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RESIDUAL STRESSES AND FRETTING, CRACK INITIATION AND PROPAGATION

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ABSTRACT

The effect of residual compressive stresses in the surface of a component on the resultant improvement in fatigue performance is well known. Fretting is a surface effect which causes local wear and is an efficient initiator of fatigue cracks. It also may cause a rise in surface temperature. The effect of residual stresses in cases of fretting is not so straightforward as in plain fatigue. Many of the usual methods of inducing compressive stresses in a surface also cause hardening, e.g. surface rolling, shot peening and nitriding. Increased surface hardness tends to reduce fretting wear. It is known, however, that in situations where the wear rate is high, the initiation of fatigue cracks by fretting is prevented. Some results are presented on the effect of shot-peening on the fretting wear of a carbon steel and an austenitic stainless steel. Experiments have been designed to separate the hardening effects and the compressive stress effects in the fretting fatigue of certain aluminium alloys and austenitic stainless steel. Surface roughening by shot-peening also has an effect on crack initiation in fretting fatigue of an aluminium alloy. Fading of compressive stresses under the influence of fretting is more rapid than in normal fatigue. Some results are given on the initiation and propagation of short fatigue cracks in a compressive stress field.

INTRODUCTION

Fretting is the term given to the small amplitude (typically ≃ 20 μm) oscillatory tangential relative motion occurring between contacting surfaces which are subjected to vibration or cyclic stressing, i.e. fatigue. Where the contacting surfaces are metallic, e.g. steel or aluminium, local welding may occur in the early stages of the process, resulting in plastic deformation such that it can be said that the material involved in intimate contact is subjected to a form of high strain fatigue. It is in this stage of the process that fatigue cracks may be initiated. Whether these propagate into the bulk of the material depends on the level of alternating stress in the test-piece or component as a whole. Roughening of the surfaces also occurs [1] and since local plastic deformation is taking place, energy is being consumed and there may be an increase in temperature, which different investigators have concluded may amount to anything between 20 and several hundred degrees [2-4]. Other investigators have found that the process also induces residual stresses in the surface, and it is likely that these also arise in this early stage [5,6]. Other changes which may occur are work-hardening, or work-softening particularly where the material is an age-hardened or heat-treated material, e.g. an aged aluminium alloy [7].

In the latter stages of the fretting process a wear mechanism takes over [8,9]. Debris is formed which consists mainly of the oxide of the metal concerned. It was originally suggested that the debris was formed by continuous scraping off and regrowing of oxide films [10], but this idea has been superseded by the delamination theory of wear [11,12], in which platelets of oxide coated metal are removed by a surface fatigue mechanism. Because of the small amplitude of movement the debris stays where it is formed and becomes further comminuted and oxidized by the fretting action. The specific wear rate in fretting is much lower than that experienced in unidirectional or large amplitude reciprocal motion, due to the protective nature of the oxide debris in preventing further metal-to-metal contact, and the lower cyclic stresses at small amplitudes [13]. In circumstances where there is a higher level of fretting wear, e.g. because of a higher amplitude of movement or the fretting of a hard abrasive non-metal against a metal surface, the initiation of propagating fatigue cracks is less likely [14]. This has been attributed again to the protective action of the debris and also to the removal of material containing crack nuclei so preventing their propagation [15].

The situation is very different in the fretting of non-metals, e.g. polymers and ceramics. Where a polymer is fretted against a metal metal oxide may be transferred to the polymer surface and wear of both surfaces is the result, but the initiation of fatigue cracks is unlikely [16,17]. Fretting of a ceramic against a metal can result in heavy wear of the metal surface but no initiation of fatigue cracks. Fretting of ceramic surfaces produces little wear and results in a polishing of the surface. Initiation of fatigue cracks is not generally observed [18], although glass seems to be an exception and fretting here can lead to failure [19].

As the subject of this review is confined to the effect of residual stresses and since these are frequently produced commercially by processes involving local plastic deformation, only metals will be considered.

The Effect of Residual Stresses on Fretting Fatigue

Before considering the processes of surface treatment depending on surface working and plastic deformation, some mention should be made of the process of nitriding which has been applied to steels to improve their performance in fatigue. The modern process is termed sulphidizing and a number of commercial processes are available. It involves treatment in a molten salt bath containing cyanates or thiocyanates. Nitrogen diffuses into the surface taking up interstitial sites in the ferrite lattice resulting in a surface compressive stress as high as 1155 MPa, becoming zero at a depth of 200 μm [20]. This treatment applied to a press fit hub on axle assembly, a situation in which fretting is commonly experienced, increased the fatigue strength from 77 MPa to 181 MPa [21]. The author compared various surface treatments applied to mild steel and found that the number of fretting cycles to initiate a propagating fatigue crack was five times greater for a sulphidized surface compared with an untreated one [22]. Besides inducing a compressive stress in the surface, nitirding also considerably changes the microstructure and hardness of the surface layer and these effects can also influence the fretting behaviour. However, it is thought that the compressive stress has the major effect and this aspect is discussed later.

Another group of methods for putting a surface in compression is based on local plastic deformation of the surface by surface rolling, roll peening and shot peening. Because of its versatility and ease of application to complicated shapes shot-peening is the most widely used method and wil be considered in detail. It should be said, however, that surface rolling does produce a finer quality surface finish and is very suitable for treating cylindrical components such as axles and shafts [23]. Fretting damage is often experienced at rivet holes and a method named ballising is often applied to counteract it. The process involves pressing a hardened steel ball of slightly greater diameter than the hole through the hole, causing local plastic deformation of the circumference of the hole and thereby producing a residual compressive stress with possibly some work-hardening.

Considerably more work has been carried out on the process of shot-peening and its beneficial effect in improving the fatigue life of components is well known. It has three main effects: (a) to work harden the surface, (b) to put the surface into compression, and (c) to roughen the surface. The first two effects are generally agreed as having the major effect in prolonging fatigue life, but a rough surface containing potential stress raisers is usually to be avoided. Figure 1 shows the effect on the S-N curves for an aged Al-4Cu-1Mg alloy (2014A). Shot peening raises the fatigue strength at 10^7 cycles from 105 MPA to 160 MPa. However, if the surface is then lightly polished to reduce the surface roughness, the fatigue strength is further increased to 185 MPa. This question of the initiation of cracks in a shot-peened surface has recently been investigated on notched specimens of the alloy Al-6Zn-2.5Mg-1.7Cu (7010). The surface of the semicircular notch was lightly polished to give a satisfactory surface from which replicas could be taken. Specimens were tested in four-point bending with a stress ratio of R = 0. Replicas were taken until the crack was well established when its progress was followed by the potential drop method. Some preliminary results are shown in Fig. 2, where it is seen that the crack is initiated much earlier in the peened surface but propagates at a much lower rate for a longer time so that the curve crosses that for the unpeened specimen. The reason for the earlier initiation of the crack in the peened surface is attributed to the higher hardness occasioned by work-hardening and resultant reduction in the fracture toughness of the surface material. This points to a warning against overpeening. If the surface is completely work-hardened there is a danger of the surface becoming a brittle material containing many flaws. The slow rate of propagation of the crack in Fig. 2 is entirely due to the residual compressive stress.

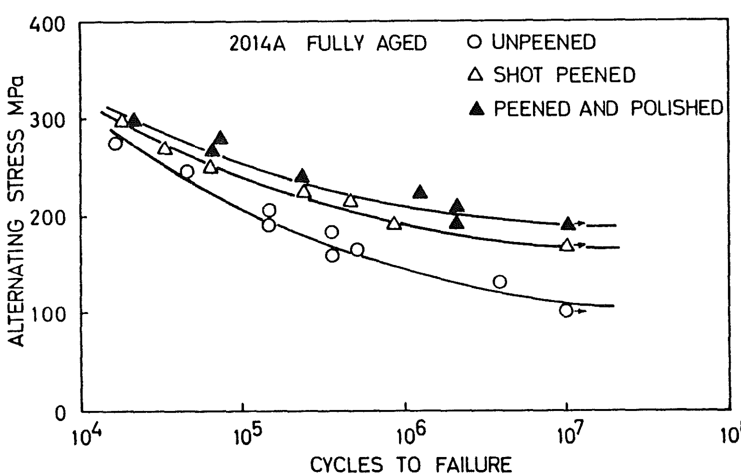

Fig. 1 S-N curves in plain fatigue for Al-4Cu-1Mg alloy in (a) unpeened, (b) shot-peened and (c) shot-peened and polished condition.

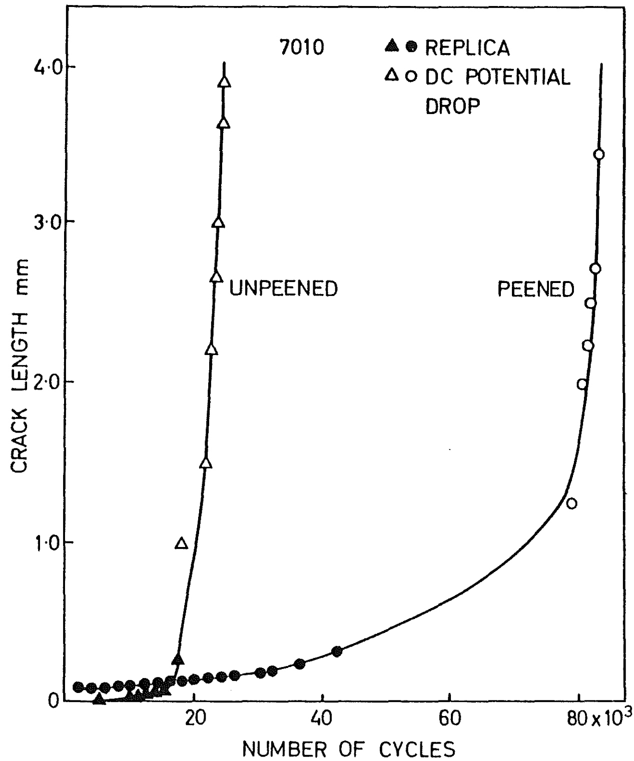

Fig. 2 Crack propagation curves for Al-6Zn-2.5Mg-1.7Cu alloy in unpeened and shot-peened condition.

In fretting fatigue the effects of shot-peening are again highly beneficial as can be seen in Fig. 3 where the fatigue strength is raised from 57 MPa to 153 MPa. In this case, however, polishing the surface produces a reduction in fatigue strength to 130 MPa. This effect has been noticed before, that a rough or grooved surface has a higher fretting fatigue strength than a smooth one [24]. The explanation is that (a) there may be some elastic deformation of the asperities and (b) by restricting the volume of material involved in any particular contact, the chances of initiating a fatigue crack are reduced.

Intensity of Shot Peening

Since some of the effects of shot-peening may actually encourage the initiation of fatigue cracks, although their propagation may be impeded, it is important to determine the minimum level of peening that will give optimum results. Figure 4 shows the effects of three levels of peening intensity on the fretting-fatigue curves for the Al-4Cu-1Mg alloy (2014A) [25]. The heaviest peening (Almen scale 8-10C) gives the lowest fatigue strength at 10^7 cycles of 88 MPa. However, at the high stress levels, i.e. about 210 MPa, the fatigue life is longer than for the two lower levels of peening. It is in this region of the S-N curve that fretting has least influence since its main effect is to initiate fatigue cracks and at these high stresses fatigue cracks would in any case be initiated in a relatively short time. This part of the curve is dominated by

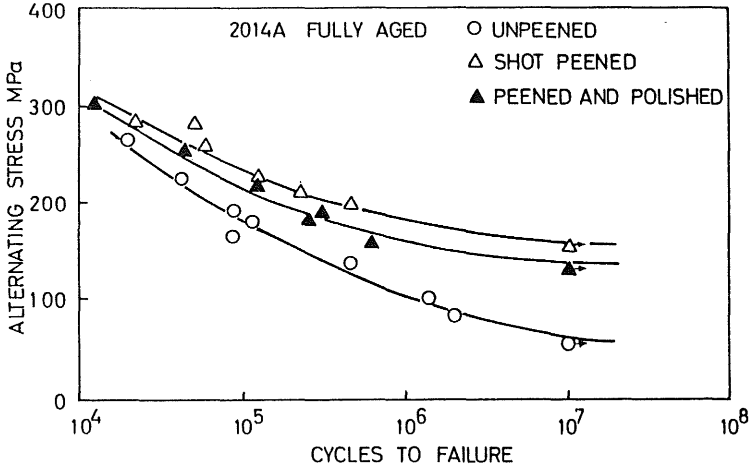

Fig. 3 S-N curves in fretting fatigue for Al-4Cu-1Mg alloy in (a) unpeened, (b) shot-peened and (c) shot-peened and polished condition.

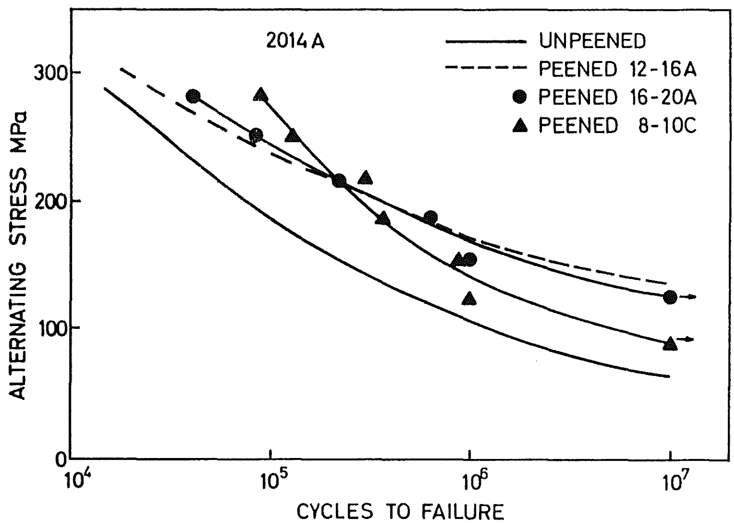

Fig. 4 S-N curves in fretting fatigue for Al-4Cu-1Mg alloy in (a) unpeened condition, and (b) shot-peened to Almen intensities 12-16A, 16-20A and 8-10C.

the propagation rate of the crack, and it is obvious that the heavy peening has retarded crack growth. The two lower levels of peening give very similar curves although the lightest peening (Almen scale 12-16A) gives a slightly better fretting-fatigue strength at 10^7 cycles. The stress distribution curves for these three levels of peening are shown in Fig. 5. The lightest peening gives a lower peak stress intensity but has a greater depth of penetration. From these results it is apparent that to improve low cycle fretting-fatigue life,

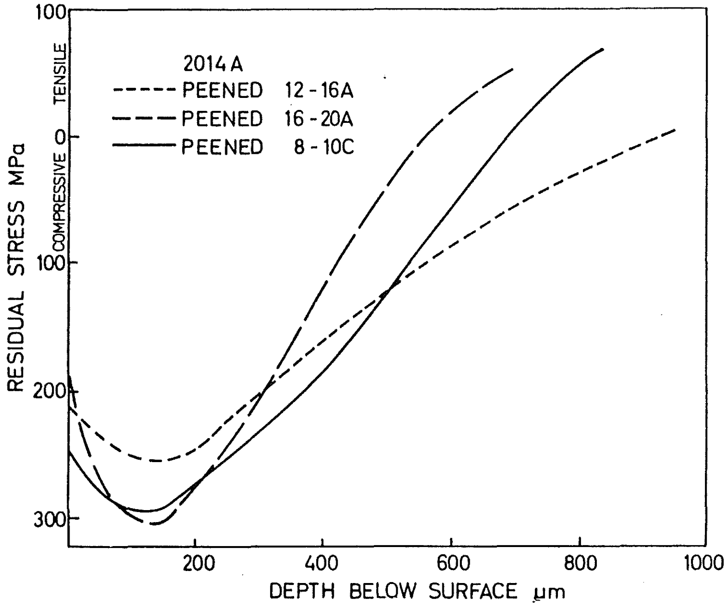

Fig. 5 Stress distribution curves for Al-4Cu-1Mg alloy shot-peened to Almen intensities 12-16A, 16-20A and 8-10C.

heavy shot-peening is recommended, but for high cycle fretting-fatigue, i.e. where fretting is most dangerous, lighter shot-peening is most beneficial..

The Contributions of Work-Hardening and Residual Compressive Stress in Shot Peening

The question arises as to the relative contributions of work-hardening and the residual compressive stress to the improvement in fretting fatigue behaviour. A method of removing or reducing the residual stress without seriously affecting the hardness of the surface has been to give specimens a permanent strain of 0.5 to 1.0 per cent. Figure 6 shows that this does not alter the surface hardness very much. The reason why the stretched surface shows a lower hardness is because the compressive stress in the unstretched specimens tends to reduce the size of the Vickers hardness indentations thereby give a higher apparent hardness. This method has been applied to the aluminium alloy Al-4Cu-1Mg (2014A) and an annealed austenitic stainless steel (En 58A). The results are shown in Figs. 7 and 8 [26]. With both materials the removal of the compressive stress has reduced the fatigue curve so that it is coincident with the fretting-fatigue curve for the unpeened material. The stainless steel was chosen because of its high work-hardening potential as can be seen in Fig. 6, but even this degree of hardening has not contributed to improving its resistance to crack initiation by fretting-fatigue. Shot-peening is very effective against fretting-fatigue in this austenitic stainless steel; the fatigue strength is raised to that of the unpeened material in plain fatigue [27].

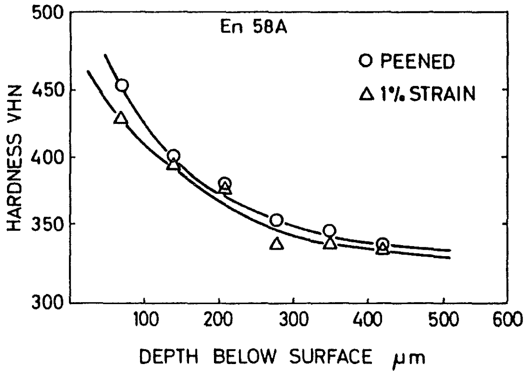

Fig. 6 Hardness vs depth for annealed 18Cr-8Ni austenitic stainless steel in (a) shot-peened and (b) shot-peened and stretched condition.

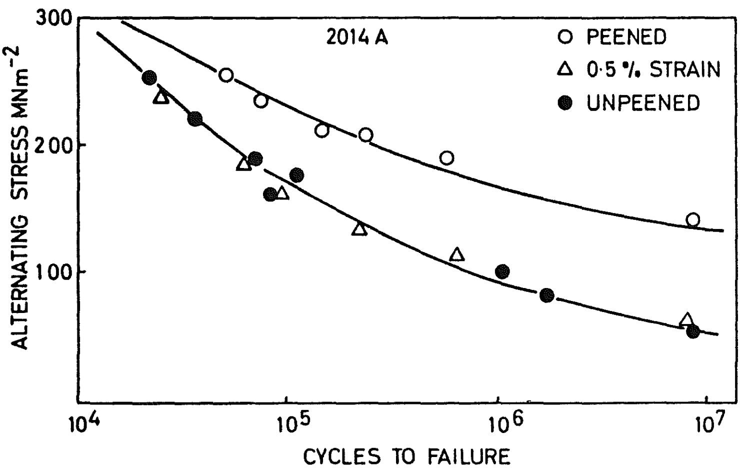

Fig. 7 S-N curves in fretting fatigue for Al-4Cu-1Mg alloy in (a) unpeened, (b) shot-peened and (c) shot-peened and stretched condition.

The Stability of Residual Compressive Stresses in Fretting-Fatigue

Residual stresses fade under the influence of fatigue, but in fretting-fatigue the effect is much more marked as shown in Fig. 9 [28]. This is due to the local plastic deformation occurring in the fretting contacts encouraging shake-down of the stress system. Thuis is not surprising since in the introduction it was stated that fretting can itself give rise to residual stresses and also result in local temperature rises. This reduction in the compressive stress could be the reason why the crack initiated by the fretting eventually is able to propagate into the material.

Methods to increase the stability of the residual stresses are being developed. One possibility in age-hardening alloys is to use a modified heat treatment combined with the peening operation. This has been applied to the aluminium alloy Al-4Cu-1Mg (2014A) by carrying out the shot-peening while the material is in the solution heat treated condition and then ageing. The results can be

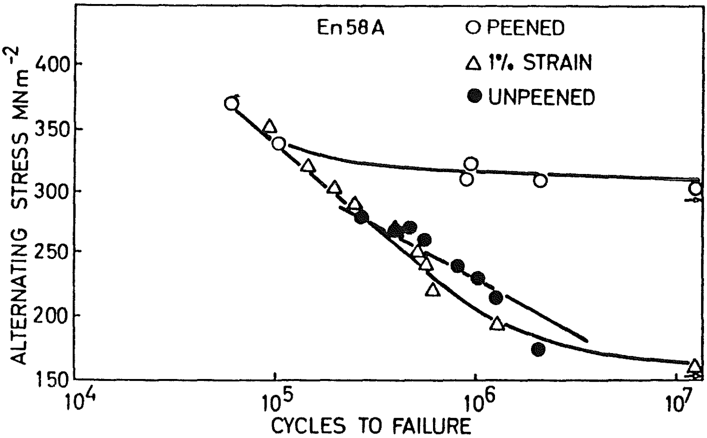

Fig. 8 S-N curves in fretting fatigue for annealed 18Cr-8Ni austenitic stainless steel in (a) unpeened, (b) shot-peened and (c) shot-peened and stretched condition.

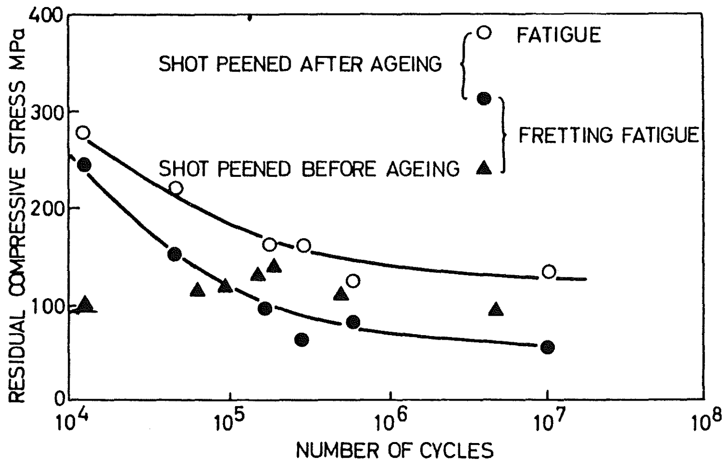

Fig. 9 Fading of residual compressive stress for Al-4Cu-1Mg alloy in fatigue and fretting fatigue when shot-peened (a) before and (b) after ageing.

seen in Fig. 10, where they are compared with the curves for the material when peened in the normal manner, i.e. after the ageing treatment. The results for plain fatigue and fretting-fatigue produced by the special heat treatment lie on the same curve (which is not drawn in to avoid confusion), i.e. the material is completely insensitive to fretting. The ageing treatment after peening does reduce the compressive residual stress in the surface as can be seen in Fig. 9, but on the other hand, the stress remains more or less constant with cycles of fretting-fatigue. The result is that the fatigue strength at 10^7 cycles is the same as the fretting-fatigue strength but less than the plain fatigue strength

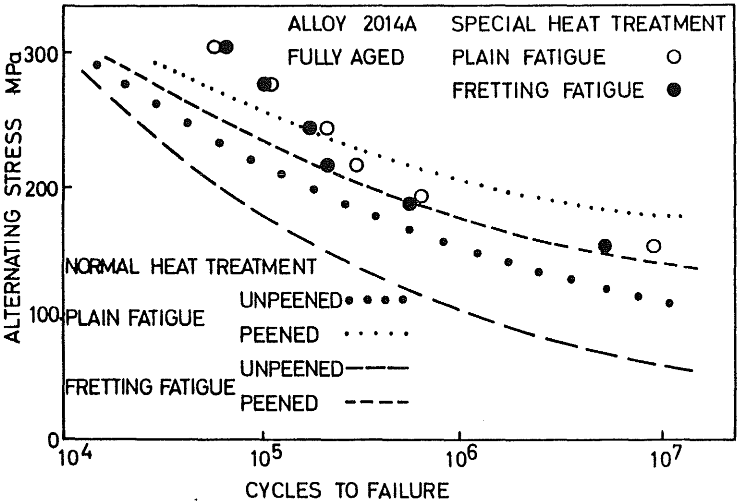

Fig. 10 S-N curves in plain fatigue and fretting fatigue Al-4Cu-1Mg alloy when shot-peened (a) before and (b) after ageing.

of the normally peened material. The interesting result is that the fatigue at high stresses, i.e. low cycle fatigue, is significantly increased. This is the area in which more rapid fading of the residual stress is to be expected. The explanation of the improved behaviour is that the increased dislocation density in the surface material caused by the peening results in a finer dispersion of the θ' transition phase. Also the alloy is softer in the solution heat treated condition so that the same level of peening will influence a greater depth of material. Other work has shown that in titanium alloys dislocation structure produced in the surface by shot-peening is as important as residual compressive stress in improving the fatigue strength. High dislocation density in the surface delayed the nucleation of fatigue cracks [29].

The Effect of Residual Stresses on fretting Wear

The sulphidized coatings mentioned in an earlier section are also applied to improve wear resistance of steels. However, recent tests by the author on an example of this type of coating produduced disappointing results. The specimens were 12.5 mm dia. cylinders 200 mm in length, and were loaded into an electromagnetic fretting rig in a crossed cylinder configuration. The applied load was 3N, the peak to peak amplitude 40 μm and the frequency 50 Hz. The fretting scars were cleaned ultrasonically and then surveyed with a Talysurf profilometer at 28 μm intervals. The areas below the original surface datum line were determined with a planimeter and hence the volume of material removed calculated. Both contacting surfaces were so surveyed and the total volume recorded as a function of the number of fretting cycles. The results are shown in Table 1. Each determination is the average of two individual determinations. The wear volume on the untreated steel gradually increases, whereas the sulphidized coating shows a high initial rate of wear but appearing to flatten off. The reason why this coating is so satisfactory in fretting fatigue is the high wear rate in the initial stages which is the period in which propagating fatigue cracks are initiated, as described above.

TABLE 1 Wear Volumes ($mm^3 \times 10^{-4}$) vs Number of Fretting Cycles

Material	Fretting cycles 10^4	10^5	10^6
En8	0.90	1.05	2.65
En8 sulphidized	5.78	8.65	8.49

The effect of shot peening on fretting wear is under investigation. Early results indicate that it can have significant effects [30]. The type of test was identical with that described above, 12.5 mm dia. cylinders in En8 and an austenitic stainless steel 316 were tested in the crossed cylinder configuration in the unpeened and peened condition. The coefficient of friction was monitored throughout the tests and the results are shown in Figs. 11 and 12. Each curve is the average of three determinations. With the carbon steel En8 the shot peening produced a reduction in the coefficient of friction in the early stages but eventually the two curves approach one another after about 10^5 cycles. This may be due to the unpeened specimens themselves becoming work-hardened in the fretting contact as a result of the fretting action. This has been observed previously on mild steel [31]. It might be thought that the increased roughness of the peened surfaces would have some contribution to the frictional behaviour by interlocking of asperities, but this appears not to be the case. Peening has less effect on the friction of the stainless steel, which is surprising since this material has a much greater work-hardening capacity than the mild steel. The wear volumes are shown in Fig. 13 where it can be seen that the stainless steel has a much higher wear rate than the mild steel in both the unpeened and peened conditions. The wear process on the peened specimens progresses by a wearing off of the peaks of the asperities so that the surface roughness gradually decreases as fretting proceeds. On the peened mild steel specimens the surface roughness decreases from 13.5 μm to 3.5 μm after 10^5 cycles. At this stage it is difficult to say what effect the residual compressive stresses are having on the wear rate, but work is in hand to separate the effects of surface roughness, hardness and residual stress as has been applied to cases of fretting fatigue.

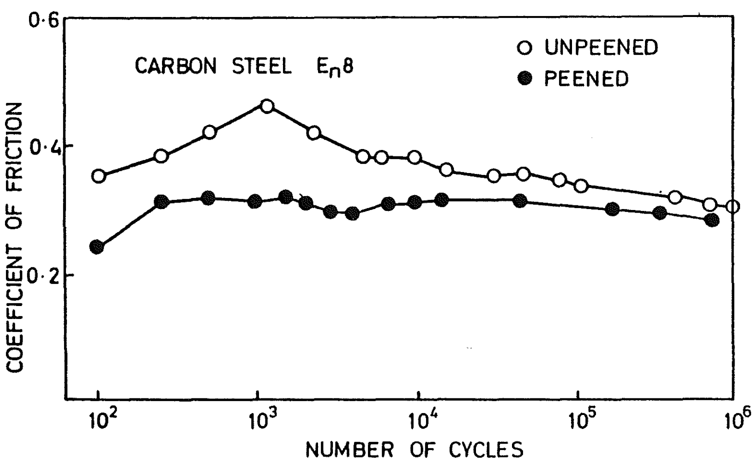

Fig. 11 Coefficient of friction vs number of cycles of fretting for 0.4C steel in the unpeened and shot-peened condition.

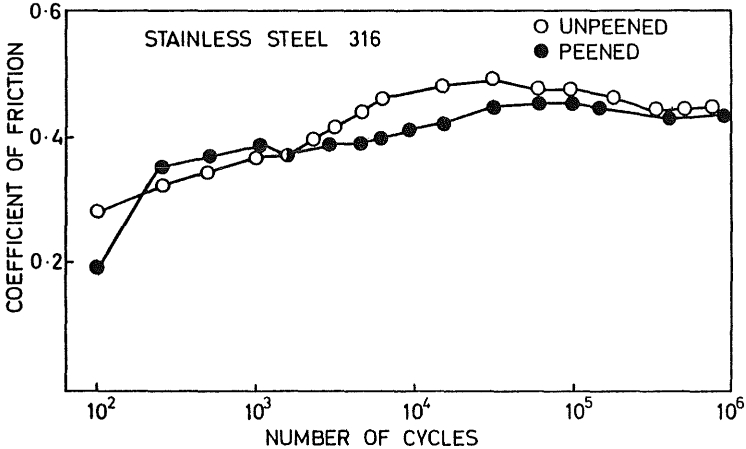

Fig. 12 Coefficient of friction vs number of cycles of fretting for annealed 18Cr-8Ni austenitic stainless steel in the unpeened and shot-peened condition.

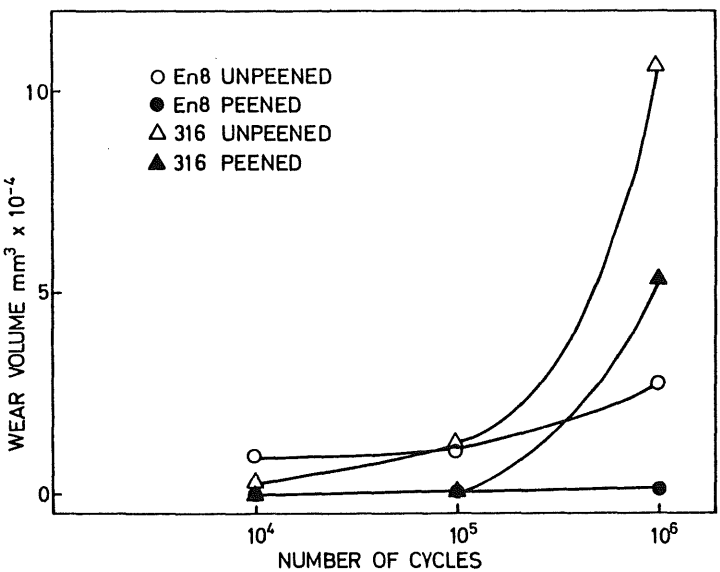

Fig. 13 Fretting wear volume vs number of cycles of fretting for 0.4C steel and annealed 18Cr-8Ni austenitic stainless steel in the unpeened and shot-peened condition.

Residual Stresses and other Surface treatments

One of the main methods of combatting fretting damage is the application of surface coatings. Many of these, e.g. electrodeposited and metal sprayed, themselves result in residual stress fields which in many cases are of a tensile nature and therefore deleterious, particularly where fatigue is concerned. Where the metal coating is applied as molten metal as in spraying and hot-dipping, a brittle intermetallic layer may be formed at the interface which aggravates the problem. It is a common practice, therefore to apply shot-peening to counteract the adverse effects of the coating process [32]. In addition the roughened peened surface provides excellent keying for the coating.

Some working processes result in surface residual stresses, e.g. wire drawing. Figure 14 shows the circumferential stress distribution in a drawn 0.7C steel wire 5 mm in diameter. This wire is used in the manufacture of steel ropes and hawsers for marine applications. The wire is galvanized by hot-dipping in molten zinc and this necessarily modifies the stress distribution, Figure 15. Fretting is a major problem in steel ropes because of the many inter-wire contacts but the zinc coating does provide excellent protection against fretting wear in sea water but the effect of the reduced residual compressive stress has yet to be evaluated in fretting-fatigue experiments [33].

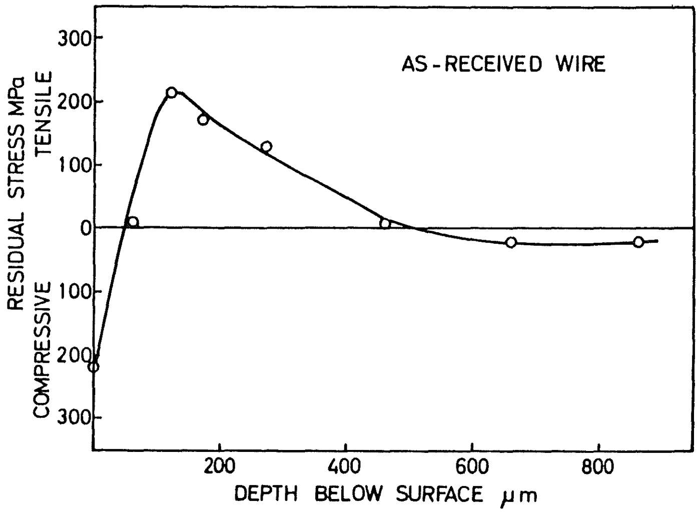

Fig. 14 Stress distribution curve for cold-drawn 0.64C steel wire 5 mm dia.

A surface treatment which induces compressive stresses in the surface is ion implantation. Although the depth of penetration is only of the order of 0.1 μm the improvement in wear behaviour is remarkable. Particularly effective is the implantation of steel surfaces with nitrogen [34]. The author has investigated the effect of ion implantation on the fretting wear of four titanium alloys [35]. At room temperature in some cases the wear rate was increased. The major effect in reducing wear was at temperatures between 400 and 600°C, but this was attributed to the influence on the oxidation behaviour rather than any effect of the residual stress.

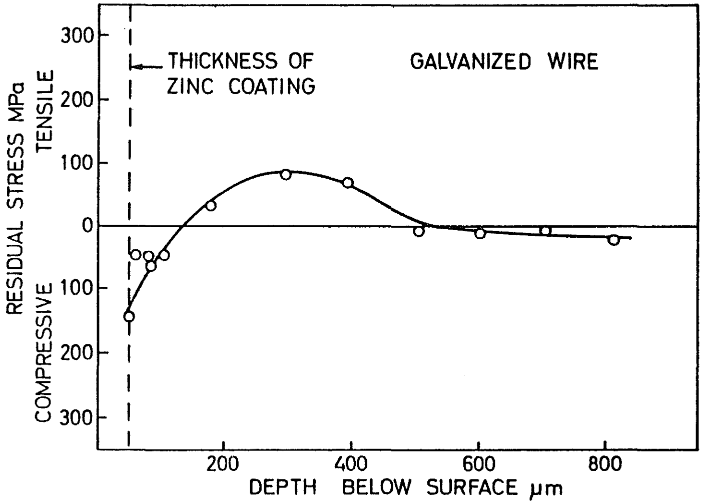

Fig. 15 Stress distribution curve for cold-drawn 0.64C steel wire 5 mm dia. after coating with zinc in molten zinc bath.

CONCLUSION

Fretting is a very severe form of surface disruption but its damaging effects can be counteracted by surface treatments which result in the surface being put in compression such as diffusion methods and cold working methods, particularly shot-peening. These treatments produce significant improvements in the fretting-fatigue and fretting-wear behaviour of metallic materials. Cracks are rapidly initiated by fatigue in a shot-peened surface but their propagation is impeded by the residual compressive stress. In fretting-fatigue the increase in hardness has little effect but the roughening of the surface has a beneficial effect. Fretting results in the rapid fading of the stresses but their stability can be improved in certain alloys by suitable heat treatment.

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