Chapter 15
Fretting Corrosion

15.1 Introduction

Fretting corrosion is primarily a surface damage phenomenon occurring as a result of small cyclic movements between two materials caused by cyclic loading. Fretting damage can occur in vacuum, although it then would be better to speak of fretting, rather than fretting corrosion. In normal air, corrosion plays an active role in causing fretting corrosion damage. The other contribution comes from rubbing between two material surfaces. Very small rubbing displacements are sufficient for initiating fretting corrosion damage. Such displacements easily occur in joints; bolted joints, riveted joints, clamped joints, leaf springs, etc. It also occurs inside a bolt hole between the bolt and the wall of the hole. Fretting is even possible between two metallic parts where load transmission does not occur.

Fretting corrosion is a practical problem because it can cause significant reductions of fatigue properties of structural elements. In the present chapter, the fretting corrosion mechanism is discussed in Section 15.2. Important variables on fretting corrosion are discussed in Section 15.3. Methods to avoid fretting corrosion are the subject of Section 15.4. Some practical aspects, which will return in Chapter 18 on joints. Major topics of the present chapter are summarized in Section 15.5.

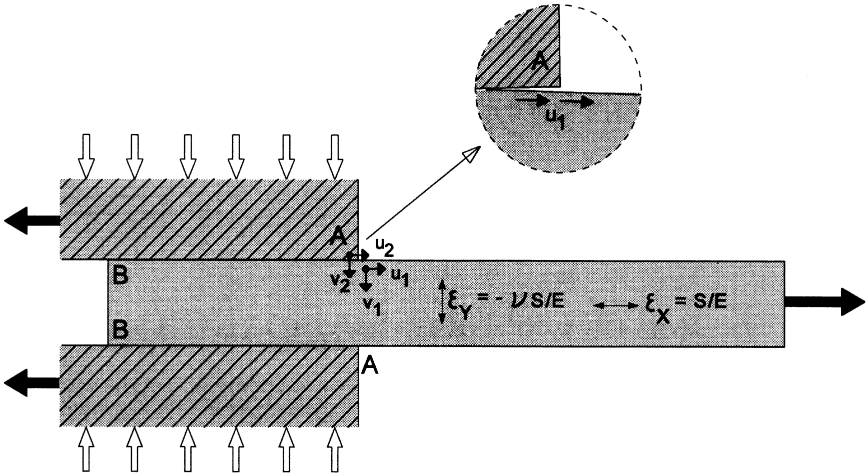
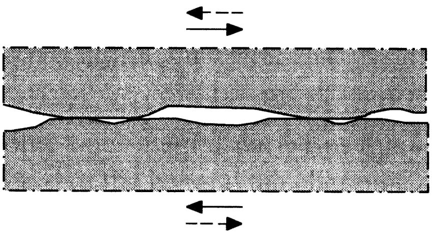


Fig. 15.1 A bar under tension slides out of the clamping area at section AA over a microscopically small distance, which is sufficient for fretting under cyclic load.

15.2 The fretting corrosion mechanism

Fretting can occur in a structure under cyclic load if a piece of material is clamped on an other piece. This will be explained by considering the simple case shown in Figure 15.1. A bar is clamped at one end and loaded in tension at the other end. Load transmission from the bar to the clamping occurs by frictional forces along the two mating surfaces AB. In the free part of the bar, a positive tensile strain occurs, $\varepsilon_x = S/E$, as well as a lateral Poisson contraction, $\varepsilon_y = -\nu S/E$ (ν = Poisson constant). Because of this contraction, the thickness of the free part of the bar including section AA is slightly reduced. Inside the clamping, the tensile stress in the bar (S_x) decreases to zero at the end BB. As a consequence, the lateral thickness constraint varies between A and B, full contraction at A and no contraction at B. The bar then will move slightly out of the clamping at section AA. It might be thought that clamping can prevent this movement. However, that would require equal displacements at point A: $v_2 = v_1$ and $u_2 = u_1$. It implies that the bar and the clamping device would then become an integral part with an extreme stress concentration at point A. However, this is illusory because a physical connection between the material of the bar and the clamping does not exist. Equal lateral displacements of the bar and the edge of the clamping cannot be maintained at point A. Material contact will be lost partly as sketched in the inset figure in Figure 15.1. Under cyclic loading, a cyclic change of the contact between the bar and the clamping occurs



(a) Local contacts (b) Crack initiation by shear

Fig. 15.2 Cyclic rubbing between two material surfaces.

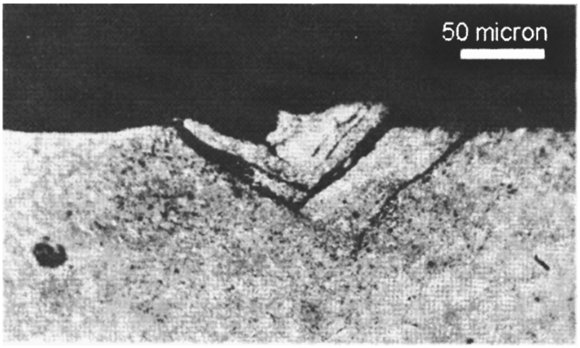


Fig. 15.3 Microcracking leading to loose fretting particles [1].

near point A, and this will cause cyclic slip between the mating surfaces. These slip displacements are very small but on a microscopic level they are substantial and large enough to cause fretting damage by rubbing between the two materials.

It should also be realized that the flat interfaces in the clamping area are not perfectly flat on a microscopic scale. Rubbing contacts are local contacts, see Figure 15.2a. It can lead to high shear stresses which can cause microcracks, see Figure 15.2b. As a results of such microcracks, small fragments of material can be torn out of the material surface, as shown by an example in Figure 15.3. Most technical alloys (ferritic steels, Ti-alloys, Al-alloys) are always covered by an oxide layer. Cracks in this brittle layer enhance the damage process, which in detail may be rather complex. Because of frictional heat development, local welding between the two surfaces is possible, which again is broken up in subsequent cycles. Oxidizing is promoting the damage process, one of the reasons why it is called fretting corrosion. The occurrence of fretting corrosion can result in a severely damaged material surface. A detrimental effect on fatigue should be expected, especially on crack nucleation, and thus on the crack initiation period in high-cycle fatigue and on the fatigue limit.

The above description of the damage process suggests a number of variables which can affect fretting corrosion:

(a) Clamping pressure between the two surfaces.
(b) Amplitude of the rubbing movements.
(c) Materials involved.
(d) Roughness of the rubbing surfaces.
(e) Corrosive contributions of the environments.
(f) Cyclic stress level.
(g) Variable-amplitude loading.

Investigations on the significance of these variables are reported in the literature. In general, fretting is studied by determining the effect on fatigue properties, in particularly the reduction of the fatigue limit and fatigue lives in the high-cycle fatigue regime. The complexity of fretting corrosion does not always allow to draw rigid conclusions, but trends have been recognized. These trends are summarized in the following section.

15.3 Effects on fretting corrosion

Experiments on fretting corrosion are often made by employing unnotched specimens on which one or two blocks are clamped. A test set-up used by Fenner and Field [2] is shown in Figure 15.4. Two pads, both with two small contact areas were clamped on flat surfaces of an aluminium alloy specimen. Under cyclic loading, the pads are causing fretting corrosion damage. The pads and specimens were made of the same Al-alloy (L65 $\approx$ 2014-T3). The clamping pressure was adjusted by two bolts mounted in a calibrated strain-gaged ring around the specimen. Fenner and Field carried out fatigue tests at an amplitude very close to the fatigue limit. Without pads, a very long endurance was obtained, $N = 8000$ kc, see Table 15.1. In another test with the pads on the specimen until failure, the life was most significantly reduced to $N = 100$ kc. Additional tests (see also Table 15.1) were done with the pads on the specimen for a small number of cycles. Removing the pads after 30 kc gave practically the same life reduction as leaving the pads on the specimen. Removing the pads after 12 kc still reduced the fatigue life from 8000 to 1300 kc. Apparently, a relatively small number of cycles under fretting conditions caused significant surface damage, which promoted crack initiation at a relatively early stage of the originally long fatigue life.

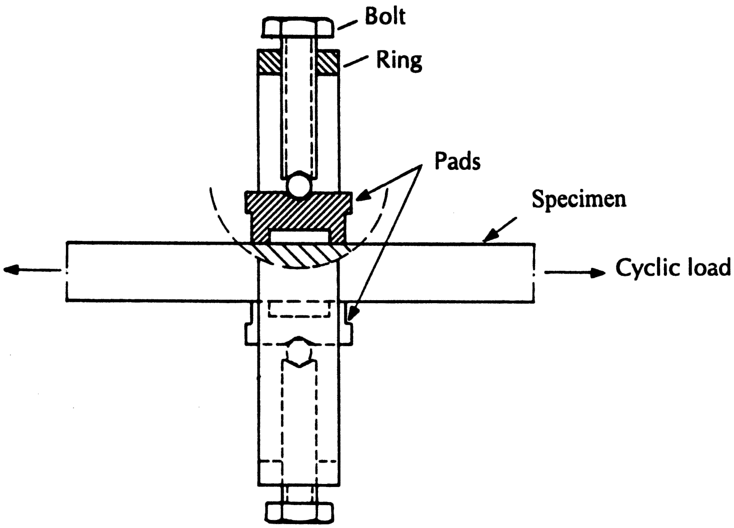


Fig. 15.4 Test set-up of Fenner and Field to study fretting corrosion [2].

Table 15.1 Results of fretting corrosion tests of Fenner and Field [2].

Fatigue tests on unnotched specimens of an Al-Cu alloy $S_m = 193$ MPa, $S_a = 134$ MPa, clamping pressure 4 MPa	Fatigue life (kc)
No pads	8000
Pads until failure	100
Pads removed after 12 kc (=12% of N with pads)	1300
Pads removed after 30 kc (=30% of N with pads)	110

A similar result was found by Endo and Goto [3] for a carbon steel (0.34C, $S_U = 549$ MPa). Obviously, fretting corrosion damage contributes to fatigue crack initiation, and it thus reduces the crack initiation period. Because fretting corrosion damage can occur at very low stress amplitudes, it also can significantly reduce the fatigue limit.

The significance of fretting for the crack growth period should be expected to be negligible because the crack is then growing away from the surface. Some effect might occur if frictional forces at the interface are changing the ΔK-value at the crack tip.

As discussed in Chapter 2, and also in Chapter 14 on surface treatments, surface effects have a large influence in the high-cycle fatigue regime, and a relatively small influence in the low-cycle fatigue regime, see Figure 2.23. This also applies to fretting corrosion as illustrated by S-N curves of a

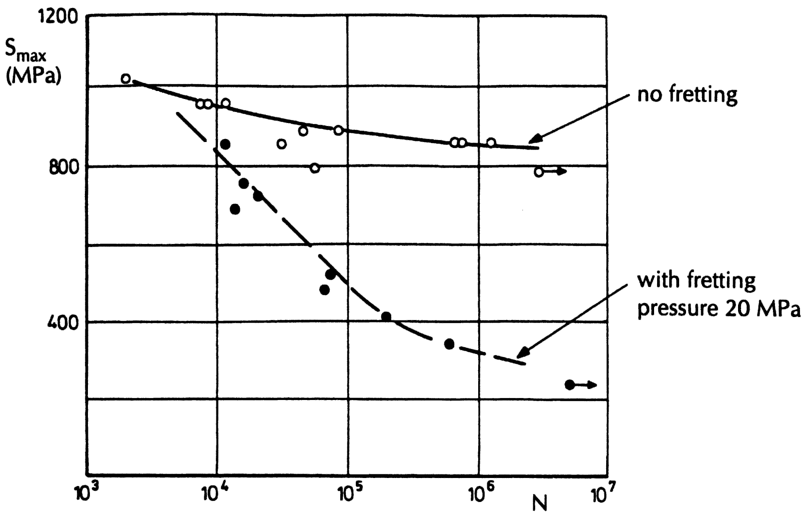


Fig. 15.5 Effect of fretting corrosion on the S-N curve of a Ti-alloy (Ti-6Al-4V) for $R = 0.1$. Results of Hoeppner and Gates [4].

Ti-alloy obtained by Hoeppner and Gates [4], see Figure 15.5. The fatigue limit is reduced by more than a factor of two, while the reduction in the low-cycle regime appears to be small.

Effect of clamping pressure

An increased clamping pressure between the two rubbing surfaces may increase fretting damage. This trend has been observed by visual inspection of surface damage. However, the question is whether it also increases the detrimental effect on fatigue properties. Literature information is not always consistent on the effect of clamping pressure. This might be expected when rubbing is associated with complex tribology aspects. It implies that wear resistance of the material, surface roughness and lubrication are involved. The presence of oxide particles produced by fretting is another complication.

Waterhouse [1] compiled the results shown in Figure 15.6. A fairly drastic reduction of the fatigue strength occurs at a low clamping pressure. Apparently, a small pressure is sufficient for a large effect. A further increase of the pressure does not add much more to a further reduction of the fatigue limit.

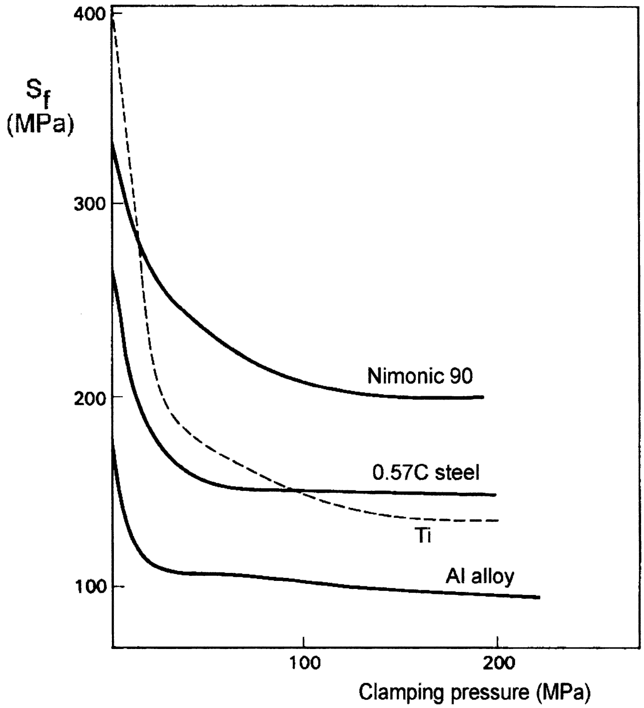


Fig. 15.6 The fatigue limit under fretting corrosion. Effect of the clamping pressure. Results compiled by Waterhouse [1].

Effect of the amplitude of the rubbing movements

Fenner and Field [2], using the test set-up of Figure 15.4, obtained different rubbing amplitudes by changing the distance between the two contact areas of the pads clamped on the specimen. They found indeed a systematically increasing effect for larger rubbing movements until about 8 μm. Still larger rubbing movements did not further decrease the fatigue limit of the Al-alloy. A systematic effect was also found by Funk [5] in fatigue tests on C-steel specimens. The results in Figure 15.7 show that a significant reduction of the fatigue limit was found again, which increased for larger rubbing movements. The difference between the results for 10 and 20 μm is relatively small.

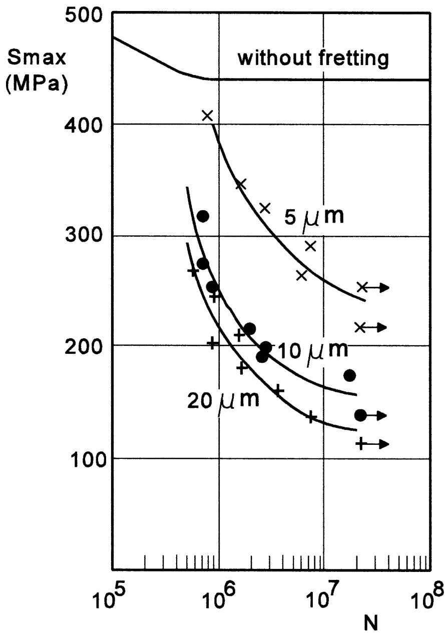


Fig. 15.7 Effect of the size of the rubbing movements on the fatigue curve of an 0.35% C-steel ($S_{min} = 0$). Pressure of fretting pad: 50 MPa. Results of Funk [5].

Fretting corrosion for different materials

The sensitivity for fretting corrosion depends on the type of material. Unfortunately, several high-strength materials used in engineering structures happen to be fretting sensitive. This is illustrated by results in Figure 15.8, based on data of [1], which shows reduction factors, i.e. ratios between the fatigue limit without fretting corrosion and the fatigue limit with fretting corrosion. The results should be considered as indicative; they were obtained in comparative fatigue tests series, each with their own specific test conditions, e.g. clamping pressure. However, some trends have a general meaning. Low ratios are in the order of 1.5, but for the high-strength alloys, reduction factors are in the order of 2 to 4. It is noteworthy that the high-strength low-alloy steels are more sensitive than the low-C steels. The high-strength steels can have a high fatigue limit provided that a high-quality surface is present. But, if damage is introduced by fretting corrosion, it implies a rough surface with micronotches or microcracks. In view of the high notch sensitivity of these materials, a large reduction of the fatigue limit can occur. Another observation is that the reduction factor for 0.7C-steel in the soft annealed condition is lower than in the hard cold drawn condition.

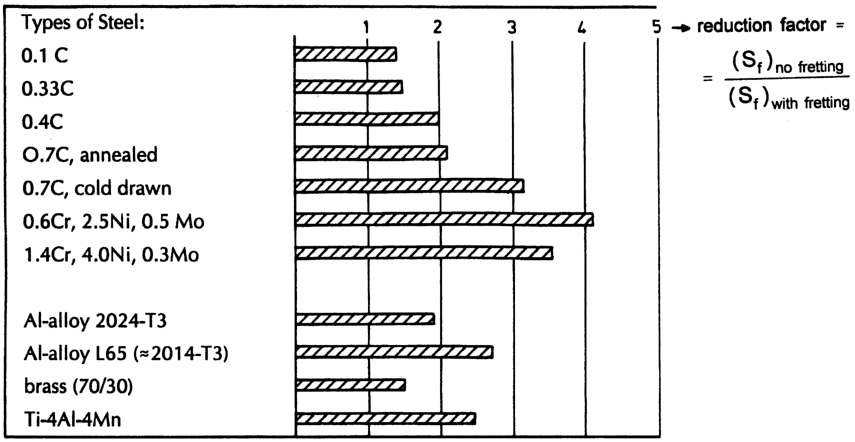


Fig. 15.8 Influence fretting corrosion on the fatigue limit of different materials [1] (specimens and pads of same material).

This difference may also be related to the lower notch sensitivity of soft materials. It does not imply that fretting damage is less in soft materials; it even may be worse and also different. However, softer materials are more tolerant against surface imperfections.

The results of Figure 15.8 apply to fretting corrosion between two surfaces of the same material. Fretting can also occur between dissimilar materials. In general, steel and an Al-alloy are an unfavorable combination. If a hard material is combined with a soft material, fretting corrosion damage of the hard material may be minute because of a superior wear resistance.

Roughness of the material surface

Fretting corrosion of polished surfaces can be more serious than for a rough material. In the latter case, contacts occur mainly at the highest points of the surface profile, which may be damaged and plastically deformed. Fretting particles can be collected in the grooves of the rough surface and thus contribute less to further fretting damage. However, fretting damage of a polished surface creates microcracks which can grow immediately. Actually, roughness effects on fretting corrosion have not been widely investigated.

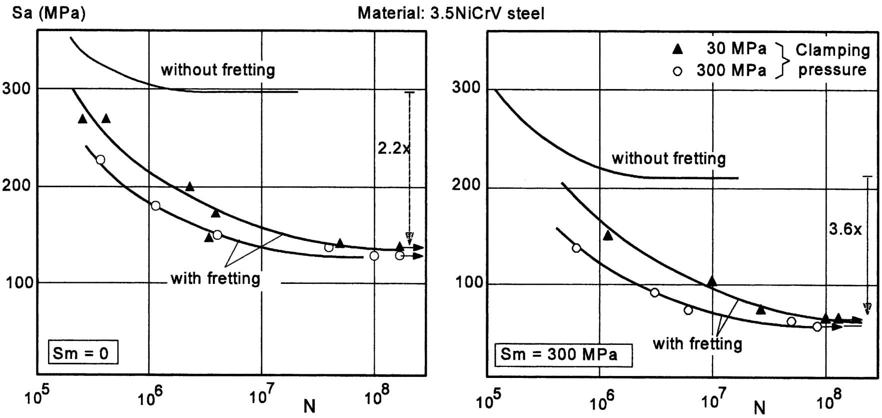


Fig. 15.9 Effect of mean stress on the reduction of the fatigue strength by fretting corrosion. Results of King and Lindley [6].

Contribution of environment on fretting corrosion

As explained earlier, fretting between two surfaces produces oxidized particles, which can enhance further damage of the surface. It then is surprising that fretting in a dry environment may be more severe than in a humid environment. It is possible that local welding between the two surfaces more easily occurs in a dry environment than in a humid environment. This could imply significant damage by tearing the welded asperities in subsequent cycles.

Investigations on fretting corrosion in very aggressive environments are scarce. However, it should be recalled that fatigue properties in such environments are minimal anyway.

Mean stress effect

Constant-amplitude loading is characterized by a stress amplitude (S_a) and a mean stress (S_m). As pointed out earlier, fretting corrosion can have a large detrimental effect on high-cycle fatigue and the fatigue limit, both associated with relatively low stress amplitudes. At high stress amplitudes fretting corrosion can also occur, but its effect on the fatigue life is limited because crack initiation at a high S_a occurs early in the fatigue life, also if fretting does not occur.

With respect to the effect of S_m, it should be recalled that the fatigue limit is a threshold stress level. It is the lowest stress amplitude, which may produce a microcrack that can grow until failure. Cycles with a slightly smaller amplitude cannot overcome barriers for microcrack nucleation or growth of a microcrack to failure. In this context, an increase of the mean stress for the same stress amplitude increases $S_{\max}$. This could assist in overcoming growth barriers for microcracks associated with fretting damage. Furthermore, microcracks are more open at higher $S_{\max}$ and can grow more easily. The mean stress effect was confirmed by results of King and Lindley [6] on specimens of a 3.5NiCrMo steel ($S_U = 733$ MPa), as illustrated by the S-N curves in Figure 15.9. The fatigue limit was reduced by a factor of 2.2 times at $S_m = 0$, whereas the reduction factor was 3.6 times at $S_m = 300$ MPa. Fenner and Field [2] for an Al-alloy (L65 $\approx$ 2014-T6) also found a significant mean stress effect on the reduction of the fatigue limit of specimens with fretting corrosion damage.

Fretting corrosion under VA loading

Research on the occurrence of fretting corrosion under VA loading is rarely reported in the literature. However, it must be expected that fretting damage can also be created by load cycles of a VA load history. A detrimental effect was indeed observed in some test programs with random loading carried out on specimens of cast iron and a low-carbon steel [7], and an aircraft aluminium alloy [8]. The fretting damage obtained by clamping pads on the specimens was again observed to occur early in the fatigue life. Although significant fatigue life reductions were found in the random load tests, the impression was that the detrimental effect is not as large as observed in similar tests under CA loading. Furthermore, shot peening [7] and anti-fretting lubrication compounds [8] were beneficial for the fatigue life under fretting corrosion conditions, but the improvement was less under random loading than under CA loading. However, improvements for practical cases in service can hardly be simulated in laboratory test program. Only some qualitative indications can be obtained.

15.4 Methods to avoid fretting corrosion problems

Two different ways can be followed to avoid fretting corrosion problems in structures. The first one is to prevent (or reduce) the occurrence of fretting, which is the more healthy approach (preventing the disease). The second is to accept the occurrence of fretting, but diminish its detrimental effect

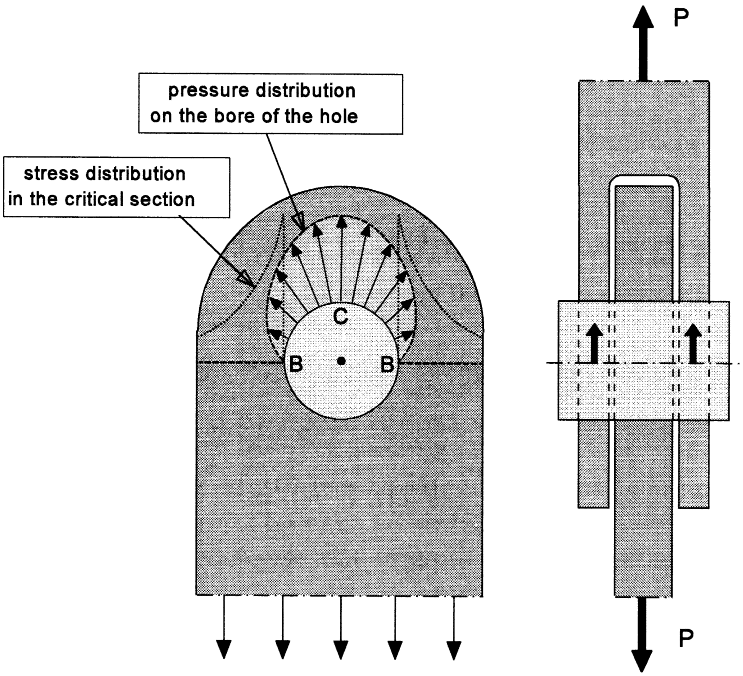


Fig. 15.10 Load transmission in a lug causing fretting corrosion inside the hole.

(controlling symptoms of the disease). It is not always possible to adopt the first method due to practical design restraints of a structure. Illustrative experience is presented below. Some examples are associated with fatigue of lugs because lugs are noteworthy fatigue sensitive structural elements due to fretting corrosion. This will be discussed first.

A lug joint is shown in Figure 15.10. The load in the lug is transmitted by a pin (or a bolt) to a clevis. The load of the pin is applying a pressure distribution on the hole in the lug. The material of the lug between points B and C along the periphery of the hole is carrying a tangential tensile stress, and it thus will be extended. This implies that the material must slide over the pin. As a result, cyclic rubbing between the inside surface of the hole and the outside surface of the pin occurs under fatigue loading. The rubbing displacement is zero at the upper point C for reasons of symmetry, and it increases towards points B. Fretting corrosion damage can occur inside the hole. Although the contact pressure between pin and hole is low at B, the peak value of the stress concentration occurs at this point. Furthermore, the rubbing movements are relatively large near the same point. Indeed, fatigue cracks nucleated at point B or in the neighborhood of this point starting from

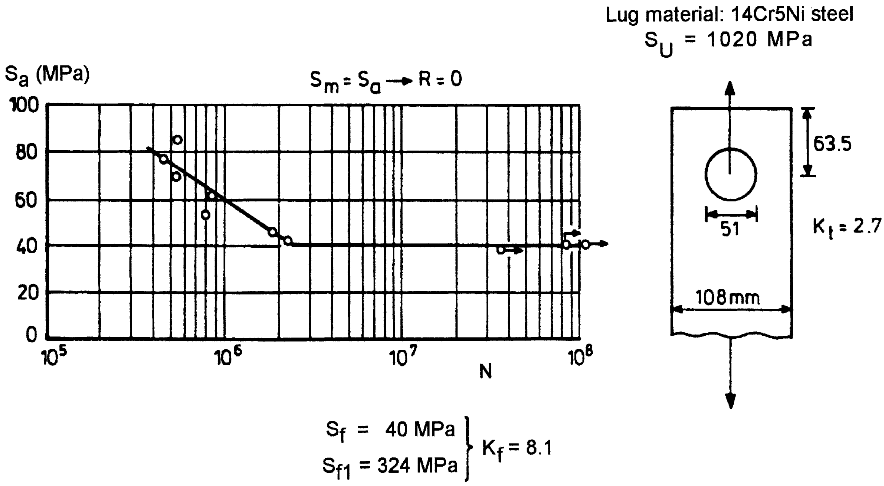


Fig. 15.11 A reduction of the fatigue limit of a lug specimen much larger than predicted by the stress concentration factor. Results of White [9].

fretting corrosion damage. As a result of fretting, the fatigue limit of lugs is exceptionally low. This is well known in the aircraft industry for Al-alloys, but it similarly applies to lugs of steel as illustrated by results of White in Figure 15.11 [9]. The fatigue limit of the lug is 40 MPa. The corresponding fatigue limit at $R = 0$ for the unnotched material is 324 MPa. It implies a notch reduction factor $K_f = 324/40 = 8.1$, which considerably exceeds the stress concentration factor $K_t = 2.7$. The very low-fatigue limit is associated with fretting corrosion inside the hole of the lug. Visual observations in lug holes clearly indicate fretting corrosion debris.

Prevention of metallic contact

The best way to avoid fretting between two rubbing surfaces is to prevent metallic contact between the two surfaces. An unusual way to avoid fretting in a lug hole, based on this principle, is offered by a so-called slotted hole shown in Figure 15.12. A thin layer of the hole edge (0.5 mm) is removed at both sides of the hole by contour milling with a cutter with a small diameter. Metallic contact between the pin and the hole edge is no longer possible between F1 and F2. The net section is slightly reduced by these slots, which gives a small increase of the peak stress at B. However, fretting at B can no longer occur, and the large reduction of the fatigue limit by fretting is eliminated. The fatigue curve of a lug with a slotted hole is compared to

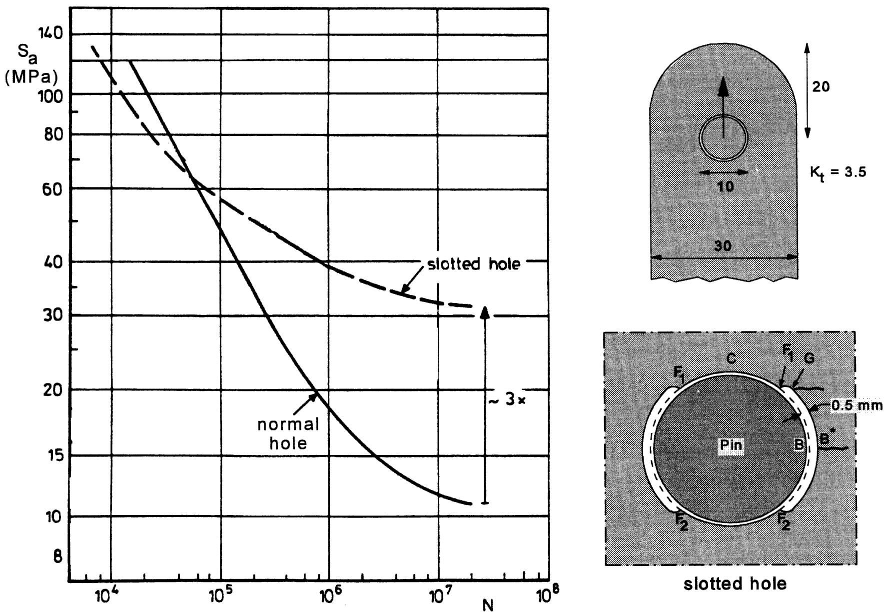


Fig. 15.12 Fretting corrosion effect on the S-N curve of a lug (2024-T3) with a slotted hole to avoid metallic contact between the pin and the edge of the hole.

the S-N curve of a normal lug in Figure 15.12. The curves confirm that an increase of the fatigue limit with a factor of three has been achieved. Fatigue cracks occurred at point B* for high endurances and at point G for low endurances. In both cases the location of a high tangential stress is free from fretting corrosion damage. As a result, a significant increase of the fatigue limit is obtained as shown by the S-N curves in Figure 15.12. Limited fretting corrosion is still possible at point F1, but at this point the tangential stress is zero.

Figure 15.12 also shows that the lug with the slotted hole is slightly inferior at high stress amplitudes where fretting corrosion is less important for fatigue crack initiation. The small reduction of the net section of the lug with a slotted hole then gives a slight increase of the nominal stress level.

A similar example of separation of locations of a maximum peak stress and the location of severe fretting corrosion is a historical one of the 19th century. August Wöhler did his classical research on fatigue failures in railway axles. Wheels were shrink fitted on these axles by a differential heating technique. A very strong joint was obtained, but it was a poor design against fatigue, see Figure 15.13. An extremely high stress concentration occurs in the axle at P, and at the same point fretting corrosion cannot be

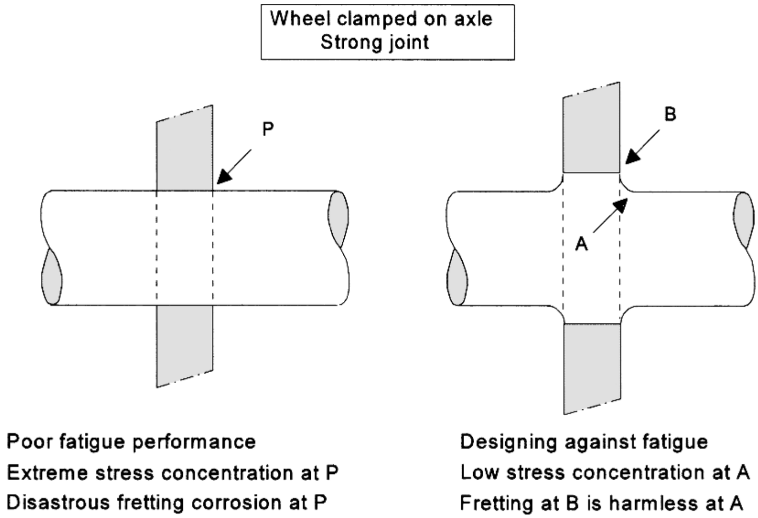


Fig. 15.13 An old improvement of a clamped joint by simple engineering means (Wöhler).

avoided. Fretting corrosion products (iron oxides and hydrates) came out of the joint as a dark-red colored powder, which was labeled as "das Bluten des Eisens" (the bleeding of iron). In the right part of Figure 15.13, the stress concentration is effectively reduced by a shoulder with a generous radius. Moreover, fretting corrosion at the interface between the wheel and the axle now occurs at a location outside the stress concentration area, point B. It was a clever engineering solution, while in the 19th century stress concentration factors and also fundamental knowledge about fretting corrosion were not yet developed.

In Chapter 13 on experiments, it was discussed that a fatigue failure of a specimen can occur at the clamped zone due to fretting corrosion. It was said that these failures could be prevented by inserting a layer of durable paper between the specimen and clamping plates. This is also an example of preventing metallic contact.

Fretting corrosion induced fatigue cracks may also occur if load transmission is not involved. A most simple example is shown in Figure 15.14. A non-loaded angle piece is attached to a cyclically loaded plate. Because the plate is subjected to cyclic strain, rubbing displacements between the plate and the angle piece occur and fretting damage around the bolt hole can initiate fatigue cracks. A simple solution is a thin non-metallic layer between the plate and the angle piece. Adhesive bonding provides a very good layer for preventing metallic contacts. It is one of the major

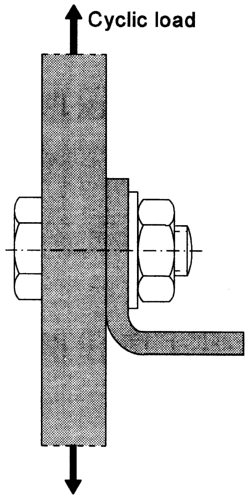


Fig. 15.14 Attachment of angle piece to plate. No load transmission, still fretting.

reasons why adhesive-bonded joints can have significantly better fatigue properties than riveted joints, see Chapter 18.

Alleviation of fretting damage

It is customary to provide lug ends of dynamically loaded connection rods with bushes, see Figure 15.15. Load transmission of the pin to the lug occurs through the bushing. The bushing is pushed with an interference fit into the hole of the lug. As a consequence, residual stresses are introduced. A clamping pressure between the lug and the bushing is present, which can be high enough to prevent rubbing between the bushing and lug. Secondly, residual compressive stresses are introduced in the bushing in the tangential direction. This will be favorable if fretting corrosion occurs between the pin and bushing. Fretting at this interface is also reduced by selecting a wear resistant material for the bushing, e.g. a hard steel or bronze. Furthermore, fretting is reduced by lubrication. Special lubricants have been developed for this purpose, but improvements are uncertain if the lubricant is not periodically replenished.

Fretting can also be controlled by surface treatments. Nitriding and other surface heat treatments reduce the occurrence of fretting damage as well as subsequent microcrack growth, see Chapter 14. Such treatments are often used for gears where sliding contacts between the teeth of the gears may

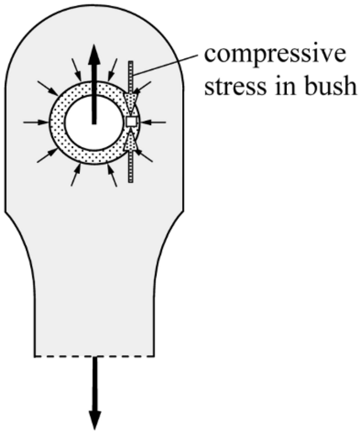
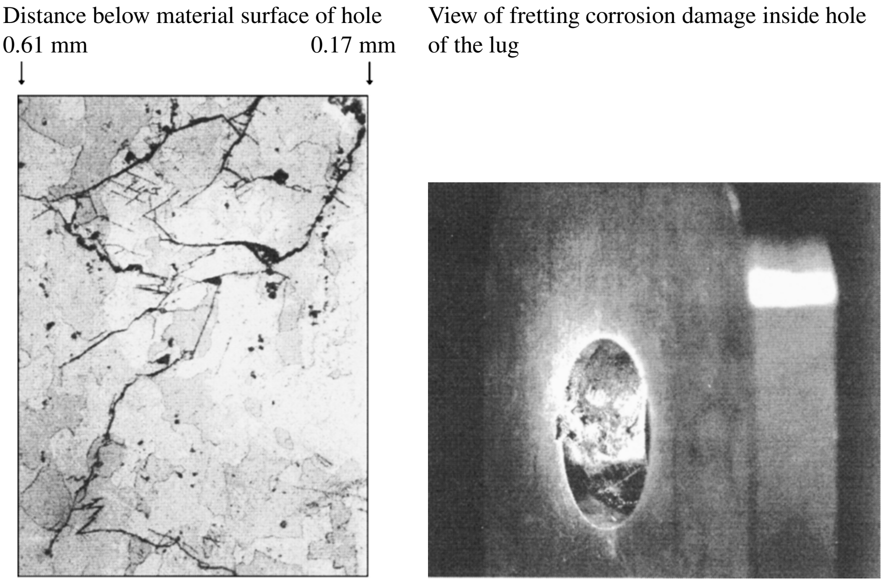


Fig. 15.15 Severe clamping between the lug and the bush due to an interference fit. As a result, there is compressive stress in the bush.

cause surface damage and fatigue. The motivation is to improve the surface wear resistance.

Shot peening is another way to combat crack growth from fretting induced surface damage. A most effective way to be applied to holes is plastic hole expansion as discussed in Chapter 4, see Figure 4.7. Commercially apparatus is available for this purpose. Residual compressive stresses around a hole can be as high as the compressive yield stress. The fatigue limit of a high-strength Al-alloy (7075-T6) loaded at a mean stress of 123 MPa was raised from 12 MPa (very low-fatigue limit) to 80 MPa (increased 6.7 times). The residual stresses did not prevent fretting between the steel bolt and lug hole. Actually, terrible fretting damage occurred, see Figure 15.16b because of the relatively high S_a and the large number of cycles. However, cracks could not grow through the zone of large compressive residual stress as shown by a microscopic section made afterwards, see Figure 15.16a. Residual stresses do not affect cyclic shear stresses. These shear stresses still caused some microcrack growth along slip bands. However, due to the compressive residual stresses, crack growth occurred in rather erratic directions. In general, fatigue cracks grow perpendicular to the main principle stress (Chapter 2) provided that this stress is a tensile stress which can open the crack tip. In this lug with a plastically expanded hole, a tensile stress did not occur at the edge of the hole and the high compressive residual stresses kept the cracks closed. As a result, strange crack growth directions were followed (Figure 15.16a).



(a) Microscopic cross section of erratic crack growth due to compressive residual stress. Width of picture 0.44 mm

(b) Lug with plastically expanded hole after 66×10^6 cycles at $S_a = 78$ MPa ($S_m = 123$ MPa). Severe fretting inside hole (diameter 10 mm)

Fig. 15.16 Severe fretting corrosion damage in hole of lug after extensive fatigue loading without failure [10].

15.5 Topics of the present chapter

1. Fretting corrosion under cyclic load cannot be avoided if metallic materials are in contact at mating surfaces. Very small rubbing displacements will occur and produce surface damage. The fatigue strength in the high-cycle fatigue region is reduced by this surface damage. Considerable reductions of the fatigue limit are common, especially for high-strength materials, due to the high notch sensitivity of these materials.
2. The fretting corrosion mechanism is affected by several variables, such as pressure on the interface surface, the amplitude of rubbing movements, the materials, surface roughness, environment, and the cyclic stress level. Although some systematic trends of the influence of these variables are recognized and partly understood in a qualitative way, the fretting corrosion mechanism is a complex phenomenon to describe in physical detail.

3. Methods to avoid detrimental effects of fretting corrosion fatigue in structures, and particularly in joints, are based on two principles: (i) Avoid metallic contact by structural detail design, or non-metallic interlayers, and (ii) surface treatments to improve surface wear resistance or introduce compressive residual stresses.

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