3.6. Explaining the effects of surface modification methods with fretting maps

Fretting maps (including running condition fretting maps (RCFMs) and materials response fretting maps (MRFMs)) are useful tools in the explanation and selection of different surface modification methods for fretting damage [89]. Surface treatments and coatings have various effects on RCMF (such as solid lubricant, hard thin films, etc.) or MRFM (an increase in fatigue strength, introducing compressive stresses). Schematic illustrations of several surface treatments or coatings on fretting maps are shown in Fig. 13.

1. The effect of decrease in coefficient of friction on fretting damage can be explained from the change in the fretting maps, as shown in Fig. 13(a). With a decrease in the coefficient of friction, the boundary between partial slip and gross slip will be shifted to a lower slip amplitude, thus reducing the possibility of the occurrence of fretting fatigue. Certain types of coatings (such as DLC) can favour gross slip and thus also diminish the partial slip regime (which is the most detrimental regime for fretting).
2. Some hard coatings quickly give rise to particle detachment, which prevents the partial slip regime by accommodating the displacement in the powder bed and favours debris formation in the slip region (see Fig. 13(b)).
3. The compressive stress can push up and reduce the cracking domain of the MRFM, as shown in Fig. 13(c). Higher resistance to crack nucleation (some types of superficial hardening treatment) can also be thought to push the cracking domain up towards a higher value of the normal load and a smaller value of slip amplitude.
4. The induced roughness can favour the stick domain of RCFM and debris formation in the gross slip domain, as shown in Fig. 13(d). However, it can enlarge the partial slip region, which may promote crack formation and propagation.

4. Coating selection method

Choosing the appropriate technology to solve a fretting wear problem is a challenge for the engineer [90] because: (1) there is still a lack of understanding of the mechanisms involved in determining the fretting behaviour of coated surfaces; and (2) for many newly developed coatings, the optimal application areas have not been identified. Some types of surface engineering methods are not good for fretting resistance and even detrimental to fretting fatigue

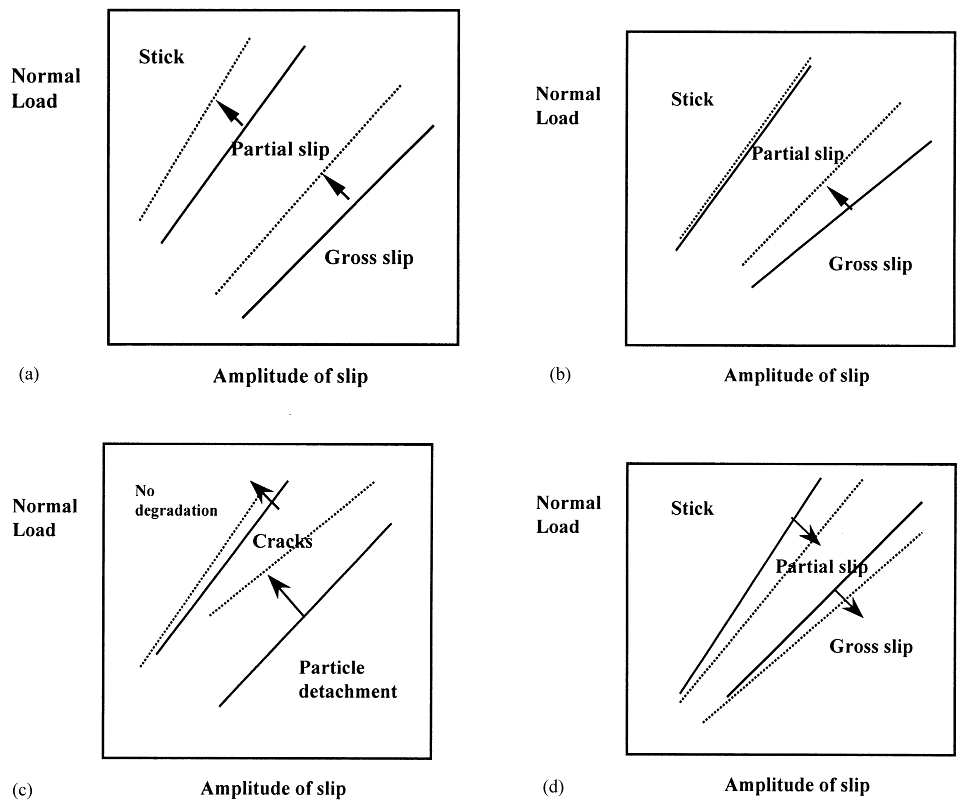


Fig. 13. Effect of surface modification technologies on the changes in fretting maps: (a) effect of decrease in the coefficient of friction; (b) effect of some hard coatings; (c) effect of increase in compressive stress; and (d) effect of increase in surface roughness.

strength. Therefore, it is very important to provide a coating selection method for the mitigation of fretting damage [91,92].

The selection of a surface coating or treatment should be guided primarily by the ability to adjust and obtain the required surface properties, with a balance between the precise control of the surface properties and the process cost. There are a large number of factors influencing coating materials or process selection, such as substrate materials, cost, size, deposition rate, geometry, process temperature, thickness and adhesion, etc. From the point of view of mitigating fretting damage, selection should be based on the effect that the palliatives have on the fatigue stress, the wear, the friction coefficient, the residual stress, the surface roughness, the durability and the cost, etc. The general procedures in the selection of surface modification methods in fretting can be listed as follows.

The first step is to decide what damage is to be avoided (i.e., sliding wear, fretting wear or fretting fatigue), thus guidelines can be obtained in order to look for the appropriate surface modification methods fitted to the specific contact problems. A very thorough analysis of the mechanical and material conditions at contact is necessary before any recommendation can be made. In this step, the service conditions (such as contact nature, normal load, vibration, frequency, design requirement, etc.), the working conditions (such as working environments, temperature, liquid, etc.) must be investigated, and the major failure modes identified (identifying the fretting problems, fretting wear or fretting fatigue, or both of them, since the effects of some surface modification methods on fretting wear and fretting fatigue are quite different). Running condition fretting maps (RCFMs) and material response fretting maps (MRFMs) are recommended to be obtained experimentally and used to identify the fretting modes, fretting wear or fretting fatigue.

The next step is to choose the appropriate coating methods. If one assumes that the life of a machine component is governed by the time for crack propagation, and that the initiation time is negligible, one should seek solutions amongst materials that are known for their good resistance to crack propagation, independent of the wear resistance of coatings, i.e., the coatings which can reduce the coefficient of friction significantly or introduce residual compressive stresses. It must be recalled that coatings introduce chemical composition changes (with or without gradients), changes in mechanical properties (strain hardening) and internal stresses, which can significantly affect the life of components. Table 2 lists the basic properties of some typical treatments and coatings [90]. According to Tables 1 and 2, suitable coating types can be roughly chosen (considering the substrate properties, such as yield strength, hardness, smoothness, thickness and hardness requirement for coating or treatments, etc.). Of course, it is also needed to consider the non-functional requirements (such as the dimensions

Table 2
Comparative characteristics of some of the main coating methods [90]

	PVD	PVD	CVD	PACVD	Ion implantation	Sol–gel	Electroplating	Laser	Thermal spray	Welding
Deposition rate (kg/h)	Up to 0.5	Up to 0.2	Up to 1	Up to 0.5		0.1–0.5	0.1–0.5	0.1–1	0.1–10	3.0–50
Component size	Limited by chamber size					Limited by solution bath		No limitation		
Substrate material	Wide choice	Wide choice	Limited by deposition temperature	Some restriction	Some restriction	Wide choice	Some restriction	Wide choice	Wide choice	Mostly steels
Pre-treatment	Mechanical/chemical plus ion implantation	Mechanical/chemical plus ion implantation	Mechanical/ chemical	Mechanical/chemical plus ion implantation	Chemical plus ion implantation	Grit blast and/or chemical clean	Chemical cleaning and etching	Mechanical and chemical cleaning		
Post-treatment	None	None	Substrate stress relief/mechanical properties	None	None	High temperature calcine	Thermal treatment	Substrate stress relief		None
Control of deposit thickness	Good	Good	Fair/good	Fair/good	Good	Fair/good	Fair/good	Fair/good	Manual (variable) automate (good)	Poor
Uniformity of the coating	Good	Good	Very good	Good	Line of sight	Fair/good	Fair/good	Fair	Variable	Variable
Bonding mechanism	Atomic	Atomic plus diffusion	Atomic	Atomic plus diffusion	Integral	Surface forces		Mechanical/chemical		Metallurgical
Distortion of the substrate	Low	Low	Can be high	Low/moderate	Low	Low	Low	Low/moderate	Low/moderate	Can be high

required to be coated, preferred coating colour and materials) and economic, procurement, fabrication cost, material costs, etc. Sometimes it is needed to consider if it is necessary to coat or treat both of the contacting surfaces. For example, for some coatings, such as phosphating and sulphuring treatments, MoS_2 and DLC amorphous coatings, one surface to be coated or treated is sufficient enough. However, in other cases, both surfaces are needed to be coated or treated, e.g., carburizing, nitriding, and hard-anodising (aluminium) treatments, etc.

Finally, quality control tests (basic physical, mechanical and fretting tests, such as thickness, adhesion, microhardness, chemistry, tribological tests, elastic modulus, yield strength, fracture toughness, etc.) are recommended in order to justify the effectiveness of the surface coatings.

5. Conclusions

This paper discussed the applications of surface modification methods in the mitigation of fretting damage. Some coatings are effective in the mitigation of fretting wear, whereas others are more effective under fretting fatigue conditions. The effects of surface modification methods on fretting resistance have been explained using fretting maps. There are at least five different mechanisms by using the surface modification methods to increase the fretting resistance: (1) to induce a residual compressive stress; (2) to decrease the coefficient of friction; (3) to increase the surface hardness; (4) to alter the surface chemistry; (5) to increase the surface roughness. Apart from this, instrinsic coating properties, such as density, mechanical and chemical properties as well as the adhesion conditions with the substrate, also significantly affect the performance of the coatings under fretting conditions. Based on this rationale, a coating selection method has been proposed for the selection of the most appropriate surface treatments or coatings to minimise the probability of fretting damage. Selection of a process is guided primarily by identification of the fretting failure modes, and the ability to adjust and obtain the required surface properties, with a balance between the precise control of the surface properties and the process cost.

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