The Journal of Shimonoseki University of Fisheries 38(2・3) 71—131 (1990)

Fretting and Fatigue of a Roping Steel in Seawater*

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Numerous inter-wire contacts in steel ropes are sites for fretting. High tensile roping steel wires (UTS 1770 MPa grade) were tested in fluctuating tension in air and seawater with a fretting device consisting of a pair of bridges constructed from the same wire clamped onto the specimen. The relative effects of fretting and corrosion on the fatigue behaviour were investigated. The effectiveness of cathodic protection and galvanising in alleviating the fatigue damage was assessed.

Fretting fatigue in seawater had a serious damaging effect on the steel wire, reducing the fatigue life at stresses well below the fatigue limit in air. In seawater fretting fatigue was much more damaging than corrosion fatigue. Fretting enhanced crack growth rates in the initial stages in both the environments. In seawater the initial crack growth rate was greater than that in air. Chemical and electrochemical effects played a major role in the fretting fatigue failure in seawater.

Cathodic protection at optimum potentials had a dramatic effect in restoring the fatigue strength. The application of cathodic protection retarded the initial crack growth rate. However, if the crack grew beyond a certain depth, which was found to be 30 μm, the effectiveness of cathodic protection was considerably reduced.

A galvanised coating significantly improved the fatigue strength in seawater by suppressing the electrochemical attack. When the ungalvanised wire was is contact with galvanised wire bridges the sacrificial protection was the same as if the wire were galvanised. However, in air the coating reduced the fatigue strength to some extent. This was attributed to the existence of the brittle Fe-Zn alloy layer. The deleterious effect of the alloy layer was more dominant than the effect of the residual stress which was altered by the galvanising on the fatigue performance.

水産大学校研究業績 第1259号，1989年10月30日受理.
Contribution from Shimonoseki University of Fisheries, No. 1259. Received Oct. 30, 1989.

* Thesis submitted to the University of Nottingham (UK) for the degree of Doctor of Philosophy, October 1988 and accepted December 1988.

Contents

1 Introduction

The distinctive surface damage of a material which is caused by small oscillatory relative motion between two contacting surfaces is well known as "fretting", "fretting corrosion" or "fretting wear". This surface damage was first scientifically observed in 1911 by EDEN, ROSE and CUNNINGHAM in their fatigue tests[1]. However, the first investigation which focused on fretting damage was carried out by TOMLISON in 1927[2] and the phrase "fretting corrosion" was coined by him in a later paper[3].

According to the glossary of terms and definitions in the field of friction, wear and lubrication complied by the Organization for Economic Cooperation and Development (OECD), the definitions of "fretting" and "fretting corrosion" are as follows[4]:

Fretting; wear phenomena occurring between two surfaces having oscillatory relative motion of small amplitude.

Note; Fretting is a term frequently used to include fretting corrosion. This usage is not recommended.

Fretting corrosion; a form of fretting in which a chemical reaction predominates.

Note; (1) fretting corrosion is often characterised by the removal of particles and subsequent formation of oxides, which are often abrasive and so increase the wear,

(2) fretting corrosion can involve other chemical reaction products, which may not by abrasive.

On the other hand, the Japan Society of Lubrication Engineers (JSLE) defined the term "fretting" or "fretting corrosion" in the lubrication terms glossary as follows[5]:

Fretting (fretting, fretting corrosion); surface damage which occurs between two solids in contact when small tangential vibration is given.

In this glossary the term "fretting" includes fretting corrosion and fretting wear. However, in recent literature the term "fretting wear" has been commonly used to describe the wear phenomena due to fretting. The author prefers the definition of "fretting" as follows: fretting is the action which produces fretting wear or fretting corrosion, in other words, fretting is the oscillatory relative motion occurring between contacting surfaces.

It is commonly known that fretting can occur in any components whose surfaces are in contact and are subjected to cyclic stresses, such as in bearings, flexible couplings, wire ropes, bolted flanges, riveted joints, keys and propeller bosses, etc[6]. If fretting occurs in components which are allowed to have oscillatory relative motion, it reduces the dimensional accuracy of machines and the accumulation of wear debris may lead to seizure. On the other hand, if fretting occurs where the contacting surfaces are not designed to move relatively to each other, it significantly reduces fatigue strength. This is known as "fretting fatique". There have been many investigations of fretting damage and the effects of various factors which influence fretting damage have been clarified considerably. Moreover, the fretting damage which occurs in particular machines and structures or in certain situations, such as gas turbine components, nuclear reactor plants and structures and wire ropes in marine environments, etc. has been investigated. However, the more sophisticated designs using high technology seem to produce more serious problems caused by fretting.

Steel ropes are widely used in marine environments, such as ships and offshore structures. Although there are many different designs of ropes, they can be divided into two main types from the structural point of view, namely the strand rope and the locked coil rope. The strand rope consists of a number of strands wound either onto a fibre core which contains a lubricant or onto one strand. The strands themselves consist of a number of layers of wires. The role of the lubricant in the fibre core is to reduce the friction occurring between the wires and to prevent corrosion. The strand rope has two types of construction which are referred to as "ordinary lay" (regular lay) and "lang lay". In the ordinary lay construction the strand wires are wound in one direction, but the strands are made up into the rope in the opposite direction. In the lang lay construction the wires in the strand are made up in the same direction as the strands wound onto the centre strand. The lang lay type rope is more resistant to wear damage than an ordinary lay type rope. The locked coil rope consists of individual wires which have a shaped cross-section so that they fit together in the finished rope. This type of rope has a higher capacity against the breaking load owing to the higher density of the steel in the cross-sectional area. The construction of these ropes involves innumerable inter-wire contacts which are possible sites for fretting to occur at if the ropes are subjected to cyclic bending and/or tensile loads by waves or flowing water, etc. in service operation.

The objects of this research were: (1) to investigate the fatigue behaviour under the influence of fretting of wire ropes used in marine environments, 2) to produce relevant experimental data on fatigue performance in seawater for the design of mooring offshore structures, 3) to assess the conventional electrochemical preventive measures, such as cathodic protection, in a fretting fatigue situation and to produce fundamental information for more effective protection.

In chapter 2, literature on fretting wear and fretting fatigue is briefly reviewed. In chapter 3, fretting fatigue tests of a high tensile roping steel are carried out in air and seawater and the effect of fretting in seawater on fatigue behaviour is investigated. In chapter 4, the effectiveness of the application of cathodic protection on fretting fatigue performance is assessed. In chapter 5, the effect of galvanising of fretting fatigue performance in seawater is investigated. Finally, general conclusions in this work are presented and further work is suggested in chapter 6.

2 Review of literature

2.1 Introduction

Fretting seems to produce two detrimental effects, namely the surface damage of materials which includes seizure, wear loss and the production of wear debris etc., and a reduction in the fatigue strength of materials. The debris formed by fretting is strongly oxidised, if fretting occurs in oxidising atmospheres. The fretting debris of steel formed in air is reddish brown in colour and is thus referred to as "cocoa". The debris is generally α-Fe_2O_3 (haematite). The particle size of the debris is extremely small (in the order of 0.1 μm or less)[7]. If relative motion occurs between two contacts, the original surfaces of any materials may be altered in any environments. Fretting is no exception. Fretting damage therefore occurs in a vacuum.

Since Tomlison et al's pioneering study on fretting corrosion in 1927, there has been a great deal of interest in this subject and a large number of papers have been published. Two excellent books have also been published[6,8]. The initial works focused on investigations to discover the causes of the onset of fretting phonomena[2,3]. In the 1940's and 50's attention was paid mainly to the mechanism of fretting damage. Thereafter, research has been extended to invididual materials or to particular problems occurring in specific situations. In this chapter literature on the wear aspect and the fatigue aspect respectively was reviewed.

2.2 Fretting wear

2.2.1 Mechanism of fretting wear

Various mechanisms of fretting wear have been proposed in the past. Most of these mechanisms comprise some of the different fracture processes of fretted surfaces. Moreover, a number of the mechanisms seem to be contradictory. These facts imply that the mechanism of fretting wear is complicated. The main mechanisms which have been proposed are briefly shown below.

TOMLISON *et al.*[2,3] found that the relative motion of contacting surfaces was necessary to produce fretting corrosion and that the minimum amplitude of the relative motion to produce this phenomenon was of the order of 10^{-6} mm. These discoveries led to the suggestion of the "molecular attrition" mechanism, which is possibly associated with a fatigue effect. However, the wear debris produced by fretting was found to be much larger than the molecular order, according to experimental results obtained by later investigators. This mechanism has not been supported by later investigators.

GODFREY *et al.* concluded from the direct observation of fretting damage by microscope[9,10] and detailed observation of the early stage of fretting damage[11,12] that fretting wear was caused by the removal of finely divided virgin material due to "adhesion" not due to oxidation. In the early stages of fretting damage, several other wear processes, namely ploughing, variations in the nature and quantity of debris and the formation of films by compacting small particles, occurred in addition to adhesion. Their relative importance varied with the materials fretted. Oscillatory motion was not necessary to initiate fretting damage since the damage occurred in a half cycle.

FENG and RIGHTMIRE[7,13] divided the process of fretting wear into the following three stage: 1) the initial stage; the production of wear particles by metal transfer and ordinary wear (roughening of the interface and shearing of the contacting points), 2) the transition stage; the change in the fretting wear mechanism from ordinary wear into abrasion by the accumulation of trapped oxide particles in the contacting surfaces due to oscillatory motion, 3) the final steady state stage: continuous abrasive wear. This mechanism shows the significant effect of oscillatory motion on fretting damage. They suggested that fretting wear was caused by the abrasive action of oxide wear particles.

UHLIG[14] introduced the first quantitative expression for the amount of fretting damage, which consists of mechanical and chemical factors, based on previous experimental results[15]. The equation is as follows:

$$W=(k_0L^{\frac{1}{2}} - K_1L)N/f + k_2lLN$$

W: total weight loss
L: load
N: number of cycles
f: frequency
l: slip
K_0,K_1,K_2: constants

The first two terms, which express the chemical factor, were derived from the idea that the clean metal surface produced by the abrasion of an asperity immediately oxidises and the next asperity wipes off the oxide film. The third term, which expresses the mechanical factor, was based on the idea that the mechanical loss of metal is produced by the digging action of asperities below the oxide films. In fact half a decade before UHLIG's investigation, SAKMAN and RIGHTMIRE[16] suggested that chemical action was of primary importance on fretting damage, but they did not develop their study further. It can be noted that UHLIG's mechanism influenced later investigations on fretting wear.

WATERHOUSE[17], in reviewing fretting corrosion, has suggested that fretting can be caused by three possible processes: 1) the removal of finely divided metal from the surface by a mechanical grinding action or by the formation of welds at points of contact, 2) the removal of metal particles which subsequently oxidise to form abrasive particles and their abrasive action, 3) the direct oxidation of the metal surface and the continuous removal of oxide films by mechanical action. In non-oxidising environments or on non-metallic materials, fretting damage is essentially mechanical, is similar to unidirectional wear and is caused by the first process. In the presence of a large amount of oxygen, fretting damage is essentially chemical. The second process is of importance where the oxide is very hard, for example, with aluminium or chromium, and where the debris is unable to escape. The fretting wear of steel in normal surroundings is mostly explained by the third process. However, HALLIDAY and HIRST[18,19] have shown that the main causes of fretting are the first two processes and that the third process is relatively unimportant.

More recently, HURRICKS[20] reviewed the mechanisms of fretting wear and showed that the process of fretting wear could be devided into three stages: the initial stage, debris generation and the steady state. Adhesion and metal transfer leading to subsequent wear damage occur in the first stage. In the second stage, virgin debris is oxidised and the formation of a layer of oxide debris reduces metallic contact. The third stage is characterised by a disintegration and dispersal of the zone affected by the initial stage of fretting damage. The significant factor in fretting wear at this stage is fatigue not abrasion.

The delamination theory proposed by SUH[21], which deals with wear from the fracture phenomena of a material, is introduced in order to explain the removal of debris in fretting wear. WATERHOUSE and TAYLOR[22,23] showed from SEM observations and adhesion measurements of fretted surfaces that macroscopic adhesion, which eventually falls off, occurred in the early stages and that the removal of material from the surfaces occurred according to the delamination theory. SPROLES and DUQUETTE[24] also showed that the delamination mechanism was the most suitable model for the material removal processes in fretting. The delamination theory is based on the dislocation theory and the plastic deformation and fracture of metals near a surface. Small cracks are initiated by the decohesion of the matrix-particle interface and by the plastic flow of the matrix around hard particles. Wear particles are formed by the propagation of these cracks parallel to the surface.

However, results showing that there is no difference between the fretting wear mechanism and the unidirectional sliding wear mechanism have been reported. SASADA[25] investigated wear loss, wear debris, wear phenomena and the effectiveness of lubrication in both fretting wear and unidirectional sliding wear. He concluded that both fretting wear and sliding wear result from the same wear mechanism, apart from the fact that fretting is characterized by the existence of the non-slip region in the contacting area within which lubrication is restricted. Stower and RABINOWICZ[26] suggested that since the wear coefficient of fretting was similar to that of continuous sliding wear, fretting wear was the same as continuous sliding wear caused by adhesive wear.

It seems to be insufficient to cover the mechanism of fretting wear with one theory or one model. As suggested by WATERHOUSE[17], different wear processes occur at the same time during fretting and their relative importance changes according to the experimental conditions. The processes of fretting wear are functions of time[7,20]. Moreover, further fretting wear processes seem to be strongly affected by the processes which have already occurred.

2.2.2 Effect of various factors on fretting wear

2.2.2.1 Number of cycles

In most investigations, a linear relation between the wear volume and number of cycles has been obtained[18,25,27,28,29]. Typical results obtained by FENG *et al.*[7,15] showed that, after the higher wear rate during the run-in period, the wear volume increased linearly with the number of cycles. These run-in periods were 1.5×10^5 cycles in air and 3×10^4 cycles in nitrogen.

2.2.2.2 Normal load

Three different results on the effect of normal load have been reported. Firstly, the wear volume increased parabolically [15,28,29] or linearly[27] with increasing normal load. Secondly, there was no significant change in surface damage [3], the wear volume decreases with increasing normal load [30]. Thirdly, the experimental relation between wear volume (V) and normal load (L) was found by SODA and AOKI[29] to be $V \propto L^{0.7}$. They cited that this relation was one of the main features of fretting wear.

With some experimental apparatus the increase in contact load reduces the amplitude of actual relative slip. In such cases, an increase in load reduces the wear volume. ITO[30] suggested that the decrease in wear volume under higher load was due to the decrease in actual slip between the contacting surfaces. When amplitude of slip is kept constant, the wear volume is thought to be nearly proportional to the normal load.

2.2.2.3 Frequency

In general, under a constant slip amplitude, as the frequency increases the wear volume decreases. FENG and UHLIG[15] investigated the effect of frequency on fretting wear in air and in nitrogen. The weight loss in air was lower, the higher the frequency, for a given number of cycles until 17 Hz, but over this the frequency effect was not significant. The greater the slip amplitude the greater was the frequency effect. In nitrogen no frequency effect was seen. These experimental results indicate that fretting wear is a chemical process (oxidation process) which is time dependent. However, much higher frequencies, such as 10 KHz, result in greater wear volume due to the higher interfacial strain rate and higher surface temperature[31].

2.2.2.4 Amplitude of slip

Most investigations on the effect of slip amplitude show either a linear increase in wear volume with increasing amplitude of slip [15,25,28] or a drastic increase in wear volume over certain amplitudes of slip [18,19,32,33,34]. HALLIDAY and HIRST[18] found that there was a critical amplitude of 100 μm, above which wear increased sharply in the fretting wear of mild steel. The critical amplitude in the fretting wear of duralumin on mild steel and mild steel on duralumin was found to be 120 μm and also wear volumes at amplitudes less than 50 μm were found to be negligible[19]. OHMAE and TSUKIZOE[32] investigated the effect of slip amplitude on the mechanism of the fretting wear of a mild steel. The critical amplitude was found to be 70 μm. At amplitudes less than 70 μm oxidative wear occurred. At amplitudes lerger than 70 μm oxidation, adhesion and abrasion caused fretting wear. SATO *et al.*[34] defined the critical amplitude as the amplitude at which the non-slip region disappears in the elastic contact. This valume was about 12 μm. KAYABA and IWABUCHI[35] showed that the value of the critical amplitude was dependent on the normal load and the materials used, namely the higher the load, and in carbon steel rather than in copper, the larger the critical amplitude.

Another investigation on slip amplitude was concerned with the determination of the minimum amplitude which can produce fretting damage. TOMLINSON[2] found in the first ever investigation of fretting damage that this amplitude was in the oeder of 10^{-3} μm, which is extremely small. In recent years, KENNEDY *et al.*[36,37] have reinforced TOMLINSON's findings and have shown that in the fretting produced by the twisting motion of a plate specimen against a ball the minimum amplitude which can produce damage is 0.075 μm.

2.2.2.5 Surface finish

There is little agreement on the effect of surface finish. REED and BATTER[38] showed that the rougher the surface, the lower the surface damage produced. WATERHOUSE[39] has explaned this as follows: 1) the rougher the surface the higher the plasticity index, so the rough surface absorbs the tangential movement due to fretting to some degree, 2) wear particles easily escape from the contacting surfaces and are entrapped into the adjoining depressed regions. However, it has been reported that the larger the virgin surface roughness, the larger the resultant wear volume become both in air and in oil[40,41]. Under very small amplitudes (0.05−5 μm), no surface finish effect has been observed[36].

2.2.2.6 Hardness

Hardness can affect fretting wear in the following two possible ways[42]. Firstly, in the case of fretting wear caused by the breakdown of a surface under local high stress fatigue, a decrease in damage can be expected in higher hardness steel. Secondly, higher hardness steel seem to have a higher resistance against the abrasive action of the oxide debris between two surfaces. In literature there are two different results reported on the effect of hardness on fretting wear. The wear volume decreases linearly with increasing hardness[28,30], and the wear volume is inversely proportional to hardness to the 2.5−3rd power [43,44]. On the other hand, KAYABA and IWABUCHI[45] showed that hardness had only a minor influence on fretting wear and that the significant factor was the action of the oxide debris produced between two surfaces.

2.2.2.7 Environments

2.2.2.7.1 Humidity

The water vapour in air seems to act in two different ways in wear. It causes corrosive wear, which can increase with increasing humidity, and also influences mechanical wear which can be reduced by the lubricating action due to the increased humidity. When these two opposite actions occur simultaneously, the wear volume shows a peak at a certain humidity. Such wear behaviour has often been reported[27,29,46,47]. A typical result was obtained by SODA and AOKI[29]. The wear volume increased with increasing humidity, reached a peak at 30−40 % relative humidity and after that decreased. The maximum wear volume was five times greater than that at 100 % relative humidity. However, in the absence of oxygen, the water vapour had little effect on fretting wear[15].

2.2.2.7.2 Temperature

Temperature can influence both the corrosion (oxidation) rate and the mechanical properties of matetials. FENG and UHLING[15] carried out fretting tests in the temperature range of −125℃ to 100℃ and showed that weight losses were greater the lower the temperature, and that a drastic decrease in weight loss occurred between 0℃ and 50℃. The investigation carried out by SODA and AOKI[29] in the temperature range from room temperature to 140℃ showed that wear volume increased linearly up to 100 ℃ and then became constant. The diserepancy between the two results implies that the humidity might have a greater influence than the temperature since temperature can change relative humidity. At high temperatures, there are two possible ways in which oxide films can influence the fretting process[48]; 1) the fretting disrupts protective oxide films, promotes increased chemical attack, and results in corrosive wear, 2) the oxide films act as a solid lubricant and thereby reduce friction and wear. In most cases of fretting at high temperatures in oxidising environments, the latter was found to occur. The reduction of friction and wear at high temeratures was due to the formation of tribologically beneficial oxide films which are generally called "glaze"[49]. These "glaze" oxides consisted of fine, crystalline oxide particles generally 10 to 50 nm in diameter and they were compacted onto a substrate of materials[50]. There was nothing unusual about the composition of the glazes. The structure of "glaze" oxides formed on alloys of nikel, chromium and iron was of a spinel type[51]. The temperature at which "glaze" oxides could be formed was found to be dependent on the materials and experimental conditions. On mild steel it was 380℃[52] or 200℃[53], on austenitic stainless steel 300℃[52] or 650℃ (in CO_2)[54], on nickel-base alloy (inconel 718)[48] 280℃ (at amplitude of 40 μm) and 540℃ (at amplitude of 10 μm), and on titanium alloys[48,55] 400–500℃. In non-oxidising environments, fretting wear was greatly influenced by the change in material properties due to temperature. In argon the fretting damage decreased in the temperature range of 200 to 300℃ and then drastically increased[56]. In a vacuum the wear volume at high temperatures was small, but the wear damage was very severe, consisting of both vertical and horizontal cracks under the surface[57].

2.2.2.7.3 Liquid lubricants

Wear phenomena under lubrication are influenced not only by the chemical and physical properties of lubricants and additives, but also by mechanical conditions, such as contacting shape, load, velocity and amplitude of relative motion. Liquid lubricants can affect the process of fretting wear in the following ways[58]: 1) by restricting the access of oxygen, 2) by sweeping away debris, and 3) by altering the friction. In the past, most investigators have shown that fretting damage is much smaller with a lubricant than without. When fretting is caused by mechanical and chemical components, the elimination or reduction of the oxidation of a clean surface and/or wear debris by the Lubricants can directly affect the wear rate. MacDowell[59] and Tsukizoe and Ohmae[41] showed that no oxidation occurred in oil. Wright[27] mentioned that the oxidation characteristic of fretting damage was reduced by the presence of a lubricant. On the other hand, Endo[60] stated that oxidation could occur in oil to the same degree as in air since oil contains a considerable amount of air. Tomlinson *et al.*[3] reported that the oxidation phenomenon occurred, though not as severely as in air. The physical properties of lubricants influence the damage which is caused by the mechanical component of fretting. Lower viscosity oil generally results in less damage since it facilitates the easier removal of wear debris. Therefore, oil is more effective than grease[43,44,61]. Oil or grease with additives showed further reductions in the wear rate[61,62,63]. However, some detrimental effects of the lubricants on the fretting wear rate have been reported[30,44,62].

2.2.2.7.4 Aqueous environments

The main studies of fretting wear in aqueous environments have been carried out on materials used in marine environments[64-69] and on those used for surgical implants[70,71]. The relative motion between the contacting surfaces in an electorolyte modifies the electrochemical processes occurring at the surfaces and the corrosion products formed as the result of these electrochemical processes can alter the wear behaviour[72]. Bethune and Waterhouse[73] were probably the first to conduct electrochemical investigations on fretting corrosion. They made polarisation measurements on copper and aluminium alloys in 1% sodium chloride under fretting conditions and found a great increase in the corrosion current when the specimens were fretted. This was attributed to the continuous disruption of oxide film by fretting. Other factors which could have affected the crrosion rate were the stirring effect and plastic deformation of contacting surfaces by fretting[74,75]. The relative importance of these factors were also depedent on the corrosion resistance of the meterials and/or the corrosiveness of the electrolyte.

Overs and Waterhouse[64] found that the fretting wear of weldable structural steels (HY80,50D) in seawater was a corrosive wear process and was greatly reduced by cathodic protection (−850mV(SCE)). On roping steels[65-69], the increase in wear volume in seawater was due to the additional electrochemical contribution. Cathodic protection (−950mV(SCE)) and zinc coating were effective methods in reducing fretting damage. However, the results on a bearing steel in seawater showed that the lubricating effect of seawater could occur in a fretting situation[76]. This lubricating action overcame the electrochemical components of the electrolyte[77,78]. Most wear debris removed itself easily from the contacting surface and did not accelerate the wear rate by working in the same way as the adrasive particles which are often observed in air[76]. In some cases the lubricating effect of liquid was also observed on other materials[65,68].

Syrett and Wing[70] carried out fretting tests on surgical implant materials in a physiological saline solution. They found that fretting increased the corrosion rate and that a cast vitallium alloy (Co-Cr-Mo alloy) had a significantly higher resistance to fretting corrosion than other stainless steels. The addition of serum to the saline solution was found to greatly reduce the fretting damage of 316LVM stainless steel[71].

2.3 Fretting fatigue

Fretting fatigue is fatigue damage which is directly attributable to fretting. It is well known that simultaneous fretting and fatigue, compared with fatigue alone, result in a considerable reduction of the fatigue strength of materials. Therefore, fretting fatigue damage may cause unexpected serious problems since it can occur even well below the calculated allowable stress.

The exploratory work on fretting fatigue carried out by Peterson and Wahl[79] showed that the fatigue strength of shafts with press-fitted members was reduced to 50 per cent of that of plain shafts without collars under the fit pressure of 11 MPa and 69 per cent under 0.62 MPa. They noticed that the "rubbing corrosion" (fretting corrosion) which occurred between the shaft and press-fitted member was an important factor in reducing fatigue strength. They also found that the rolling of the shaft surface and the use of a grooved construction in the press-fitted member were very effective in increasing the fatigue strength. The aim of the former method is to increase residual stress in the surface and that of the latter method is to decrease stress concentration. It is surprising that mitigation against fretting fatigue has not basically changed since it was first shown half a century ago.

Warlow–Davies[80] carried out fatigue tests on previously fretted specimens and investigated the effect of fretting corrosion on fatigue strength. The reductions in fatigue strength after fretting were found to be 13 per cent for a medium carbon steel and 18 per cent for a nickel chromium molybdenum alloy steel. There have been many investigations on fretting fatigue since their studies.

2.3.1 Mechanism of fretting fatigue

Fretting fatigue cracks are initiated in the very early stages of fatigue life and also the propagation of the cracks is accelerated by fretting. These are the main reasons for the considerable reduction of fatigue life and fatigue strength by fretting. Endo and Goto[81] showed that small cracks were already initiated at the 4 per cent stage of a fatigue life. In order to understand the mechanism of fretting fatigue, it is thought to be necessary to discuss the initiation and propagation of a fretting fatigue crack separately.

2.3.1.1 Initiation of fatigue cracks

The mechanisms proposed in the literature on the initiation of fatigue cracks under fretting conditions may be mainly divided into two groups: 1) local surface (asperity) fatigue by fretting[82-87], 2) high stress concentration due to either the surface roughness (pits) formed by fretting[17,88] or the stress conditions composed of contact stress caused by the frictional force due to fretting and of repeated stress[89-97].

A typical model for the mechanism in the first group was proposed by HOEPPNER and GOSS[85]. The model is as follows: 1) when a normal load is applied, surface asperities come into contact and are then deformed, 2) in addition when a fatigue load is applied, damage and debris are then produced, 3) after sufficient cycles, cracks, which result in fatigue failure, are initiated at the trough between the asperities. This proposed model is a surface fatigue mechanism and is mainly of a mechanical nature. Environment is a minor factor in this process. COLLINS and TOVEY[86] experimentally investigated two postulated mechanisms of fretting fatigue which were an asperity contact microcrack initiation mechanism and an abrasive particle-pit digging mechanism. In the former mechanism fatigue microcracks are initiated by cyclic stresses perpendicular to the direction of fretting at the base of each asperity. In the latter mechanism small grooves or pits produced by the asperities and abrasive debris, which are parallel to the fretting direction, work as a local stress raiser leading to the initiation of fatigue cracks. The results showed that the fatigue strength of the specimens prefretted parallel to the direction of the subsequent fatigue loading motion was much lower than that of the specimens prefretted perpendicular to the fatigue loading direction. COLLINS and TOVEY concluded that the asperity contact microcrack initiation mechanism was dominant. From the fractographic analysis of the fractured surface by fretting fatigue, KOVALEVSKII[87] proposed that the stress concentration formed by the destruction of local surface layers due to low cycle fatigue was the main factor in the reduction of fatigue strength.

With regard to the crack initiation mechanism in the second group, WATERHOUSE[17] stated that the main cause for the reduction of the fatigue strength was the pits formed by fretting since a roughly calculated stress at the bottom of the pits was four times the nominal tensile stress. NISHIOKA and HIRAKAWA[89,90] and ENDO and GOTO[93,94] explained the mechanism of the initiation of fatigue cracks from the viewpoint of the contact stresses comprising frictional force by fretting and repeated stress. Their explanation was based on the following facts; 1) pits formed by fretting were not always the nuclei of crack initiation[89], 2) the fatigue test of the prefretted specimen showed little reduction in fatigue life. The fatigue life was greatly reduced when fretting and repeated stress were simultaneously applied to the specimen, 3) there was not always a correlation between fretting fatigue strength and the amount of fretting wear[98].

NISHIOKA and HIRAKAWA[89,90] derived an alternating bending stress to initiate a fretting fatigue crack (σ_1) as shown in equation (1) from the analysis of the stress state in bending fatigue considering the main stress in the tangential direction.

$$\sigma_1 = \sigma_2 - 2\mu P_o [1 - \exp(-2s/k)]^{\frac{1}{2}} \quad (1)$$

σ_1: alternating bending stress to initiate a fatigue crack under fretting conditions

σ_2: alternating bending stress to initiate a fatigue crack without fretting

μ : coefficient of friction

P_o : maximum contact pressure

s : slip amplitude

k : constant

SATO *et al.*[96,99] also showed that the initiation of the cracks in the glass plate fretted against a steel ball was due to a maximum principal tensile stress.

ENDO and GOTO[93,94] assumed that a fatigue crack was initiated by the maximum repeated shearing stress which was the combination of repeated stress and tangential fretting stress. They obtained a reduction rate in fatigue strength by the initiation of a fatigue crack as shown in equation (2),

$$\frac{\sigma_2 - \sigma_1}{\sigma_2} = 1 - \frac{1}{1 + (2q_o / \sigma_1)} \quad \text{(bending fatigue)} \qquad (2)$$

$$\frac{\tau_2 - \tau_1}{\tau_2} = 1 - \frac{1}{1 + (q_o / \tau_1)^2} \quad \text{(torsional fatigue)}$$

τ_1 : alternating torsional stress to initiate a fatigue crack under fretting conditions

τ_2 : alternating torsional stress to initiate a fatigue crack without fretting

q_o : the maximum tangential stress on the contacting surface by fretting.

NISHIOKA *et al.* and ENDO *et al.*'s ideas on crack initiation are thought to be based on LIU *et al.*'s model[82] as shown in equation (3),

$$\sigma_a = (4\tau_a - 1.04 \times 10^6 \frac{\mu H^2}{0.151 + 4\mu^2})^{\frac{1}{2}} \qquad (3)$$

σ_a : allowable alternating bending stress

τ_a : shear fatigue limit (a half of bending fatigue limit)

μ : coefficient of friction

H : hardness of grip material

Their model showed that the repeated frictional shear stress together with the repeated bending stress at the contacting surface (asperities) initiated a fatigue crack.

As mentioned above, if the initiation of fretting fatigue cracks is due to the contact stress, which consists of frictional force and repeated stress, it can be assumed that the cracks originate where the maximum contact stress is to be expected. This was experimentally confirmed by WATERHOUSE and TAYLOR[91,92] and ALIC *et al.*[95]. Fatigue cracks were initiated at or near the boundary between areas of slip and non-slip where high strains and/or stresses existed.

2.3.1.2 Propagation of fatigue cracks

ENDO and GOTO[81] measured crack depths in the fretting fatigue of mild steel using an electrical resistance method. They found that the crack propagation curve, which was plotted on a log scale against the number of cycles, was composed of a straight line of higher initial slope and then a line of lower slope after the knee point. The maximum repeated shear stress (composed of the tangential force due to fretting and the repeated stress) accelerated not only the crack initiation, but also the crack propagation until a certain crack depth (knee point) and then the crack was propagated by repeated stress alone. The knee point, which coincided with the fretting fatigue damage threshold[100,101], was obtained at about 25 per cent of the fatigue life.

From the fractographic examinations of striation spacings, ALIC and HAWLEY[102] showed that the growth rates of fretting fatigue cracks in the early stages were much higher than those of normal fatigue cracks. Similar results were reported in the recent work by SATO *et al.*[103,104].

Most investigations showed that a crack propagating in the early stage was oblique to the surface and then it propagated perpendicularly to the surface. The oblique crack in the early stage was due to the combined effects of fretting and repeated stress. When the crack reached a certain depth, the effect of fretting (tangential stress) became negligible.

Recently, a fracture mechanics technique has been applied to investigations on fretting fatigue. The main advantages of this technique are that it may be possible to predict a fretting fatigue life and to determine the threshold stress intensity factor range leading to the self-arrest of the crack. For an accurate fracture mechanics analysis under fretting conditions, the following knowledge is necessary: 1) the stress states produced by the normal load and frictional force at and under the contact, 2) the stress states at the crack tip, e.g. stress intensity factors under the above conditions, 3) the relation between crack growth modes (K I, K II and K III) and the crack growth rate and the crack direction. EDWARDS *et al.*[105] calculated stress intensity factors under the assumed distributions of frictional force and normal pad load and made a prediction of fretting fatigue lives. The predicted fretting fatigue lives at the lower stress levels agreed well with the experimental results, but at the higher stress levels there were some large errors in predicted lives. HATTORI *et al.*[106] applied a finite element method (FEM) to the calculation of the contact pressure and tangential stress distributions and evaluated crack growth behaviour and the fretting fatigue limit by means of the stress intensity factors. EDWARDS *et al.* and HATTORI *et al.* assumed that the direction of a fretting fatigue crack was perpendicular to the surface. Their calculations for the stress intensity factors were based on the solutions derived by ROOKE and JONES[107] and only the mode I crack propagation was taken into account. On the other hand, SATO *et al.*[108] calculated stress intensity factors (K I and K II) for a crack which is oblique to the surface using a boundary element method (BEM). They showed that both the mode I and mode II were involved in the crack growth under fretting conditions. A three dimensional analysis of the propagation behaviour of a semi-circular oblique crack existing near the fretting contact was made by KANETA *et al.*[109]. They showed that both tips of the crack on the surface propagated in mode I and mode III, but the bottom of the crack growing into the bulk of the material propagated in mode I and mode II. This means that fretting fatigue crack growth should be considered as a mixed mode mechanism. However, NOWELL *et al.*[97] in their analysis predicted crack growth behaviour as follows: a crack was initiated by the shear mechanism and then propagated according to mode II at stage I (an oblique crack) and finally propagated according to mode I at stage II (a perpendicular crack to the surface).

2.3.2 Effect of various factors on fretting fatigue

2.3.2.1 Amplitude of slip

Fretting fatigue tests on an aluminium alloy were carried out by FENNER and FIELD[110] using bridges of different lengths of the same material or mild steel. They showed that the fatigue strength decreased with increasing amplitude, then became constant after an amplitude of about 8 μm. On nickel-chromium-molybdenum steel[111], the most damaging range of slip was found to be 8 to 14 μm. However, the fatigue strength reduction factor (ratio between the fatigue strength of a fretted specimen and that of an unfretted specimen at zero mean stress) was changed not only by the amplitude of slip, but also by mean stress. The increase of mean stress appeared to promote crack propagation. More detailed work on mild steel by NISHIOKA and HIRAKAWA[90,112], using a fretting fatigue machine capable of changing the amplitude of slip, showed results similar to those of FENNER and FIELD. However, the fatigue stress at which cracks were initiated decreased as the amplitude increased, showed a minimum value at amplitudes between 15 and 20 μm and then increased. The increase in the stress which initiated cracks at larger amplitudes was attributed to the removal of micro cracks due to the high wear rate by the abrasive action of the wear debris[111]. A more recent investigation of quenched and tempered 4130 steel showed that a minimum in fatigue resistance was obtained at relative slip amplitudes of 20 to 30 μm[88]

2.3.2.2 Contact pressure

As stated previously, the investigations[79] have already shown that contact pressure greatly influences fretting fatigue life. Most investigations showed that the fretting fatigue strength greatly decreased with increasing contact pressure and became constant above a certain pressure[79,82,113,114,115]. Fenner *et al.*[114] showed that fatigue life was dramatically reduced by even a very small value of normal contact pressure (0.15 MPa). Harris[116] carried out torsional fatigue tests on an aluminium alloy under a constant shear stress amplitude using various pad materials. He showed that contact pressure which could minimise fatigue life existed. A similar result was observed in push-pull fatigue tests of an aluminium alloy[117]. The work by Goss and Hoeppner[118] on the effect of normal pressure showed that an aluminium alloy was insensitive to changes in normal load, but a titanium alloy was very sensitive. The difference in behaviour was attributed to the different local microstructure and microscopic toughness in the fretting process. In the tests mentioned above, the amplitude of relative slip was not controlled. In practice the slip amplitude decreases as the contact pressure increases. This influence cannot be discounted when calculating the fatigue strength. Nishioka and Hirakawa[113] investigated the effect of contact pressure in bending fatigue tests on mild steel under a constant controlled slip amplitude. They found that fatigue strength decreased with increasing contact pressure and became constant above a contact pressure of 200 MPa. However, the stress which initiated cracks was found to decrease linearly as the contact pressure increased.

2.3.2.3 Frequency

Although the chemical component of fretting is time dependent, there have been no investigations other than that carried out by Endo, Goto and Nakamura[119] on the effect of frequency on fretting fatigue. They carried out torsional and bending fretting fatigue tests on a mild steel and showed that fretting fatigue was time dependent, and that the lower the frequency the lower the fatigue strength. These results were associated with the behaviour of frictional force. It was concluded that fatigue cracks were initiated earlier at the lower frequency since frictional force was time dependent and also that the coefficient of friction became higher at the lower frequency. The degree of reduction in fatigue strength was larger in bending fatigue than in torsional fatigue.

2.3.2.4 Combination of materials

The initiation of a fretting fatigue crack can be influenced by the mechanical action of fretting, especially the frictional force between contacting surfaces. Therefore, fretting fatigue damage is thought to be associated with the combination of materials. Horger[115] found that the fatigue strength of a steel shaft fitted with the same material was lower than that fitted with cast iron. The investigation on a titanium alloy combined with various materials (different hardness) which was carried out by Liu *et al.*[82] showed that the difference in hardness between two surfaces had a great influence on the fatigue strength of the specimens. Fatigue strength decreased as the hardness of the gripping pad increased. The decrease in fatigue strength was small when the hardness of the gripping pad was lower than that of the specimen. However, the work carried out by Nishioka and Hirakawa[113] on mild steel (170 to 630 Hv) fretted against a gripping pad of the same material (250 Hv) showed that the specimen hardness had little influence on fatigue strength. WATERHOUSE[120] found that the gripping materials which had the least deleterious effect on the fretting fatigue damage of a mild steel had low hardness, high thermal conductivity, high stacking fault energy (low work hardening ability), and a low recrystallisation temperature. ENDO *et al.*[93] and TANAKA *et al.*[121] paid attention to the frictional force between the specimen and the gripping pad in their investigation on the effect of the combination of materials. They showed that the lower the coefficient of friction the lower the decrease in fatigue strength.

2.3.2.5 Environments

Most investigations on the effect of atmosphere have been carried out in connection with oxidation. In the case of normal fatigue, it is well known that oxygen and water vapour in air decrease the fatigue life of a material. With regard to fretting fatigue, it was reported that there was no difference between the fretting fatigue strengths in air and in argon gas of titanium alloy[122] and 0.37 per cent carbon steel[123]. REEVES and HOEPPNER[124] stated that the mechanical damage due to fretting was more dominant in fretting fatigue damage than the chemical damage due to oxidation, since there was no difference in the fretting fatigue curves in air and in a vacuum. On the other hand, two-stage fatigue tests of an aluminium alloy by FENNER and FIELD[83] showed that the strength reduction factors were 3.2 in a vacuum and 4.6 in air. They stated that the initiation and propagation of fretting fatigue cracks were assisted by atmospheric corrosion. Similar results were found on aluminium alloy[125] and quenched and tempered 4130 steel[88]. ENDO and GOTO[126] carried out a more detailed investigation on the effect of oxygen and water vapour. On carbon steel the effect of water vapour was negligible but oxygen had a deleterious effect on the initiation and propagation of fretting fatigue cracks. However, on an aluminium alloy oxygen had little effect but water vapour accelerated the initiation and propagation of fretting fatigue cracks.

In aqueous environments there have been very few investigations on fretting fatigue. In such environments, both the corrosiveness of aqueous media and the deleterious effect of fretting greatly influence fatigue strength. WATERHOUSE and TAYLOR[127] investigated the relative effect of fretting and corrosion on the fatigue strength of a non-corrosion resistant material (0.7% carbon steel) in 1% NaCl solution. They showed that 1) fretting considerably lowered the fatigue limit compared with plain fatigue, 2) corrosion fatigue was more serious than fretting and had no fatigue limit, 3) with fretting and corrosion the fatigue behaviour was similar to that in fatigue with corrosion alone. On corrosion resistant material (18Cr-8Ni stainless steel)[128], corrosion fatigue was less damaging than fretting fatigue and corrosion plus fretting fatigue produced similar results to that of the non-corrosion resistant material. However, in some cases the aqueous medium had a cooling effect and improved the fatigue life at higher alternating stress. Also corrosion products formed in humid argon or 1% NaCl solution were found to be protective against fretting fatigue[129].

2.4 Prevention of fretting damage

As described in the previous section, the mechanisms of fretting wear are clearly different from those of fretting fatigue. Moreover there have been no established or widely accepted mechanisms of fretting wear. It is thus not surprising that the methods of mitigating fretting damage are varied and, in some cases, contradictory. However, the review of the effect of various factors which affect fretting wear and fretting fatigue throws some light on the mitigation of fretting damage.

As mentioned in the introduction, fretting damage takes place at the contacting surfaces which are designed either to allow small relative movement or to not allow any movement. In the former case either the fretting itself or, on the contrary, the frictional force between two surfaces should be reduced. In the latter case the methods which can reduce fretting action should be considered.

The basic principle behind mitigating fretting wear is to eliminate or reduce the mechanical components and chemical components of fretting and also to increase the resistance of materials against the detrimental effects of fretting. In the mitigation of fretting fatigue, the following process should be prevented by reducing adhesion due to the direct metal to metal contact: 1) the formation of a fatigue crack initiator, 2) the initiation of the fatigue crack, and 3) the subsequent propagation of the crack.

The reduction of the mechanical components of fretting should be achieved at the design stage. UHLIG[14] showed that an increase in load reduced relative movement and resulted in less damage. The slip amplitudes smaller than some critical values resulted in much less damage[18,32,35].

Adhesion and abrasion due to fretting, which lead to the acceleration of oxidation of the metal surface in the case of an oxidising atmosphere, facilitate fretting damage. This damage can be governed by the application of metallic or non-metallic coatings[67,131-137] or by the insertion of metallic or non-metallic sheets[131,138]. BOWERS *et al.*[131] showed that the sprayed coating of aluminium−1%zinc alloy significantly improved the fatigue life of an aluminium alloy. It was found that the cracks formed by fretting propagated only within the sprayed metal, and that they did not penetrate from the coating layer into the base metal. WATERHOUSE *et al.*[137] found that electrodeposited coatings which improved the fretting fatigue lives of a mild steel were in the order silver, copper, lead, tin, zinc, nickel, chromium. They suggested that relatively soft and high thermal conductive metals were useful as an anti-fretting coating. Another advantage of the coating is that soft coatings or high elastic modulus inserts can absorb relative movement to some extent and reduce the mechanical action of fretting[139]. However, it should be noted that the metal coatings which are beneficial in a fretting situation reduce the normal fatigue strength in some cases, for example, sprayed molydbenum coatings[140].

Another method of reducing the oxidation of the metal surface is the use of lubricants. Lubricants also reduce the friction between two surfaces. MACDOWELL[59] showed that the use of oil suppressed the oxidation of a metal surface and the formation of wear debris and resulted in much less fretting damage compared with the damage formed in air. The addition of extreme pressure additives gives a further reduction in the amount of fretting damage[61,62].

Improvements in material resistance against fretting and optimum material selection are also useful ways of reducing fretting damage. A compressive residual stress induced in the surface of a material by shot-peening[138,141,142], surface rolling[143], and nitriding or carburizing etc. is beneficial in improving fretting fatigue strength. It should be noted that combined preventions, for example, shot-peening plus resin bonding[138], MoS_2 graphite coating plus 2% tricresylphosphate (TCP)[144] etc. are more effective than a sole method in reducing fretting damage.

3 Fretting fatigue of a high tensile roping steel in air and seawater

3.1 Introduction

The wire ropes considered in this work are the spiral strand type and six-strand type which are used for mooring large structures in deep water. The construction of these ropes is illustrated in Fig. 3.1. The former rope consists of a number of layers of helically laid wires, each layer concentric and coaxial around the strand axis. Therefore, the wires contact their neighbours in the same layer along line contacts, but the contacts between wires in adjacent layers are crossed at an angle, and are referred to as "trellis contacts". In the latter rope, six strands are closed around a central core which is itself a separate strand. The wires in each strand have line contacts but trellis contacts occur between the strands. These ropes are filled with a heavy grease during manufacture, and sheathed with thick high density polyethylene. The aim of this is to exclude seawater but if the sheath is damaged by being dragged against a rock or other object there is a possibility of seawater entering the rope so that any inter-wire fretting would be taking place in seawater.

The detrimental effects of fretting are not only the increasing rigidity of the ropes due to the increase in friction between the contacts caused by the accumulation of wear debris, but also the formation of gaps in the outer layer of wires resulting in leakage of the lubricant leading to atmospheric corrosion. Another more serious problem is that, when the materials are simultaneously subjected to both cyclic stress and fretting, the fatigue strength is dramatically reduced by fretting compared with normal fatigue alone. Figure 3.2 shows fretting damage, which may lead to failure, formed in the rope tested in a normal fatigue experiment. The report recently published in Japan[145], on accidents caused by the failure of wire ropes, has concluded that the main cause of the failure of such ropes is fretting.

There have been some investigations on fretting wear in seawater. BETHUNE and WATERHOUSE[73] have found that fretting action stimulates the electrochemical processes occurring between two surfaces. The works on roping steels carried out by PEARSON and WATERHOUSE[64-69] have shown that the additional electrochemical components result in further wear loss in seawater, and that these components are entirely eliminated by the application of cathodic protection. On the other hand, the author *et al.*[76-78] have found that the lubricating effect of seawater can occur under fretting conditions, and that this lubricating action overcomes the electrochemical attack of the electrolyte.

However, there has been little information

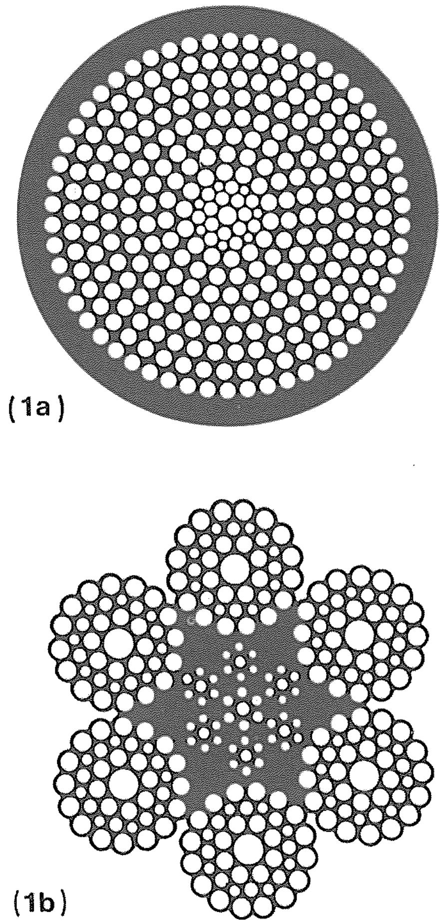
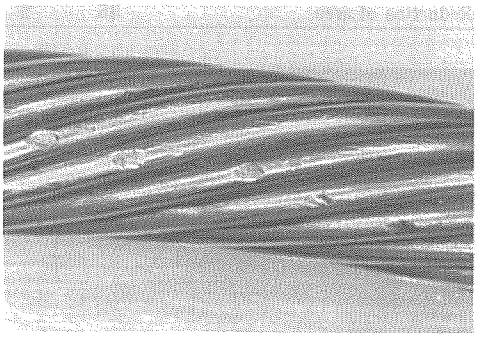
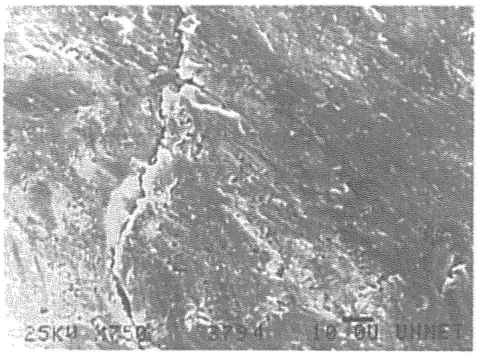


Fig. 3.1. Construction of the wire ropes used in deep water; high density polyethylene sheathed spiral strand rope (1a), six-strand wire rope (1b).

on fretting fatigue in seawater[127,128] and unfortunately, no investigation of roping steels. Moreover, when assessing fretting fatigue strength, the amount of fretting wear cannot always be used as a reliable indicator. Therefore, the present investigation was set up. In this chapter, fretting fatigue tests of a roping steel were carried out in air and seawater to obtain fundamental information on fatigue behaviour under the influence of fretting. The effect of fretting on fatigue behaviour and the initiation and propagation of fretting fatigue cracks were investigated.



(2a)



(2b)

Fig. 3.2. Fretting damage in a six-strand rope; fretting scars formed on a strand (2a), cracks initiated in the scars which may lead to fatigue failure (2b); tested in fluctuating tension in air, 3.9 × 10^5 cycles, (the specimen supplied by A.E. Potts, Reading University).

3.2 Experimental details

3.2.1 Apparatus and specimens

The fatigue machine employed, as shown in Fig. 3.3, was the Schenck Horizontal Midget Pulser PHG which was a push-pull type. Figure 3.4 shows a schematic illustration of the fretting cell and clamping system. The nylon cell was made in order to carry out fretting fatigue tests in seawater. The wire used as the fatigue specimen was clamped with two pairs of fretting specimens which were staple shapes of the same wire in the form of fretting bridges. Figure 3.5 shows details of the specimen's holder part. The clamping load was applied by the proving ring outside the cell. The applied load was measured using strain gauges attached to the proving ring. The distance between the two contacts was 8 mm. When alternating tensile stress was applies to the fatigue specimen, fretting occurred at the right angle contacts between the fatigue specimen and the fretting bridge, so that the fatigue specimen was subjected to both fretting and alternating stress at the same time.

The specimen used for this investigation was a cold drawn high carbon steel wire which

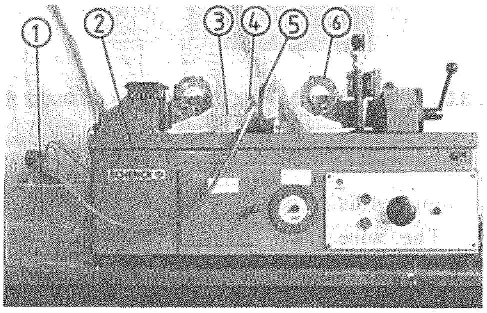


Fig. 3.3. Fretting fatigue apparatus; 1) external reservoir, 2) fatigue machine, 3) fatigue specimen (wire), 4) fretting cell, 5) proving ring, 6) capstan grip.

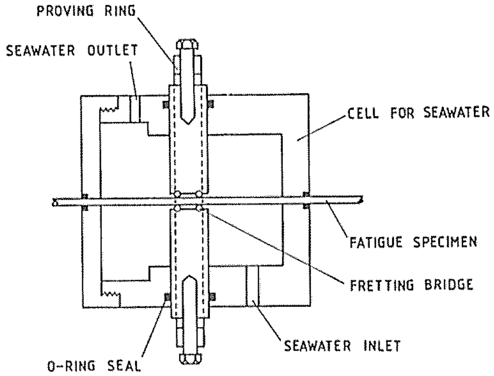


Fig. 3.4. Details of the fretting cell.

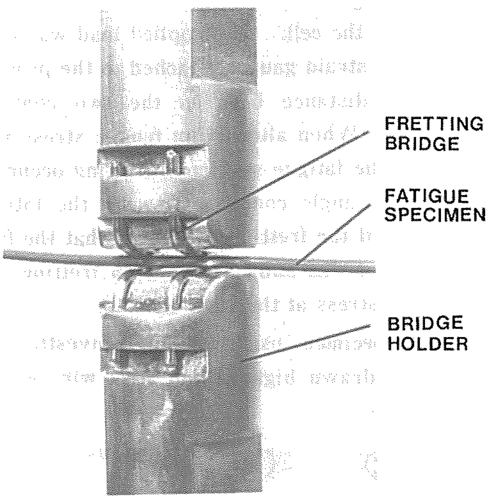


Fig. 3.5. Photograph showing the specimen clamping system.

was supplied as a "bright wire" by British Ropes Ltd. The wire was 1.5 mm in diameter. Its chemical composition and mechanical properties are listed in Table 3.1 and 3.2 respectively. Figure 3.6 shows the micro-structure of the wire. The severely elongated ferrite and pearlite structures by cold work are seen. Figure 3.7 shows the micro-vickers hardness distribution of the specimen.

Table 3.1. Chemical composition of the specimen (%)

C	Si	Mn	P	S	Cr
0.66	0.24	0.58	0.014	0.015	0.02
Mo	Ni	Al	Cu	Ti	V
0.03	0.02	0.01	0.02	0.01	0.01

Table 3.2. Mechanical porperties of the specimen

U.T.S.	1765	MPa
Proof stress (0.2%)	1443	MPa
Young's modulus ($\times 10^4$)	18.6	MPa
Elongation (50 mm)	5.0	%
Reduction of area	35	%

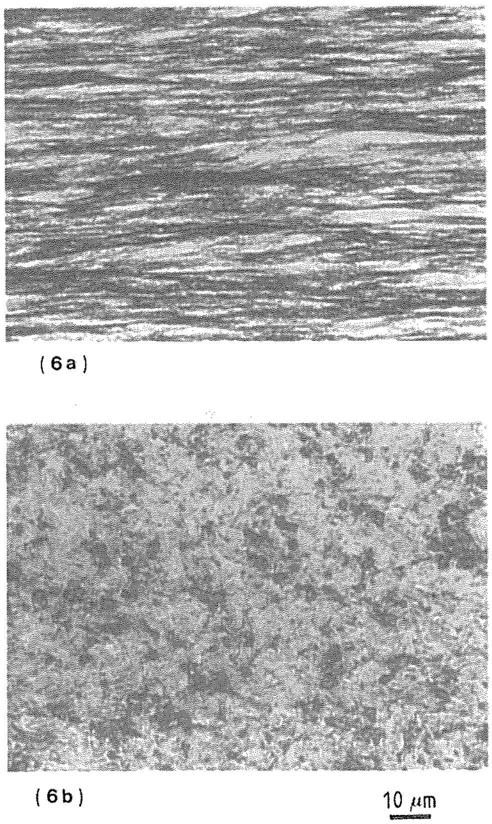


Fig. 3.6. Microstructure of steel wire (as received); longitudinal section (6a), transverse section (6b), etched in 2% nital.

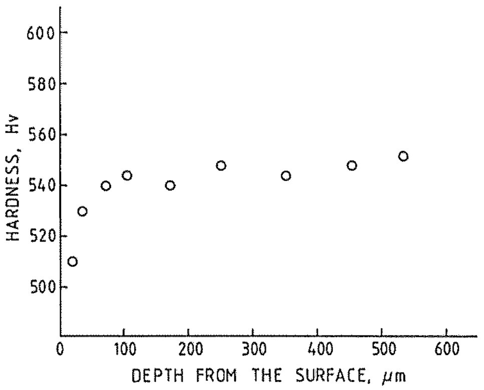


Fig. 3.7. Microhardness tranverse on the longitudinal section of a steel wire.

3.2.2 Experimental conditions and procedure

The experimental conditions were as follows:

nominal clamping load ; 400 N
stress ratio ; 0.3
frequency ; 5 Hz,
environments ; air, seawater
room temperature ; 16–25 ℃
seawater temperature ; 14–23 ℃

Neither the room temperature nor the seawater temperature was controlled in the tests. The clamping load was designed to be the same at each contact, but in practice it was not because of the high rigidity of the clamping device. Careful measurement showed that the load at one pair of bridge feet was 3 times greater than that at the other. The load at the lighter contact was adjusted to 100 N. All the slip occurred at the more lightly loaded contact as shown in Fig. 3.8. Failure always occurred at the lighter contact. The amplitude of the relative slip between the fatigue specimen and the fretting specimen (bridge feet) depends on the amplitude of the alternating stress. A simple calculation shows that the slip amplitude varies from 1.2 to 12 μm in the range of the alternating tensile stress 30 to 300 MPa.

Both ends of the fatigue specimen were wound on to the capstan gripping devices, which were specially made in order to prevent failure due to fretting occurring in the grip. The length between the two capstans was 320 mm. The specimens were covered with a black layer which was the residue of the drawing lubricant. This was carefully cleaned off with 1200 grit abrasive silicon paper and the specimens were degreased with acetone prior to the test. A run-out time of approximately 10^6 cycles was used.

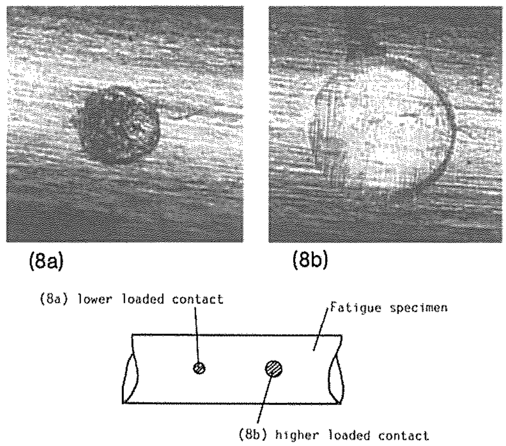


Fig. 3.8. Scars formed at both the contacts showing unequally loaded contacts; fretting scar at lower loaded contact (8a), non-macro slip at higher loaded contact (8b), total clamping load 400 N, σa = 168 MPa, 1.3 × 10^6 cycles, in air.

Synthetic seawater was made according to BS3900/2011. Its composition is listed in Table 3.3. The pH of the seawater was 8.2. In the tests in seawater, as can be seen in Fig. 3.3, seawater was continuously circulated using the peristaltic pump (25 ml/min) from an external

Table 3.3. Composition of BS3900/2011 seawater

Component	Wt. of Component (g/l)
NaCl	26.5
$MgSO_4$	3.3
$MgCl_2$	2.4
$CaCl_2$	1.10
KCl	0.73
NaBr	0.28
$NaHCO_3$	0.20

reservoir to the fretting cell.

In order to determine a crack growth rate, it is necessary to monitor the crack growth during tests. However, the methods which are widely used to monitor crack growth during normal fatigue tests, such as the DC potential drop, the visual observation of a crack with an optical microscope and the compliance method are not useful under fretting conditions. Moreover, the tests were carried out in an aqueous environment. Therefore, the following method was employed. The fretting fatigue tests were carried out for a given number of cycles below the failure limit. The specimens were then sectioned and by careful repeated grinding and polishing, the depths (perpendicular to the surface) of cracks were measured with an optical microscope.

Finally, the specimens were examined in the JEOL scanning electron microscope.

3.3 Results

3.3.1 Fretting fatigue curves

Figure 3.9 shows the fretting fatigue curves

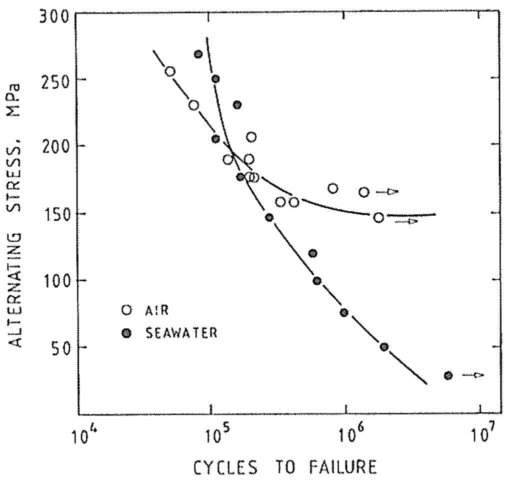


Fig. 3.9. Fretting fatigue curves for bright wire in air and aerated seawater.

determined in air and aerated seawater. The curve in air showed a fretting fatigue limit of 150 MPa. On the other hand, in seawater longer fatigue lives than those in air were obtained at higher alternating stresses but the curve fell steeply at extremely low stresses.

3.3.2 Crack depth vs. number of cycles curves

The maximum depth of a crack in each specimen was measured. The results at alternating stresses of 160, 200 and 260 MPa are plotted in Figs. 3.10 to 3.12 respectively. At the alternating stress of 160 MPa, micro cracks were already initiated at 5×10^3 cycles in sea-

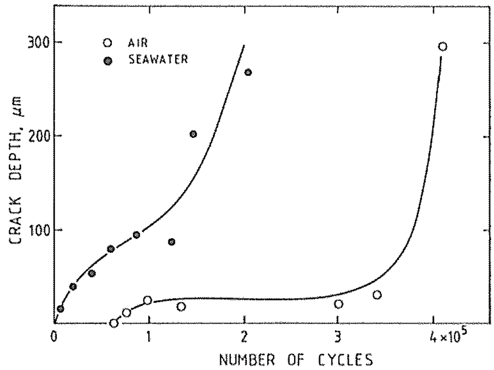


Fig. 3.10. Crack depth vs. number of cycles in air and seawater at an alternating stress of 160 MPa.

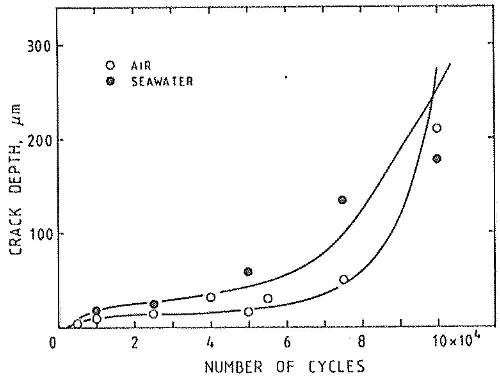


Fig. 3.11. Crack depth vs. number of cycles in air and seawater at an alternating stress of 200 MPa.

water and then the cracks propagated rapidly. The initiation of the cracks in seawater occurred within 3% of the fatigue life. In air the cracks were initiated 8×10^4 cycles (20% of the fatigue life) and they propagated rapidly after 3.5×10^5 cycles. At alternating stresses of 200 and 260 MPa, micro cracks were initiated at the early stage in both air and seawater.

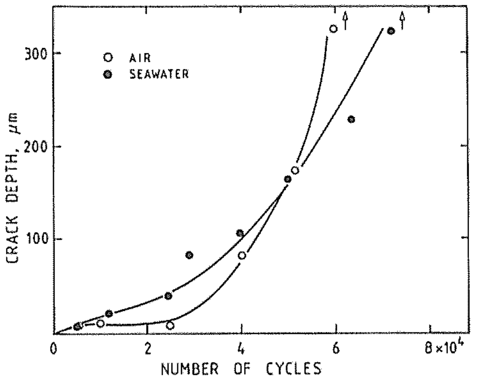


Fig. 3.12. Crack depth vs. number of cycles in air and seawater at an alternating stress of 260 MPa.

3.3.3 Crack growth rate (da/dN) vs. crack depth curves

Crack growth rates, i.e. "da/dN" were calculated from the crack propagation curves shown in Figs. 3.10 to 3.12. The "da/dN" at a certain crack depth was defined as follows[103]:

$$\frac{da_i}{dN_i} = \frac{1}{2}\left(\frac{\Delta a_1}{\Delta N_1} + \frac{\Delta a_2}{\Delta N_2}\right)$$

$$\frac{\Delta a_1}{\Delta N_1} = \frac{a_i - a_1}{N_i - N_1}$$

$$\frac{\Delta a_2}{\Delta N_2} = \frac{a_2 - a_i}{N_2 - N_i}$$

where

$a_1 < a_i < a_2$

$N_1 < N_i < N_2$

a : crack depth

N : number of cycles

The results are plotted against the crack depths in Figs. 3.13 to 3.15 respectively. The higher crack growth rates were obtained at the initial stage of the crack propagation in both air and seawater. The curves passed through a minimum and then increased. Similar crack growth rate behaviour was observed at all three alternating stress levels.

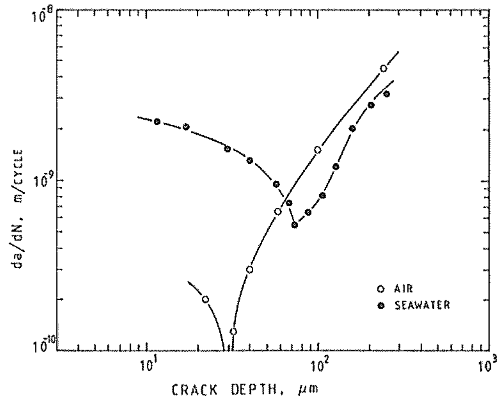


Fig. 3.13. Crack growth rate (da/dN) vs. crack depth in air and seawater at an alternating stress of 160 MPa.

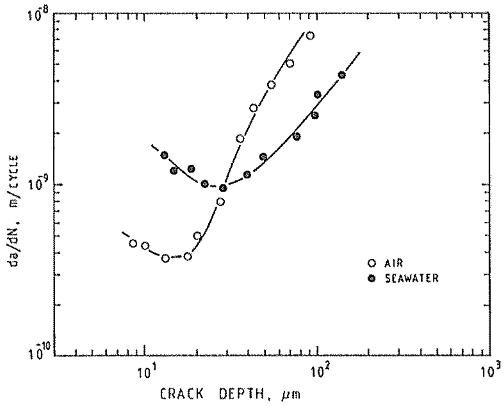


Fig. 3.14. Crack growth rate (da/dN) vs. crack depth in air and seawater at an alternating stress of 200 MPa.

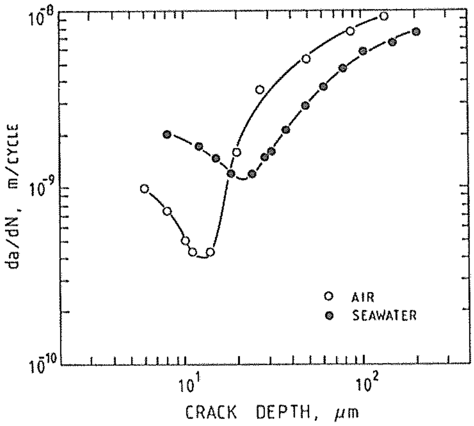
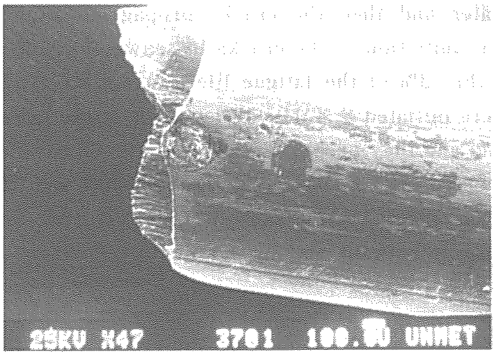


Fig. 3.15. Crack growth rate (da/dN) vs. crack depth in air and seawater at an alternating stress of 260 MPa.

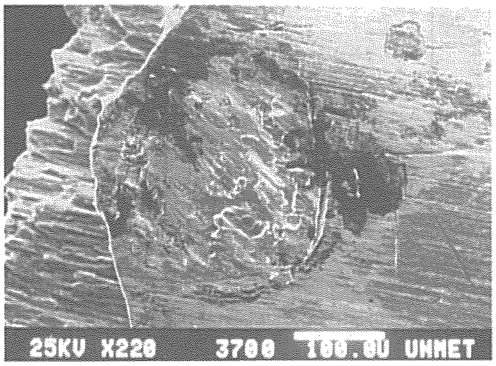
3.3.4 Scanning electron microscope examination

After fatigue failure, the specimens were examined in the scanning electron microscope. Those that failed in seawater were often immersed in the seawater for several hours after the fracture and so some corrosion of the fracture surfaces took place. They were ultrasonically cleaned in 10% sulphuric acid containing 0.1% thiourea before examination.

Figure 3.16 shows a general view of the fractured specimen in air (16a) and the higher magnification (16b). A typical fretting tongue was visible. It was apparent that the crack which caused the fracture followed the left hand side of the scar (Fig. 3.16 (16b)). Similar cracks were visible on the diametrically opposite side of the scar. The centre of the scar was mainly compacted and smeared with debris. Figure 3.17 shows the corresponding pictures of such failure in seawater. Multiple cracks were visible on the right hand side of the scar and the central region of the scar was free of debris (Fig. 3.17 (17b)).

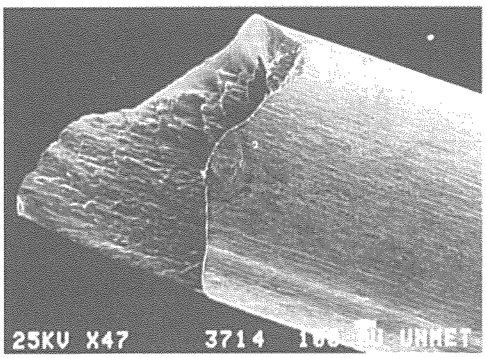


(16a)

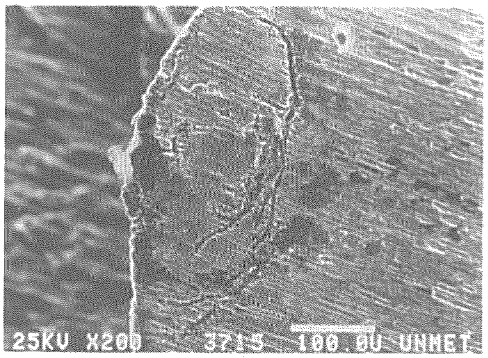


(16b)

Fig. 3.16. SEM photographs showing a general view of the fracture in air (16a) and the higher magnification (16b); σa = 200 MPa, 8.62×10^{4} cycles to failure.



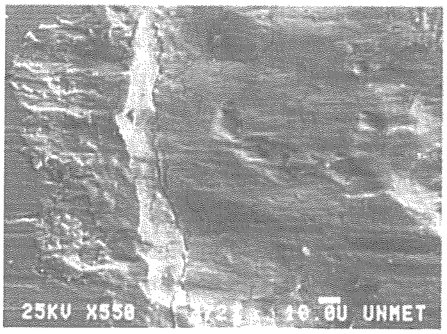
(17a)



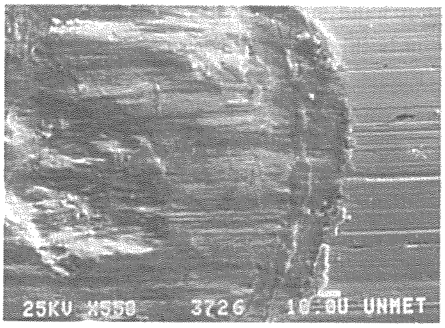
(17b)

Fig. 3.17. SEM photographs showing a general view of the fracture in seawater (17a) and the higher magnification (17b); σ a = 73MPa, 10×10^6 cycles to failure.

In some cases the actual rupture of the specimen led to further superficial damage to the fretting scar region as it pulled away from the bridge foot (see Fig. 3.16). Therefore, some tests were stopped before the failure limit and the fretting scars were examined. The fretting scars tested in air and in seawater for 10^5 cycles are shown in Figs. 3.18 and 3.19 respectively. In air the scar area was covered with compacted and smeared debris. Large cracks were visible on both sides in the scars in air and in seawater. It is noted that these cracks were initiated where the maximum shear stress induced by fretting existed, and also that the cracks on

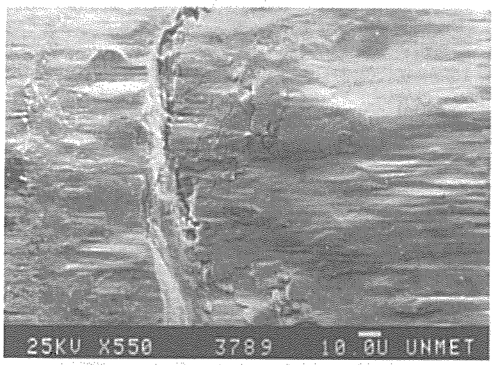


(18a)

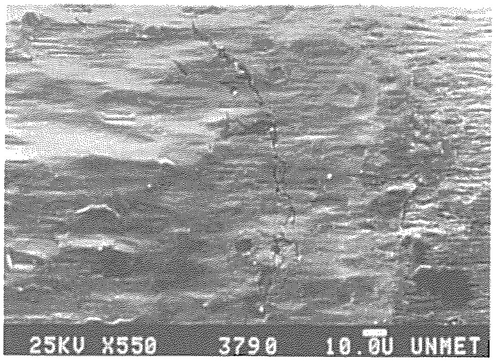


(18b)

Fig. 3.18. SEM photographs showing the details of the fretting scar formed in air; σ a = 195 MPa, 10^5 cycles, cracks at the left hand side of the fretting scar (18a), cracks at the right hand side of the fretting scar (18b).



(19a)

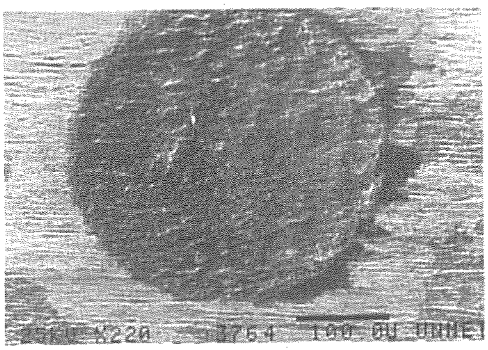


(19b)

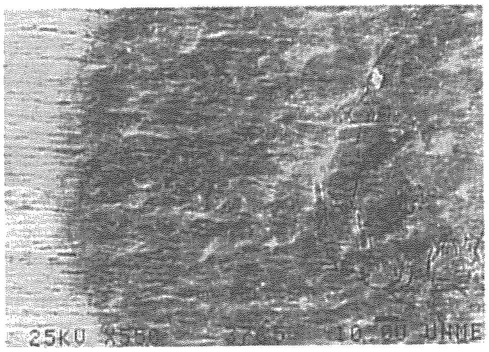
Fig. 3.19. SEM photographs showing the details of the fretting scar formed in seawater; σ a = 195 MPa, 10^5 cycles, cracks at the left hand side of the fretting scar (19a), cracks at the right hand side of the fretting scar (19b).

the left hand side may have led to the actual failure in both air and seawater.

Figure 3.20 shows the multiple cracks formed in the fretting scars of the specimen which was stopped at 5.94×10^6 cycles in seawater. The specimen would, therefore, have eventually failed.



(20a)



(20b)

Fig. 3.20. SEM photographs showing the fretting scar formed on the specimen which was run out in seawater (20a) and the higher magnification (20b); $\sigma a = 30$ MPa, 5.94×10^6 cycles.

The fracture surfaces formed in air and seawater are shown in Figs. 3.21 and 3.22 respectively. In seawater the tests were stopped before the failure limit in order to avoid any further corrosion of the crack surface after fatigue failure. The specimens were fractured in air by

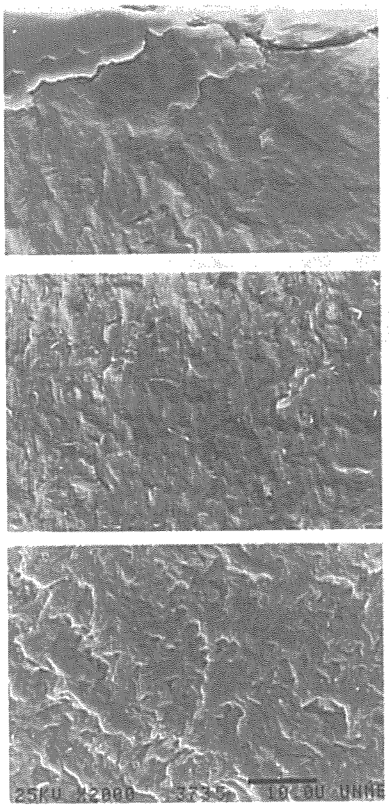


Fig. 3.21. SEM photoraphs showing the crack surface formed in air; $\sigma a = 260$ MPa, 5.13×10^4 cycles.

impact bending. In air the crack surfaces just under the fretted surface were covered with severely compacted wear debris (Fig. 3.21 (21a)) and abrasive tracks were visible (21b). In seawater the crack surface was covered with compacted corrosion products and wear debris (Fig. 3.22 (22a)). The crack surface at greater depths showed mainly a ductile fracture mechanism (21c, 22c). Figures 3.21 and 3.22 clearly show that fretting took place between the crack walls during the fatigue test. The wear debris produced by fretting occurring between the crack walls is also visible in the higher magnification of Fig. 3.16 (Fig. 3.23). This is due to crack closure.

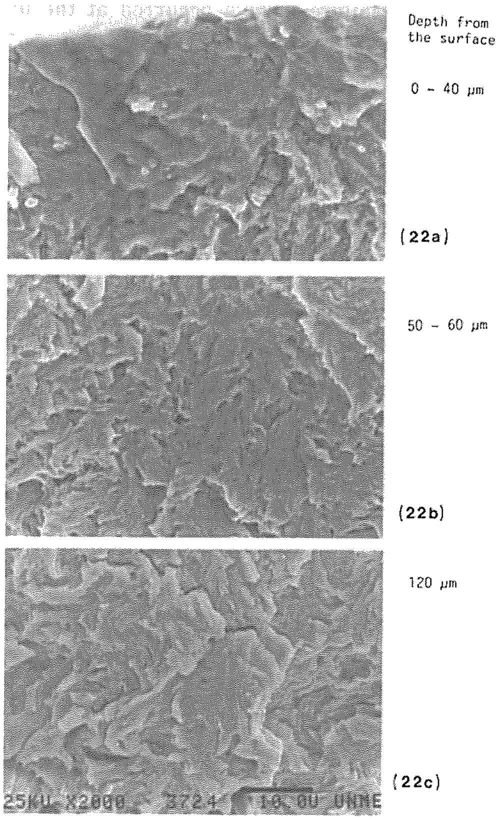


Fig. 3.22. SEM photographs showing the crack surface formed in seawater; $\sigma a = 260$ MPa, 6.8×10^4 cycles.

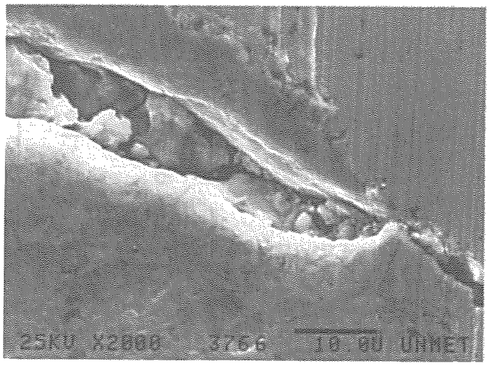


Fig. 3.23. SEM photograph showing the wear debris produced by fretting occurring between the crack walls; higher magnification of Fig. 3.16.

3.3.5 Profile of fretting fatigue cracks

In order to determine the change in profile of the cracks, the specimens were tested for a given number of cycles and then the specimens were sectioned by careful repeated grinding and polishing. The crack depths and the ground thickness of each specimen were measured using an optical microscope and a dial gauge respectively. Some of the results are illustrated in Fig 3.24. The profiles of the cracks at the early stages of fretting were rather elliptical and then became semi-circular. Figure 3.25 shows the relationship between the aspect ratio of the crack shape and the crack depth. The aspect ratio (a/c) was defined as the ratio between the depth of the crack (a) and half the length of the crack at the surface (c).

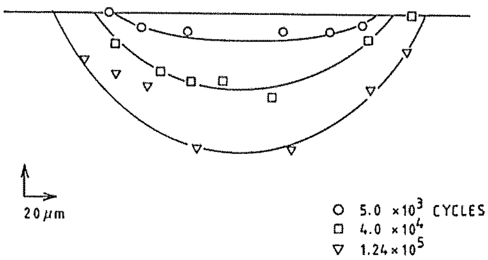


Fig. 3.24. Crack profile of the cracks growing in seawater at an alternating stress of 160 MPa.

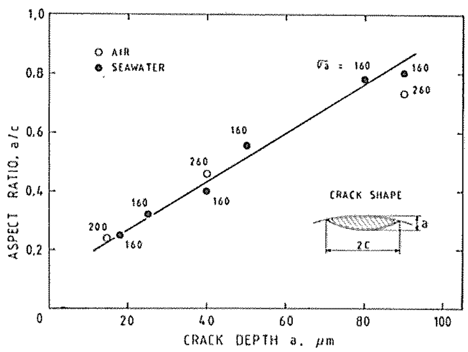


Fig. 3.25. Aspect ratios for the cracks growing in air and seawater as a function of the crack depth; the stress level of individual points is indicated.

3.4 Discussion

3.4.1 The effect of fretting on fatigue behaviour in seawater

The result in Fig. 3.9 indicates how severe is the effect of fretting in seawater on the fatigue life of these wires. However, the question remains whether the effect is merely corrosion fatigue or fretting. The investigation on the fretting fatigue and corrosion fatigue of a eutectoid steel (0.7% carbon steel) in NaCl solution showed that corrosion caused a dramatic reduction in fatigue strength, but that fretting itself did not result in further damage[127]. On corrosion resistant material (18Cr-8Ni stainless steel), corrosion fatigue was less damaging than fretting fatigue[128]. Therefore, in order to investigate the relative effects of corrosion and fretting, corrosion fatigue tests (without fretting) were carried out. At first a problem was encountered with failure due to crevice corrosion where the specimens passed through the O-ring seal on the fretting cell. This was overcome by use of an epoxy resin coating on the aforementioned part. After this, failure always occurred at the uncoated region due to pure corrosion fatigue. The results are shown in Fig. 3.26. The corrosion fatigue curve was similar to the fretting fatigue curve but showed a much longer fatigue life. This indicates that fretting causes much more severe damage than does corrosion. The corrosion fatigue limit was found to be 110 MPa. CONGLETON *et al.*[146] found a similar value of the fatigue limit for 1400 MPa grade wire in seawater with cathodic protection at −650 mv(SCE).

At higher alternating stresses the fatigue lives in seawater tend to be longer than those in air (Fig 3.9). The reason for this is thought to be the lubricating effect of liquid leading to lower values of the coefficient of friction and hence a reduction in the alternating shear stress in the contact surface arising from the fretting. This has been observed in tests on fretting wear in seawater[66,76,77]. Moreover the cooling effect of seawater may also contribute to further improvement in fatigue life[128].

Since corrosion processes are time-dependent, it is necessary to investigate the effect of cyclic frequency on fatigue behaviour in a fret-

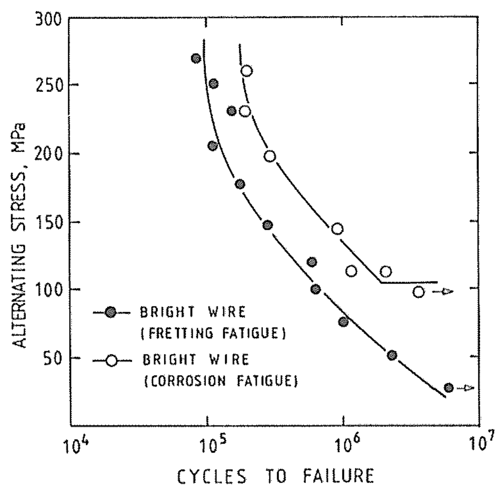


Fig. 3.26. Fretting fatigue and plain fatigue curves for a steel wire in seawater.

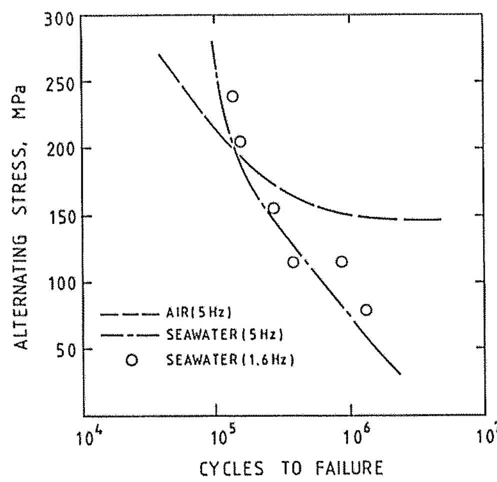


Fig. 3.27. Effect of cyclic frequency on the fretting fatigue behaviour.

ting situation. Some tests were carried out at the cyclic frequency of 1.6 Hz. This was the minimum frequency which could be controlled by the fatigue machine. The results presented in Fig. 3.27 showed that the reduction in the frequency from 5 to 1.6 Hz did not have any influence on the fretting fatigue behaviour of this wire. But this would not necessarily be true at much lower frequencies, e.g. 0.1 Hz.

There have been many investigations on the effect of frequency on corrosion fatigue, but unfortunately no investigations on fretting fatigue in aqueous environments. NISHIJIMA *et al.*[147] showed that the normal fatigue lives of carbon steels in 3% NaCl solution monotonously decreased with decreasing frequency in the region of 30 to 0.03 Hz. PETTIT *et al.*[148] showed that there was little difference between the corrosion fatigue lives obtained at 0.2 and at 1 Hz for a drill-pipe steel, but that much longer fatigue lives were obtained at 20 Hz. The increases in the crack growth rate (da/dN) for BS4360 grade 50D structural steel were found to be 1.3-fold by the reduction of the frequency from 10 to 1 Hz and 4-fold from 1 to 0.1 Hz at the stress intensity range (ΔK) of 30 $MPa{\cdot}m^{1/2}$[149]. These results indicate that corrosion fatigue behaviour in seawater is a function of cyclic frequency. Moreover, the work carried out by OVERS and WATERHOUSE[64] showing the reductions in wear volume by a factor of 1.7 in the region of 50 to 15 Hz, and by a factor of 8.3 from 15 to 1 Hz indicates that the frequency effect may be a dominant factor in fretting fatigue behaviour. The reduction in the frequency from 5 to 1.6 Hz might not give sufficient time to show the effect of corrosion under fretting conditions. Therefore, it is thought that further tests at much lower frequencies, such as 0.1 Hz which occurs in service operation, should be carried out.

Another consideration is the effect of crevice corrosion on fatigue behaviour since fretting contact in seawater is a crevice situation. PEARSON and WATERHOUSE[66] found that crevice corrosion resulted in hardly any measurable wear loss over a seven day period of immersion in seawater. However, any extremely localised material loss, such as pits, can be the initiator of a fatigue crack. Therefore, in order to investigate the effect of crevice corrosion on fatigue behaviour, the specimens clamped with the bridge feet were immersed in seawater for 5 days under the static condition and then fatigue tests were carried out with fretting or without fretting (corrosion fatigue) in seawater. The results plotted in Fig. 3.28 indicate that crevice corrosion itself does not have a deleterious effect. In contrast, the crevice situation increases the fretting fatigue life of this steel to some extent. This is thought to be due to the corrosion products formed around the contact before the fatigue test leading to the reduction in the coefficient of friction. In corrosion fatigue, the pre-crevice situation does not have a noticeable influence on the fatigue life.

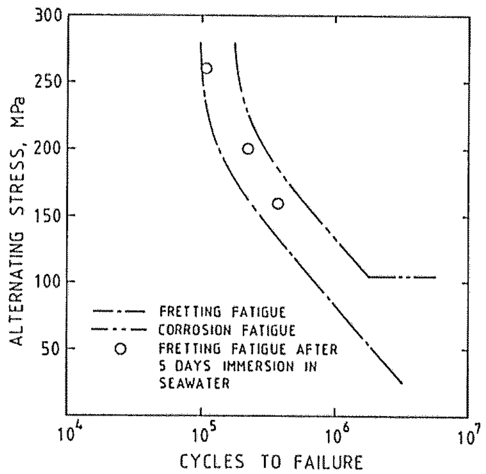


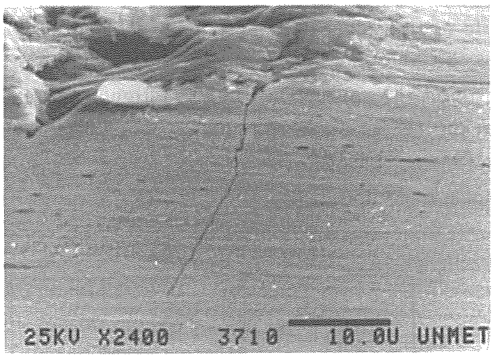
Fig. 3.28. Effect of 5-day immersion in seawater in a crevice situation on fretting fatigue and corrosion fatigue.

3.4.2 The effect of seawater on the initiation and propagation of fretting fatigue cracks

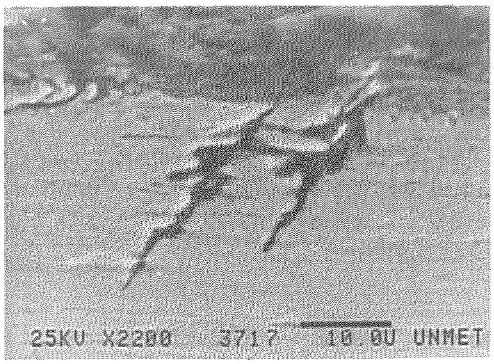
It is possible to determine the crack propagation curves by means of the method described in the experimental details. As shown in the earlier works[76-78], the coefficient of friction can be reduced by the lubricating effect of seawater. The stress state at the fretting contacts is thought to be much more severe in air than in seawater. At a stress level of 160 MPa (Fig. 3.10), the results, which show the earlier initiation of the micro cracks in seawater than in air, indicate that electrochemical attack due to seawater is more dominant than the severity of the stress state due to fretting in the crack initiation stage. However, at higher stress levels (200 and 260 MPa, Figs. 3.11 and 3.12), the cracks initiate at approximately the same stage in both air and seawater. This indicates that the severity of the stress state due to fretting overcomes the deleterious effects of seawater. Figure 3.29 shows micro cracks initiated just within the fretting scar in the early stages of the fretting cycles.

Figures 3.13 and 3.15 show clearly the initial higher crack growth rate. This is the result of the additional cyclic shear stress due to fretting on the surface. Endo and Goto[81] showed that the enhanced crack growth rate in the early stage where the tangential force was influential was dependent on contact pressure and repeated stress, namely the greater the contact pressure and repeated stress the higher the crack growth rate. They also showed that the subsequent crack growth rate was dependent on the range of the stress intensity factor (ΔK) calculated solely from the repeated stress. This has been confirmed again by Sato *et al.*[103].

Figures 3.30 and 3.31 show the sections of the wires tested for a given number of cycles in



(29a)



(29b)

Fig. 3.29. Micro cracks initiated in the early stage: in air, $\sigma a = 200$ MPa, 3.5×10^4 cycles (29a); in seawater, $\sigma a = 260$ MPa, 1.2×10^4 cycles (29b).

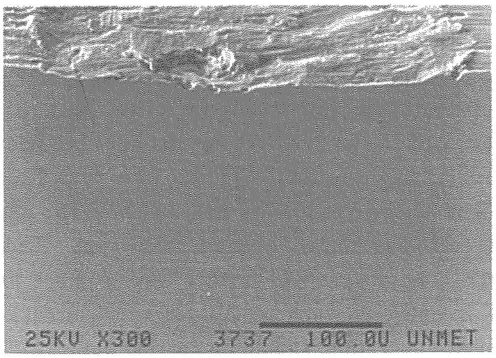
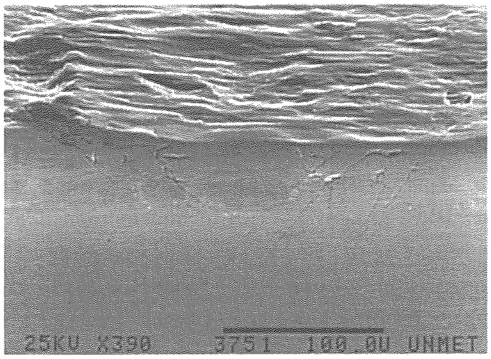
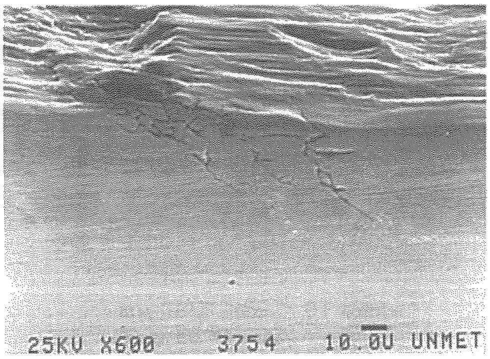


Fig. 3.30. SEM photograph of section through fretting scar showing the single crack initiated in air; $\sigma a = 260$ MPa, 5.13×10^4 cycles.

air and seawater respectively. Only a single propagating crack is seen in air but multiple cracks are initiated in seawater. The propagation of the oblique cracks is due to the cyclic stress composed of the tangential force of fretting and normal repeated tensile stress. When the cracks grow out of the region of influence of the fretting, their direction becomes perpendicular to the direction of the cyclic principal stress, and the crack growth rate is governed simply by the stress intensity factor which is related to the applied stress and the crack length.



(31a)



(31b)

Fig. 3.31. SEM photographs of section through fretting scar showing the multiple cracks initiated in seawater (31a) and the higher magnification at the left hand side (31b); $\sigma a = 195$ MPa, 1×10^5 cycles.

The initial crack growth rates are greater in seawater than in air by a factor of 10 at the stress amplitude of 160 MPa, and by a factor of 4 at 200 and 260 MPa, but the subsequent crack growth rates at the longer crack lengths are smaller in seawater than in air. The observation that the minimum in the crack growth rate curve is at a greater crack depth in seawater seems to belie the supposition that seawater may have a lubricating effect. If it were so, the sphere of action would be less in seawater because of the reduced shear stress. The results showing the greater initial crack growth rate in seawater suggest that the effect of the electrochemical attack is more dominant than the lubricating effect of seawater in the early stage of crack growth. Figure 3.32 represents schematically the crack growth behaviour. In general, as shown in Fig. 3.32(32a), it would be expected that the crack growth rate would be enhanced in seawater because of electrochemical attack. However, the results obtained in the tests show the crack growth behaviour illustrated in Fig. 3.32(32b). Two possible explanations for these results can be considered. One explanation may be that corrosion products formed in the crack can have a wedge effect[150], which can reduce the strain at the crack tip, when the crack is closed, by working as a wedge to open the crack tip. This phenomenon is sometimes observed in aqueous environments[151] or in oil[152]. However, a more likely explanation is that multiple cracks formed in seawater, as shown in Fig. 3.31, compared with only a single crack formed in air, reduce the stress concentration at their tips. This explanation has been given in corrosion fatigue, where multiple cracking is common. The fatigue life is prolonged at a given stress where multiple cracks are formed, compared with the case where a few isolated cracks are formed[153].

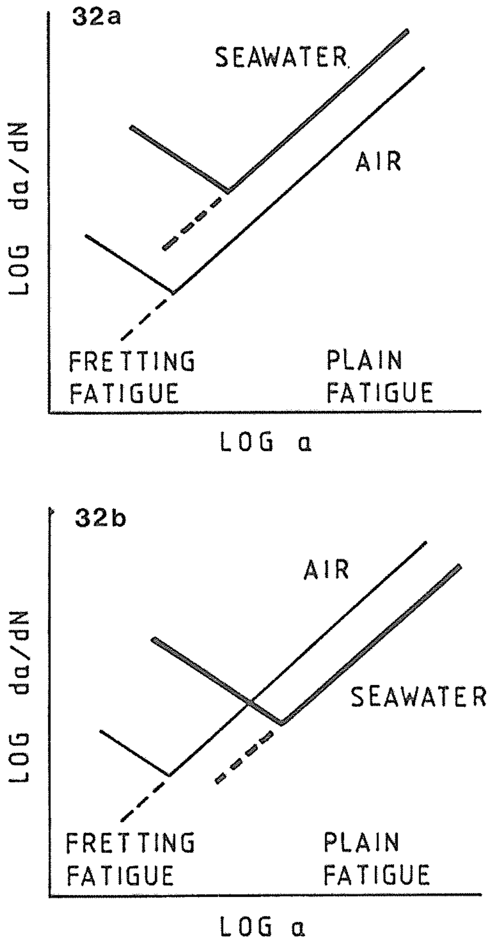


Fig. 3.32. Schematic illustration of crack growth behaviour; general behaviour (32a), the results obtained in this experiment (32b).

3.4.3 The change in shape of the fretting fatigue crack profile

The application of fracture mechanics to the analysis of the fretting fatigue behaviour of materials has been developing considerably in recent years[107,154]. Fracture mechanics can give relevant information for the prediction of fatigue life. Most of the fracture mechanics techniques applied to fretting fatigue behaviour are based on a two-dimensional analysis[97,107,108,154,155]. Although today only linear elastic fracture mechanics (LEFM) have been applied to the analysis, elastic plastic fracture mechanics (EPFM) should be considered in some cases in the same way as they have been used in normal fatigue. Very recently a three-dimensional fatigue crack growth behaviour under the influence of fretting has been investigated by KANETA *et al.*[109,156,157]. In this analysis knowledge of the crack shape is needed. The crack has been assumed to be a semi-circular shape in their analysis. However, the results obtained for short cracks in the case of normal fatigue have shown that the crack shape, namely the aspect ratio, varies according to the crack growth, and that it is greatly affected by the microstructure[158,159]. BOLINGBROKE and KING[159] found that the aspect ratios for an aluminium alloy were somewhat greater (>1.0) at short crack depths, decreased with increasing crack depth, and then tended to be around 1.0. When the crack grew to a depth of a few times greater than the grain size, the aspect ratio was much influenced by the modes of the load or stress rather than the local microstructure[160,161]. These results suggest that it is necessary to consider the change in crack shape for the three-dimensional analysis.

Figure 3.25. shows clearly the linear relationship between the aspect ratio and the crack depth. This relationship can be formulated as follows:

$$\frac{a}{c} = 8 \times 10^{-3}\, a + 0.11$$

$$\text{where } 10 < a < 100\ \mu m$$

The change in aspect ratio under the influence of fretting was found to be very different from the change in plain fatigue. The reason for this is thought to be that in a fretting situation the stress states are much more severe on the surface than in the sub-surface and also the severe stress states are widely distributed on the surface. Therefore, it can be understood that wide but shallow cracks can be initiated easily by fretting. If the cracks grow into the material, the influence of fretting is dramatically reduced so that the repeated stress alone in the bulk material governs the further crack growth and results in the rather semi-circular cracks. The results in Fig. 3.25 also indicate that neither environments (air or seawater) nor stress amplitudes have a noticeable influence on the aspect ratio under these experimental conditions.

3.5 Conclusions

The following conclusions can be drawn from this work.

(1) Fretting fatigue in seawater has a very serious damaging effect on the steel wire, reducing the fatigue strength from 150 MPa in air to 50 MPa at 2×10^6 cycles.

(2) In seawater fretting fatigue is much more damaging than corrosion fatigue.

(3) The reduction in the frequency from 5 Hz to 1.6 Hz does not influence the fretting fatigue behaviour.

(4) The initiation of micro cracks occurs within 3 per cent of the fretting fatigue life in seawater and within 20 per cent in air.

(5) In fretting fatigue in air and seawater the crack growth rate is higher at the surface, passes through a minimum and then accelerates again.

(6) The initial crack growth rate is faster in seawater than in air.

(7) The minimum in the crack growth rate curve occurs at a greater depth below the surface in seawater. Beyond the minimum the crack growth rate in air is greater than that in seawater. This is attributed to the multiple cracks formed in seawater leading to the reduction in the stress concentration at the crack tips.

(8) The profile of the crack shape at the initial stage is rather elliptical and then becomes semi-circular. The relationship between the aspect ratio, namely crack depth (a) /crack length (2c), and the crack depth is found to be as follows:

$$\frac{a}{c} = 8 \times 10^{-3}\,a + 0.11$$

$$\text{where } 10 < a < 100\ \mu\text{m}$$

Neither the environment (air or seawater) nor the alternating stress amplitude has a noticeable influence on the aspect ratio under these experimental conditions.

4 The effectiveness of cathodic protection and a reduction of oxygen concentration in alleviating fretting fatigue damage in a roping steel

4.1 Introduction

In the previous chapter, it was found that fretting in seawater had a significant detrimental effect on the fatigue behaviour of a bright wire. It is obvious that fretting in an electrolyte stimulates the electrochemical reactions occurring between the contacting surfaces and that the acceleration of the initiation and propagation of fatigue cracks is the result of this.

One of the major methods of preventing fatigue damage in an electrolyte is the application of electrochemical polarisation. Electrochemical attack can be reduced or eliminated by a potential which is either anodically or cathodically polarised. In the former case, the protective passive films formed by the anodic potential work as a barrier and isolate the bulk material from the electrochemical reactions. Cowley *et al.*[162] showed that anodic protection was beneficial in corrosion fatigue conditions. However, if the protective film is damaged by fretting, the anodic potential accelerates anodic reactions and obviously results in extremely severe damage. On the other hand, a cathodic potential suppresses the dissolution process of a metal into the electrolyte, and hence no electrochemical reaction occurs. In practice the method widely used for preventing corrosion fatigue is an application of cathodic protection. This cathodic protection can be achieved by the use of metals which are relatively less noble than the structure to be protected, or by the introduction of a cathodic potential or current to the structure using an external source.

The effectiveness of cathodic protection on fatigue behaviour is dependent on various factors, such as geometrical and loading conditions, stress intensity ranges, and materials[148,149,163-167]. For low and medium carbon steels the corrosion fatigue strength can be restored to that in air by the application of cathodic protection. For high carbon steels, namely high strength steels, hydrogen embrittlement, which is the result of cathodic reactions, can be a detrimental factor in the corrosion fatigue strength[167,168]. However, the results for high tensile roping steels recently obtained by Congleton *et al.*[146] showed that when the optimum potentials were applied to the specimens, cathodic protection was beneficial in corrosion fatigue.

Although cathodic protection is a major practical prevention technique which has been employed in marine environments, there is no information available on its effect under fretting fatigue conditions. Therefore, the present work is extended to investigate the beneficial effects of cathodic protection on fretting fatigue behaviour.

4.2 Experimental details

The apparatus, specimens and basic test procedure used were the same as those described in the previous chapter. The total clamping load was 400 N, the frequency 5 Hz and the stress ratio 0.3. The fretting cell, as shown in Fig 4.1, was equipped with a saturated calomel electrode (SCE) and a platinum counter electrode so that potentiostatic control could be applied. When seawater was introduced into the fretting cell, potentiostatic circuit connections were made and potentiostatic control was imposed to keep the potential of the specimen's surface constant with respect to the standard reference electrode.

The circulation of seawater, as described in the previous chapter, was a closed system. Deaeration of the seawater was carried out by introducing nitrogen gas into the reservoir (see Fig. 4.1) and by the additional use of 1 wt % of sodium sulphite. The concentration of dissolved oxygen in the deaerated seawater, measured by

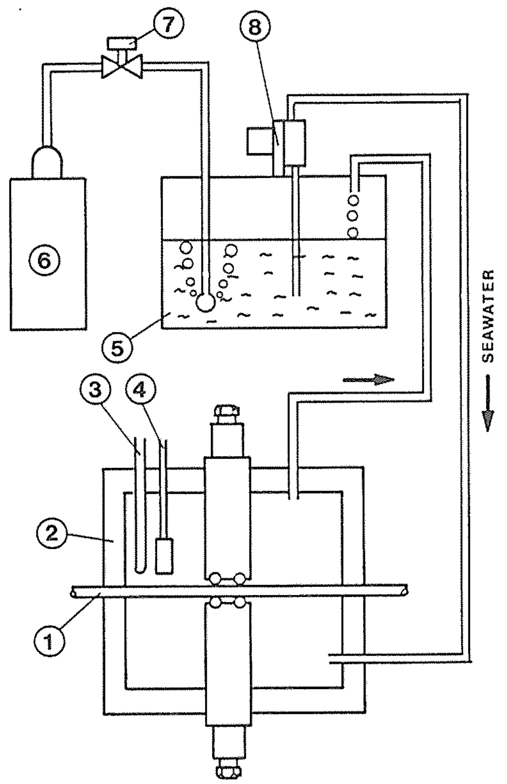


Fig. 4.1. Schematic illustration of the circulation and deaeration systems of seawater;
1) fatigue specimen, 2) fretting cell,
3) reference electrode, 4) counter electrode,
5) external reservoir, 6) nitrogen gas,
7) pressure regulator, 8) peristaltic pump.

means of a WPA-OT4 Oxygen Meter, was less than 1 ppm, compared with 8 ppm in aerated seawater. Before the introduction of the deaerated seawater into the fretting cell, the air in the circulation system, especially in the cell, was carefully flushed out by the nitrogen gas. Throughout the tests, the nitrogen gas was introduced for 3 minute periods at 20 minute intervals in order to keep the oxygen concentration at a minimum.

The polarisation curves for the wire specimen were determined under stationary conditions in the absence of fretting in both aerated and deaerated seawater. The potentiostatic polarisation measurements were made as follows: after the admission of the seawater into the cell, potentiostatic control was imposed to maintain the potential of the specimen at −1200 mV(SCE) in aerated seawater and −1400 mV(SCE) in deaerated seawater. The potential was then made more positive in steps of 20 mV using the manual fine control of the potentiostat. Each current was recorded 1 minute after the adjustment of the potential. The corrosion potentials for the wire were found to be −580 mV(SCE) in aerated seawater and −780 mV in deaerated seawater (Fig 4.2).

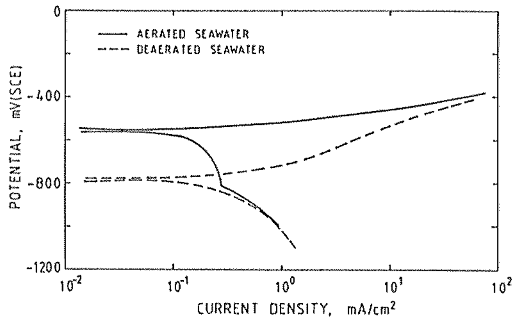


Fig. 4.2. Polarisation curves for a bright wire in aerated and deaerated seawater.

4.3 Results

4.3.1 Fretting fatigue curve under cathodic protection

Figure 4.3 shows the fretting fatigue curve determined in seawater with a cathodic protection of −850 mV(SCE). Fretting fatigue curves in air and seawater determined in the previous chapter (see Fig 3.9) are also illustrated here. The application of cathodic protection had a dramatic effect in restoring the fatigue limit and also in giving rather longer fatigue lives than in air. The cathodic protection increased the fatigue limit from 50 MPa at 2 × 10^6 cycles to 200 MPa.

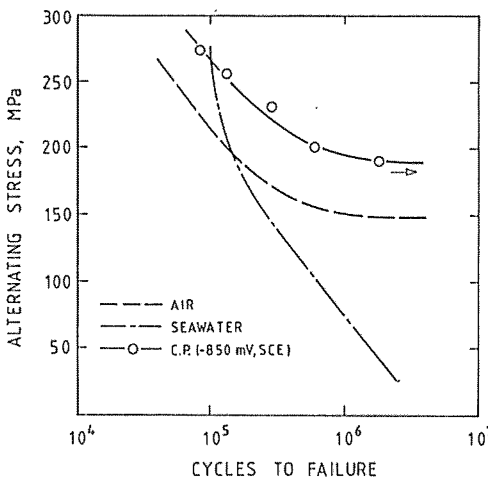


Fig. 4.3. Fretting fatigue curve in seawater with cathodic protection at −850 mV(SCE).

4.3.2 The effect of dissolved oxygen on fretting fatigue behaviour

The concentration of dissolved oxygen in seawater decreases with increasing sea depth. It is of interest to investigate the effect of the dissolved oxygen in seawater on fatigue behaviour. Figure 4.4 shows the fretting fatigue curve in deaerated seawater. The fatigue curve in seawater determined in the previous chapter is also shown in this figure. The reduction in the dissolved oxygen content of the seawater from 8 ppm to less than 1 ppm also restored the fatigue limit at 140 MPa and increased the fatigue life.

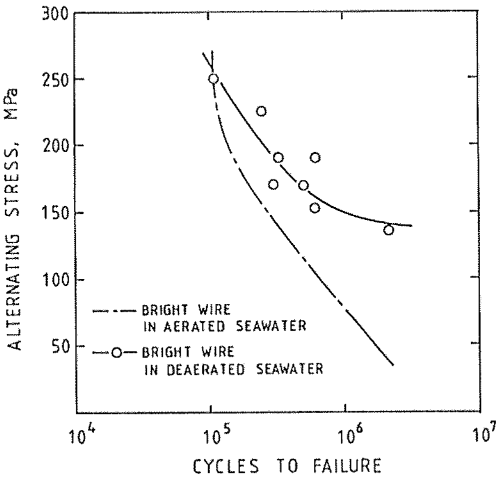


Fig. 4.4. Fretting fatigue curve in deaerated seawater.

4.3.3 The effect of applied cathodic potentials on fretting fatigue lives

The application of cathodic protection was found to be effective in increasing fretting fatigue strength. It is, therefore, necessary to know the optimum cathodic potentials in a fretting situation for practical application. Figure 4.5 shows the relationship between the applied potentials and the fatigue life. When negative potentials were applied, the fatigue life increased, and potentials in the region of -950 to -1000 mV(SCE) gave a dramatic increase in fatigue life. However more negative potentials resulted in shorter fatigue lives. This is possibly due to hydrogen embrittlement.

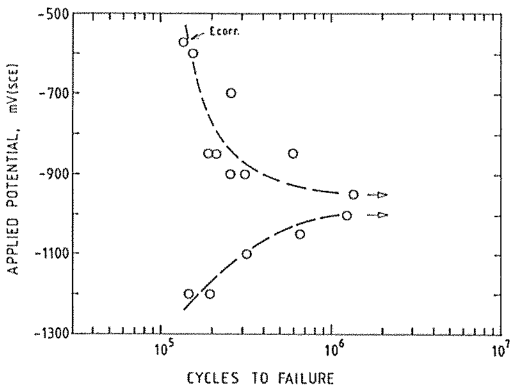


Fig. 4.5. Effect of an applied potential on the fretting fatigue life; $\sigma a = 200$ MPa.

4.3.4 Crack growth rate (da/dN) vs. crack depth curves

The crack depths at the various numbers of cycles were measured by means of the method described in the previous chapter. The results are plotted in Figs 4.6 and 4.7. The crack propagation curves in air and seawater are also shown in the figures. A micro crack was initiated at the very early stage. There was no difference in the number of cycles needed to initiate the cracks in all the environments. The applica-

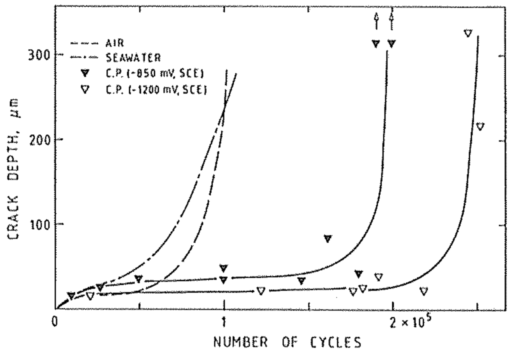


Fig. 4.6. Crack depth vs. number of cycles in seawater with cathodic protection at an alternating stress of 200 MPa.

tion of cathodic protection did not retard the initiation of the micro cracks, but retarded the subsequent crack growth. From the crack propagation curves, the crack growth rates (da/dN) were calculated and plotted against the crack depths in Figs. 4.8 and 4.9 respectively. The initial higher crack growth rates were obtained again under cathodic protection. Much lower values in the growth rate at the minimum in the subsequent crack growth, compared with those in air and seawater, were observed. After the crack growth rates passed the minimum, they rapidly increased.

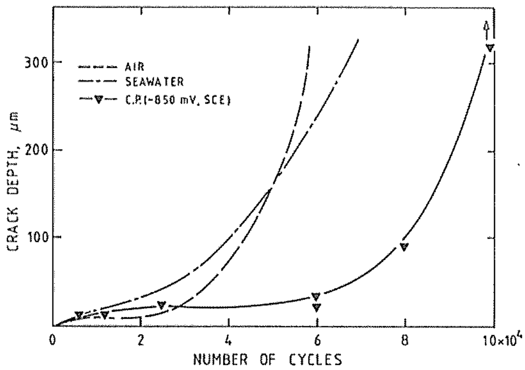


Fig. 4.7. Crack depth vs. number of cycles in seawater with cathodic protection at an alternating stress of 260 MPa.

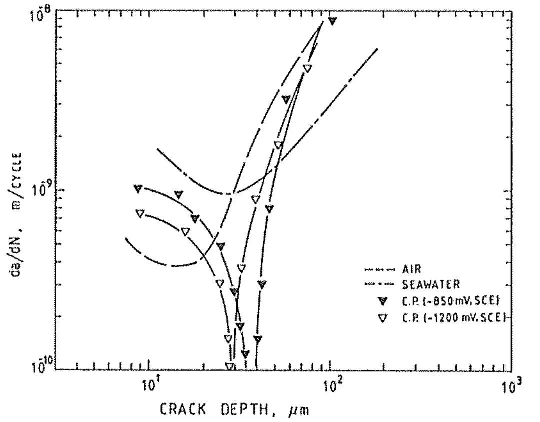


Fig. 4.8. Crack growth rate (da/dN) vs. crack depth in seawater with cathodic protection at an alternating stress of 200 MPa.

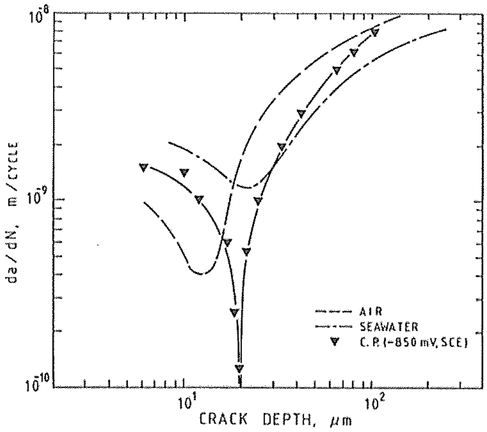


Fig. 4.9. Crack growth rate (da/dN) vs. crack depth in seawater with cathodic protection at an alternating stress of 260 MPa.

4.3.5 Scanning electron microscope examination

Figure 4.10 shows the scar area of a specimen which failed in seawater with cathodic protection at -850 mV(SCE). No subsidiary cracks were visible on the right hand side of the scar. The smearing of the scar was due to the damaging action of the bridge foot at the moment of failure. Figure 4.11 shows the fretting scar of a specimen tested in seawater with cathodic protection at −850 mV for 10^5 cycles before the failure limit. A much smaller crack compared with the cracks formed in air and seawater under the same alternating stress and number of cycles (see Figs 3.18 and 3.19 in chapter 3), was visible on the left hand side of the scar. Figure 4.12 shows photographs of the specimen which was tested at −1000 mV(SCE) but which did not fail. Corrosion products formed around the fretting scar were seen. In this case after the test the specimen was not cleaned with any solution before the examination of the corrosion products. Cracks were visible within the scar between the centre and left hand edge. It is thought that although the cracks were initiated in the early stage just near the edge in the contact region where the stress concentration was assumed to be the maximum, after the long-term tests the cracks were seen well within the scar since the fretting scar spread to the outside due to further fretting. The central region of the scar showed a smooth surface.

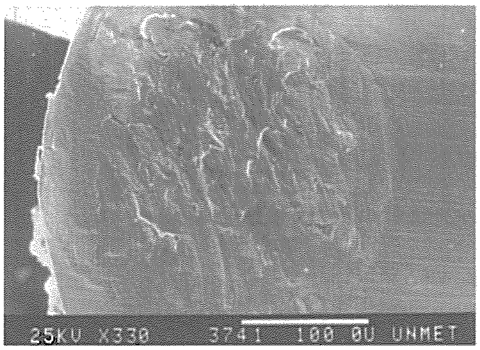


Fig. 4.10. SEM photograph showing the fracture in seawater with cathodic protection at − 850 mV(SCE); σa = 200 MPa, 5.7 × 10^5 cycles to failure.

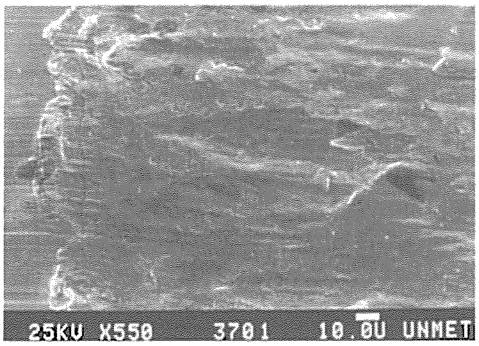
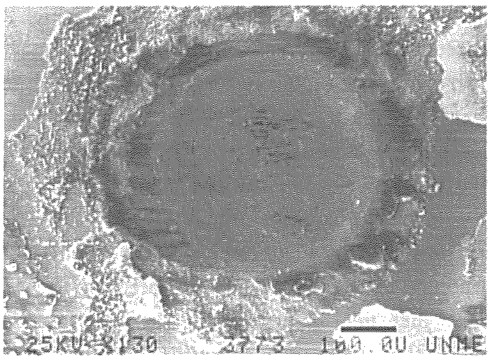
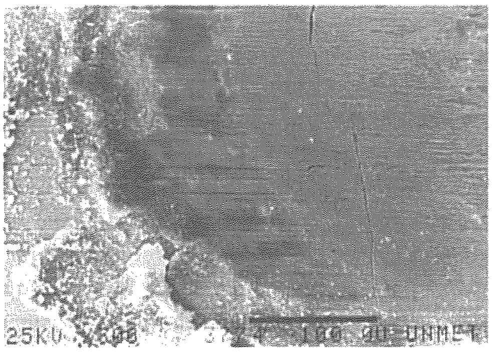


Fig. 4.11. SEM photograph showing the details of the fretting scar formed in seawater with cathodic protection at − 850 mV(SCE); σa = 195 MPa, 10^5 cycles.



(12a)



(12b)

Fig. 4.12. SEM photographs showing the fretting scar formed in seawater with cathodic protection at − 1000 mV(SCE); a general view of the scar (12a), the higher magnification (12b), σa = 200 MPa, 1.3 × 10^6 cycles.

4.4 Discussion

4.4.1 The effect of cathodic protection on fretting fatigue behaviour

In corrosion fatigue an electrochemical protection is effective in increasing the fatigue strength of the metals. An application of cathodic polarisation restores the fatigue limit in both neutral and acid solutions to that in air[146,148,165,169). Both cathodic metal[170,171) and anodic metal[148,172) coatings are beneficial in preventing corrosion and they increase fatigue strength to some extent. However, the former coating is only effective if it remains undamaged. As for the latter coating, attention should be paid to the removal of the coating due to sacrificial dissolution.

In the case of fretting corrosion fatigue, the application of a cathodic potential suppresses or greatly reduces any electrochemical reaction leaving only the mechanical action at the fretting contact. The result in Fig. 4.3 shows that the cathodic protection not only restores the fatigue limit, but also increases the fatigue life and strength. In the latter case there would be some contribution from the normal constituents of air, particularly oxygen and water vapour[83,126], and moreover from the aqueous medium which lessens the mechanical components of fretting[77]. It should be noted that the latter contribution can be expected only in a fretting situation.

4.4.2 The optimum cathodic potentials under fretting conditions

In corrosion fatigue, it is known that an applied potential more negative than a free corrosion potential under static conditions (without repeated stress) is effective in restoring the fatigue strength. This is due to the increase in metal activity with stress cycles, which results in more negative equilibrium potentials[173]. Cathodic protection is generally beneficial for lower strength steels, but is of little benefit for higher strength steels and over-protection is certainly detrimental. ENDO *et al.*[168] showed that in the case of high strength steel the maximum fatigue life was obtained at an applied potential of −800 mV(SCE) which was much more negative than the free corrosion potential (−400 mV). They also showed that potentials more negative than −800 mV reduced the fatigue life because of hydrogen embrittlement. CONGLETON *et al.*[146] recently showed that on roping steel the range of potentials from −700 mV(SCE) to −1100 mV gave the most prolonged fatigue lives.

There has been no information on the effect of applied potentials on fretting fatigue behaviour. Only the results of the fretting wear tests[64,69], showing the remarkable effects of relatively negative potentials, suggest that potentials much more negative than the free corrosion potential may give some successful protection against corrosion attack in a fretting fatigue situation. In the case of high tensile roping steels, attention should be paid to over-protection leading to hydrogen embrittlement in which the hydrogen reduces the fracture stress of the materials by directly adsorbing and lowering the surface energy at the crack tip or indirectly by diffusing to some region in advance of the crack tip. Therefore, it is of importance to investigate the optimum cathodic potentials in fretting fatigue situations, especially for practical applications.

The results shown in Fig. 4.5 indicate that more negative potentials, namely −950 mV(SCE) to −1000 mV compared with the corrosion potential (−580 mV), are necessary to give sufficient protection for this roping steel. It is noted that the optimum cathodic potential range is somewhat narrower than that obtained by CONGLETON *et al.*[146] in the normal corrosion fatigue of similar steel. This suggests that more accurately controlled cathodic potentials should be applied under the influence of fretting.

Figure 4.12 showing the cracks in the fretting scar of the specimen which did not fail at the cathodic potential of −1000 mV, indicates that failure would eventually have occurred. Cathodic potentials result in the formation of hydrogen gas and the precipitation of calcium and magnesium hydroxides. Bubbles of hydrogen gas were formed on the specimen, especially around the fretting contacts, after a few hours application of −850 mV. The more negative potentials reduced the time required to generate the hydrogen gas and increased the amount of it. It is thought that the hydrogen gas bubbles entrapped around the fretting contacts could be a barrier to prevent the direct contact between the fretting surface and the electrolyte in some cases. The deposited calcium and magnesium hydroxides surrounding the fretting scar, Fig. 4.12, indicate that three-body wear may take place under cathodic protection. It is likely that these deposits can have beneficial effects by reducing the direct metal to metal contact and lowering the coefficient of friction rather than by working as abrasive particles. However, it should be considered that these deposits could have a blocking effect between the fretting contacts and the electrolyte and could alter the electrochemical reaction subsequently occurring between the contacts.

4.4.3 The effect of cathodic protection on the initiation and propagation of fretting fatigue cracks

Figures 4.6 and 4.7 indicate that the mechanical components of fretting are dominant in the crack initiation stage as can be expected from the results in the previous chapter (see Figs 3.11 and 3.12). The application of cathodic protection does not have any significant influence on the number of fretting cycles required to initiate fatigue cracks. Figure 4.13 shows that crack initiation under cathodic protection also occurs during the very early fretting cycles.

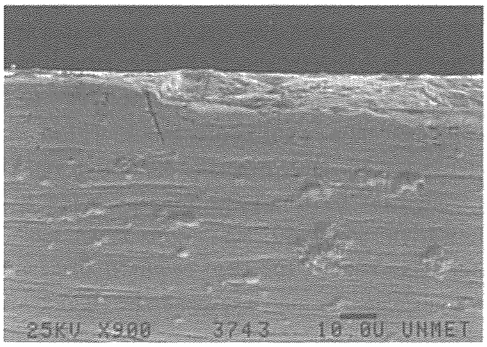


Fig. 4.13. SEM photograph showing the microcrack initiated in the early stages under cathodic protection; σa = 200 MPa, −1200 mV (SCE), 2.0 × 10^4 cycles.

As can be seen in Figs 4.8 and 4.9 the initial crack growth rates can be reduced by the application of cathodic protection, but their values under cathodic protection are still greater than those in air. It is thought that the deleterious effects of seawater, except those due to the electrochemical process, also contribute to the acceleration in the crack growth rate at this stage. Endo *et al.* reported that the adsorption of oxygen[126] and/or water molecules[174] leading to the reduction of surface energy on the newly created surfaces at the crack tip enhanced the crack growth rate. The initial crack growth rate is greater at a potential of −1200 mV(SCE) than at −850 mV. This is likely to be due to over-protection leading to hydrogen embrittlement. da/dN curves indicate that the subsequent crack growth rates are significantly suppressed by the cathodic protection. The minimum in da/dN was obtained at the region between 20 and 40 μm in crack depth. Then the crack growth rate became similar to the value in air at the greater crack depths.

Figures 4.8 and 4.9 indicate that when the cracks grow out of a certain depth, the application of cathodic protection does not seem to have any remarkable influence on the crack growth. In order to confirm this, the following two-stage environment tests under fretting conditions were carried out. At first fretting fatigue tests were carried out under free corrosion for a given number of cycles in order to produce a certain depth of cracks. Cathodic potentials were then applied to the cracks which had propagated to a certain depth. The results are shown in Fig. 4.14. When the applied potential was −950 mV(SCE) which was found to be the optimum potential (see Fig. 4.5), the propagation of the cracks formed within 3 × 10^4 cycles under free corrosion was completely retarded. The effect of cathodic protection rapidly became less as the number of cycles increased under free corrosion. When the applied potentials were −850 and −1200 mV(SCE) which were found to be insufficient and over-protective respectively, the propagation of the cracks within 3 × 10^4 cycles was also retarded, then the curve approached the fatigue life obtained under free corrosion alone.

The results shown in Fig. 4.14 suggest that there is a critical crack depth at which the effectiveness of cathodic protection changes. It is of interest to investigate the value of this critical crack depth. The crack propagation curve under free corrosion in seawater has already been obtained in Fig. 3.11 in the previous chapter. It is, therefore, possible to determine the relationship between the depth of the crack at which the cathodic potentials are applied and the number of cycles to failure. The results plotted in Fig. 4.15 show clearly the existence of the critical crack depth. If the crack depth is smaller than 30 μm, the applied potentials fully govern the crack growth but its effect dramatically decreases as the crack grows further.

Finally a crack formed in a two-stage environments test, namely 5.5×10^4 cycles under free corrosion and then 6.5×10^4 cycles under a cathodic potential of -950 mV(SCE), is shown in Fig. 4.16. This photograph clearly shows an oblique crack, which is initiated and propagated under the influence of shear stress due to fretting, and a subsequent crack, perpendicular to the surface, which is due to the normal alternat-

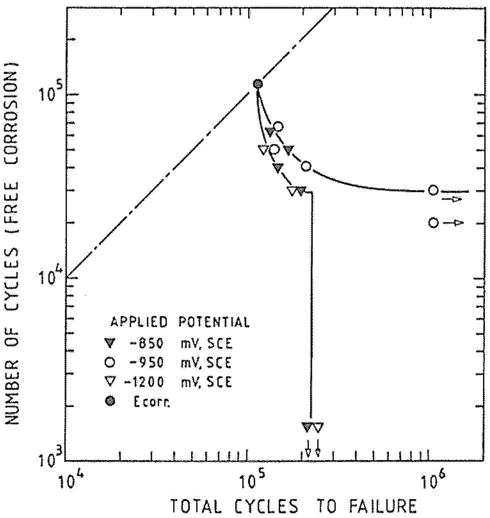


Fig. 4.14. Two-stage environments tests under fretting conditions; the cathodic potential is applied only after the wire has been subjected to fretting fatigue for a given number of cycles under free corrosion. $\sigma a = 200$ MPa.

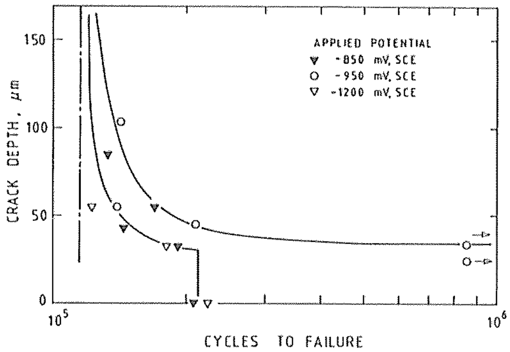


Fig. 4.15. Total fatigue life, shown in Fig. 4.14., plotted against the depth of the crack propagated under free corrosion.

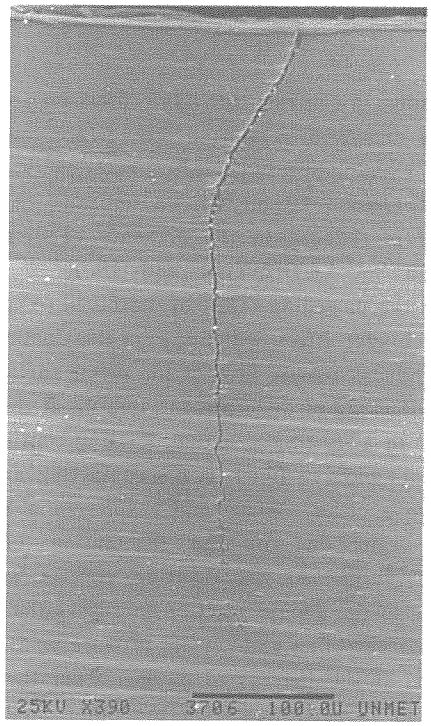


Fig. 4.16. SEM photograph showing the oblique crack and the subsequent crack perpendicular to the surface; 5.5×10^4 cycles under free corrosion and then 6.5×10^4 cycles with cathodic protection at -950 mV(SCE). $\sigma a = 200$ MPa.

ing tensile stress. The transition from the oblique crack to the perpendicular crack occurred at approximately 100 μm in depth. It is noted that no multiple cracks were formed under these conditions.

4.4.4 The effect of dissolved oxygen on fretting fatigue behaviour

Dissolved oxygen in seawater can have two effects. Firstly, it can accelerate cathodic reaction by working as follows:

$$\frac{1}{2}O_2 + H_2O + 2e \longrightarrow 2OH^-$$

or

$$\frac{1}{2}O_2 + 2H^+ + 2e \longrightarrow H_2O$$

Secondly, in contrast, the oxide films formed due to the dissolved oxygen on the surface can be a barrier and suppress corrosion reaction.

Corrosion fatigue life in aqueous environments is reduced in the presence of dissolved oxygen[169,175]. DUQUETTE and UHLIG[169] attributed the damaging effect of dissolved oxygen to the Rebinder effect, which lowers the elastic limit and induces plastic flow of the metal surface by the unlocking of dislocations piled up at the surface. In a fretting situation, fretting continually disrupts passive films in the contacting area to expose a clean surface and results in a higher wear rate due to the dissolution of the metal[65,66,68]. At the fretting contact an increase in the anodic reaction increases the metal ion concentration and results in more acidic conditions if the ingress of oxygen from the bulk solution is restricted. On the other hand, the area outside the fretting contact becomes cathodic. It is likely that the corrosion rate at the fretting contact is controlled by the cathodic reaction occurring outside the contact. This cathodic reaction is dependent on the dissolved oxygen concentration in the bulk solution. SMALLWOOD *et al.*[176] assumed that fretting contact was a crevice corrosion situation and that the conditions within the anodic area were constant. They attempted a quantative analysis to correlate fretting wear loss with the dissolved oxygen concentration in the electrolyte.

The polarisation curves illustrated in Fig. 4.2 show that the reduction of the oxygen concentration in seawater results in lower corrosion potentials. From Fig. 4.5 the fatigue life at an applied potential of −780 mV(SCE), which was found to be the corrosion potential of this wire in deaerated seawater, is obtained at 2.2×10^5 cycles. On the other hand, the fatigue life at an alternating stress of 200 MPa in deaerated seawater is obtained at 2.5×10^5 cycles (Fig. 4.4). Therefore, it is thought that the role of removing the dissolved oxygen in seawater on fretting fatigue behaviour is to give the same effect as cathodic protection.

4.5 Conclusions

The following conclusions can be drawn from this work.

(1) The application of cathodic protection has a dramatic effect in restoring the fatigue limit and also in giving longer fatigue lives than in air. The application of a cathodic potential of −850 mV(SCE) increases the fatigue strength from 50 MPa at 2×10^6 cycles under free corrosion to 200 MPa.

(2) The reduction in the dissolved oxygen concentration of the seawater from 8 ppm to less than 1 ppm also restores the fatigue limit at 140 MPa.

(3) The optimum cathodic potentials are found to be in the region between −950 mV(SCE) and −1000 mV.

(4) Cathodic protection has a dramatic effect in reducing the crack growth rate at the early stage. However, it does not have any significant influence on the number of fretting cycles required to initiate a micro crack.

(5) There is a critical crack depth which may or may not be controlled by the applied potentials. If the crack depth is smaller than 30 μm, the applied potentials fully govern the crack growth, but the effectiveness of the cathodic protection dramatically decreases as the crack grows further.

5 The effectiveness of galvanised coatings in alleviating fretting fatigue damage in a roping steel

5.1 Introduction

The application of the cathodic protection with optimum potentials was found to be a beneficial measure in restoring and increasing the fretting-corrosion-fatigue strength. However, in practice, it is difficult to apply a cathodic potential to wire ropes used in marine environments. Mooring ropes, for example, stretch from the sea bed, which is a few hundred metres down, to the surface of the seawater. Another difficulty is that in order to give the optimum cathodic potential to the wires in the central area of a rope potentials much more negative than the optimum potential are required since a significant potential drop occurs in the rope[146]. This means that the wires in the outer layer of the rope could be damaged by hydrogen embrittlement due to over-protection. An alternative electrochemical protection could be the use of sacrificial metal coatings such as galvanising.

The main function of metal coatings is to prevent corrosion and in some cases mechanical damage. In a fretting situation the following reasons for the reduction in fretting damage by metal coatings seem to be apparent: 1) softer coatings, such as lead, can absorb the movement between the two surfaces, 2) harder coatings, such as chromium, can reduce the damage caused by the abrasive particles of metal or oxide, 3) metal coatings of high conductivity can dissipate the local heat, which has a deleterious effect on both the wear and fatigue, generated by fretting[177]. Waterhouse *et al.*[67] have found that a galvanised coating is effective in reducing fretting wear. The work on the plain fatigue of a galvanised wire in seawater has also shown that galvanising delays the incidence of cracking and extends the number of cycles to failure[146]. These results instigated the present work to investigate the effect of galvanising on the fretting fatigue behaviour of wire ropes used in marine environments.

5.2 Experimental details

The apparatus employed was the same fatigue machine described in chapter 3. The details of the specimen used in the tests were as follows: hot-dipped galvanised wire, actual diameter of the wire 1.49 mm, U.T.S. 1900 MPa, zinc coat weight 187 g/m^2, carbon content of steel 0.79 wt%. Figure 5.1 is a SEM photograph showing a section through the zinc coating etched in 2% nital. A columnar structure formed between the substrate and zinc layer was visible. An energy dispersive X-ray analysis (EDAX) showed that this layer consisted of an Fe-Zn alloy with a thickness of 10 μm. This alloy layer had a hardness of 135 Hv. The zinc layer had a hardness of 65 Hv and was 20 μm in thickness. The hardness of the substrate was 550 Hv. Figure 5.2 shows the polarisation curve for the galvanised wire in seawater. The results for an ungalvanised wire are also demonstrated in the figure. The polarisation measurement was carried out according to the procedure described in the previous chapter.

The experimental conditions and the basic test procedure were the same as those described in chapter 3, namely the total clamping load was 400 N, the frequency 5 Hz, and the stress ratio 0.3. The tests were carried out in air and seawater. Some of the tests were stopped before failure and the specimens were examined in a scanning electron microscope so that the progression of fretting damage could be observed. In some tests bright wire specimens were used so that the results could be compared with the data for a galvanised wire.

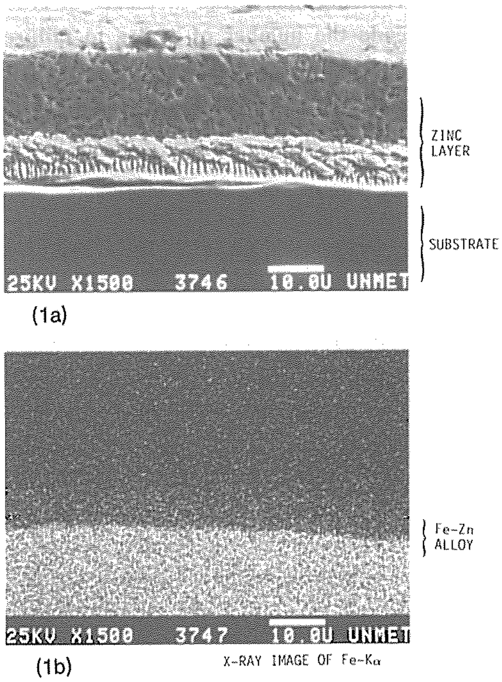


Fig. 5.1. SEM photograph showing a cross section through a galvanised coating (1a) and the corresponding EDAX photograph (1b).

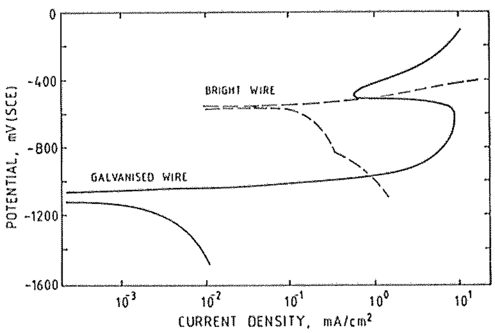


Fig. 5.2. Polarisation curves for galvanised and ungalvanised wires in seawater.

5.3 Results

5.3.1 Fretting fatigue curves

Figure 5.3 shows the curves for a galvanised wire in contact with galvanised wire bridge feet in air and seawater. The results for a bright wire obtained in chapter 3 are also shown in the figure. Although the U.T.S. of the galva-

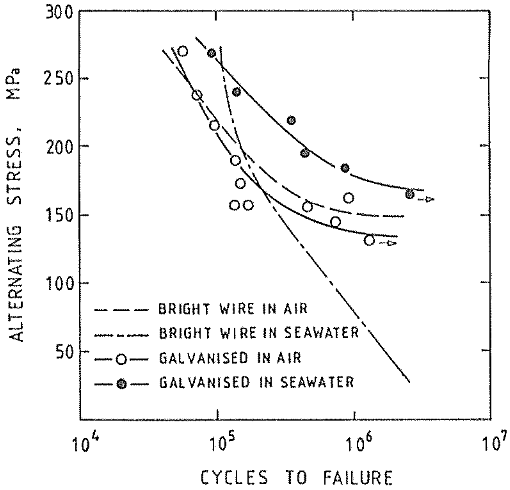


Fig. 5.3. Fretting fatigue curves for galvanised wire in air and seawater.

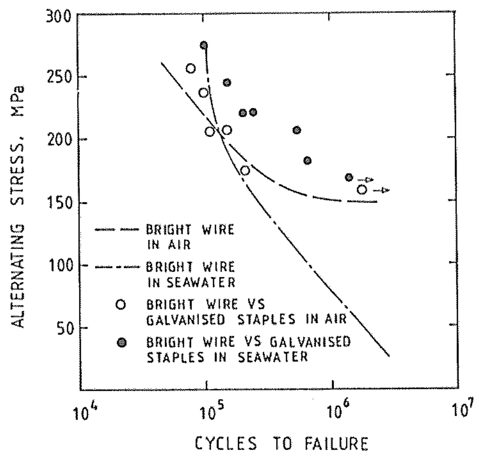


Fig. 5.4. Fretting fatigue curves for ungalvanised wire in contact with galvanised wire bridge feet in air and seawater.

nised wire was slightly higher than that of the bright wire, the galvanising increased the fatigue strength to 175 MPa in seawater but in air reduced the fretting fatigue strength to 130 MPa compared with 150 MPa for the ungalvanised wire.

Figure 5.4 shows the curves for a bright wire in contact with galvanised wire bridge feet in air and seawater. In air the curve was identical to that for a bright wire contacting ungalvanised wire bridge feet. In seawater the curve was identical to that for the galvanised wire contacting galvanised wire bridge feet shown in Fig.

5.3.2 Crack growth rate (da/dN) vs. crack depth curves

Crack growth curves for an ungalvanised wire in contact with galvanised wire bridge feet in air and seawater were determined according to the procedure described in chapter 3. The results are shown in Fig. 5.5. The initiation of a fatigue crack occurred much earlier in air than in seawater. Figure 5.6 shows the da/dN calculated from the curves in Fig. 5.5 vs. crack depth curves.

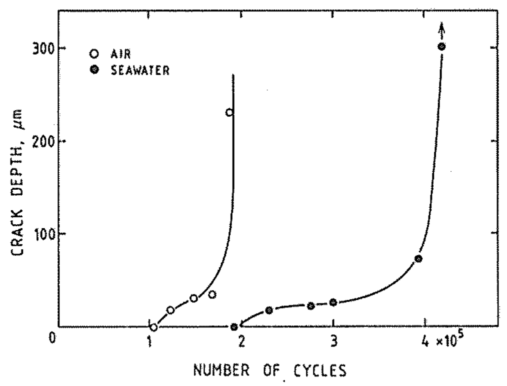


Fig. 5.5. Crack depth vs. number of cycles for ungalvanised wire on galvanised bridge feet at an alternating stress of 200 MPa.

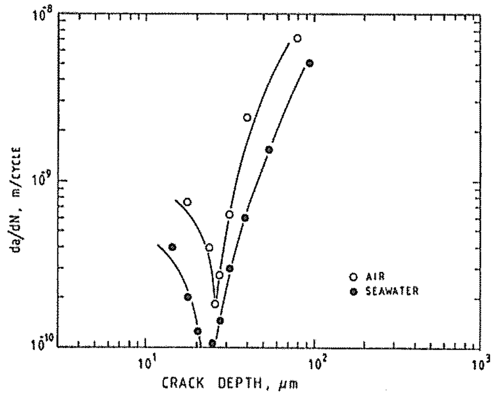
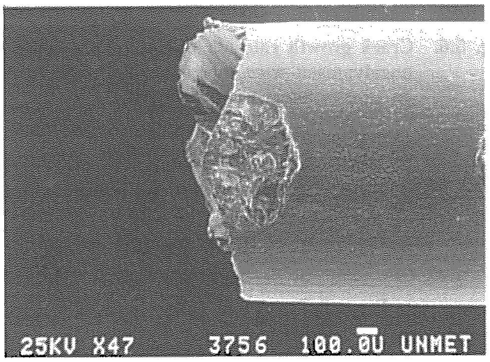


Fig. 5.6. Crack growth rate (da/dN) vs. crack depth for ungalvanised wire on galvanised bridge feet at an alternating stress of 200 MPa.

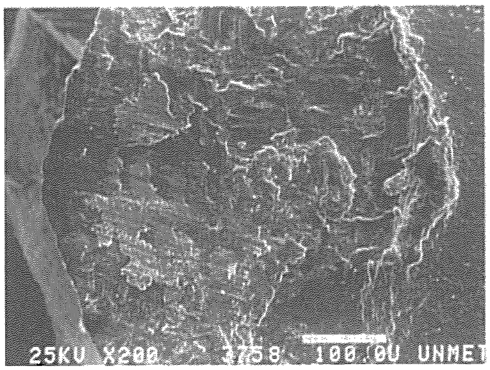
5.3.3 Scanning electron microscope examination

A general view of the fractured specimen in air and the scar at a higher magnification are shown in Fig. 5.7. The scar formed on the galvanised wire was much greater and showed a much rougher surface than that formed on the bright wire (see Fig. 3.16). This was due to the extrusion of the softer zinc layer. Superficial damage, such as smearing and scoring, was visible in the left half of the scar. This damage was caused by the fretting bridge foot at the moment of failure. Figure 5.8 shows the corresponding views of failure in seawater. A smooth surface within the scar was visible. Severe pitting of the zinc arising from its sacrificial dissolution was seen around the fretting scar.

Figure 5.9 shows the fretting scar formed on the specimen in the test which was stopped before failure in air. A considerable amount of zinc was extruded from the fretting surface. A large crack was visible on the right hand side of the scar. Figure 5.10 shows the corresponding pictures of the fretting scar formed in seawater. A smooth surface which was free of debris in the central region of the scar and a rough surface due to the dissolution of zinc around the scar were visible, but no cracks were observed. Figure 5.11 shows the EDAX photograph of the fretting scar shown in Fig. 5.10(10a). The zinc coating in the scar was completely extruded. Figure 5.12 shows a section through the fretting scar shown in Fig. 5.9. It can be seen that in the central area of the scar the zinc coating including the Fe-Zn alloy layer was extruded. An oblique crack initiated from the left hand side of the scar was seen. Figure 5.13 shows a section of the scar shown in Figure 5.10. It can be noted that the anodic dissolution of the zinc coating occurred in only the zinc layer, namely the Fe-Zn alloy did not give cathodic protection.

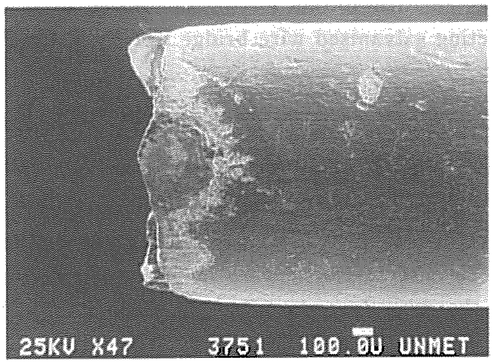


(7a)

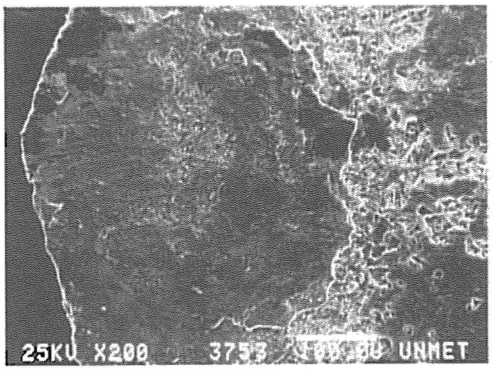


(7b)

Fig. 5.7. SEM photographs showing a general view (7a) of the fracture in air and the higher magnification (7b); galvanised wire, $\sigma a = 190$ MPa, 1.4×10^5 cycles to failure.

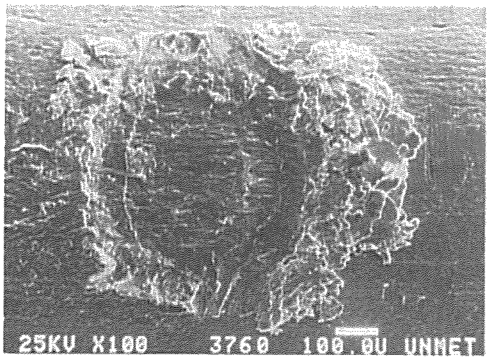


(8a)

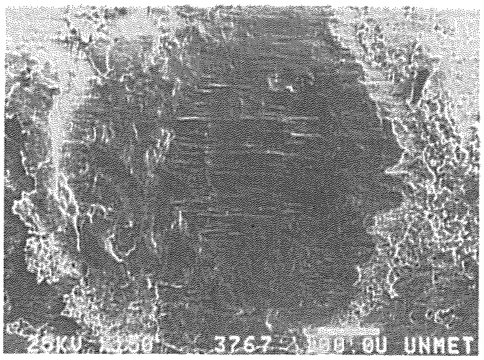


(8b)

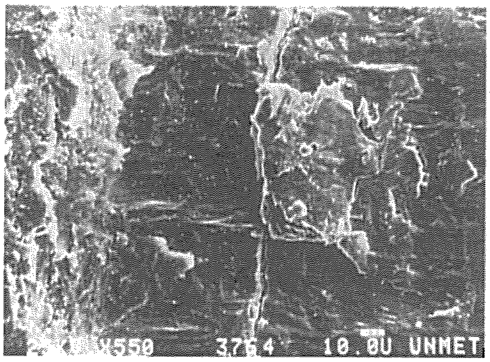
Fig. 5.8. SEM photographs showing a general view (8a) of the fracture in seawater and the higher magnification (8b); galvanised wire, $\sigma a = 183$ MPa, 8.5×10^5 cycles to failure.



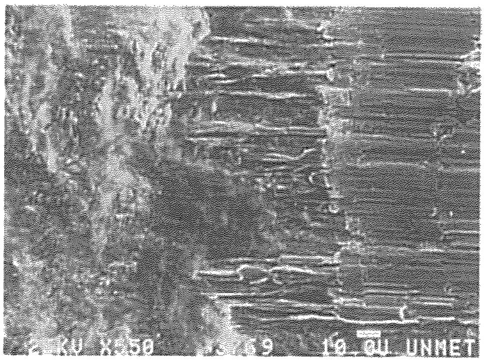
(9a)



(10a)



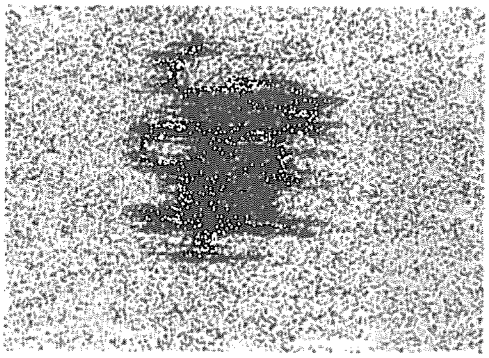
(9b)



(10b)

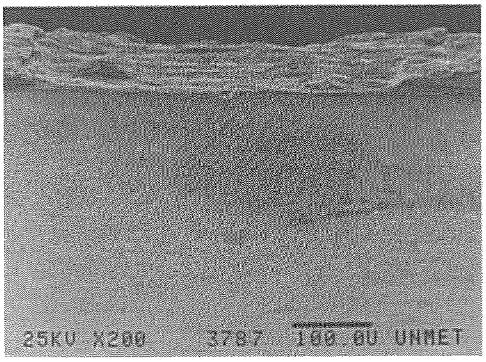
Fig. 5.9. SEM photographs showing the fretting scar on the galvanised wire tested in air for 10^5 cycles (9a) and the higher magnification (9b); σ a = 195 MPa.

Fig. 5.10. SEM photographs showing the fretting scar on the galvanised wire tested in seawater for 10^5 cycles (10a) and the higher magnification (10b); σ a = 195 MPa.

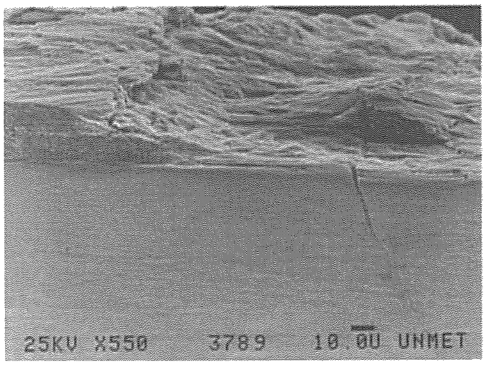


X-RAY IMAGE OF Zn-Kα

Fig. 5.11. EDAX photograph showing the extrusion of the zinc layer from the fretting contact after 10^5 cycles in seawater; the corresponding photograph of Fig. 5.10. (10a).



(12a)



(12b)

Fig. 5.12. SEM photographs showing the section through the fretting scar shown in Fig. 5.9. (12a) and the higher magnification on the left hand side of the scar (12b); in air, σa = 195 MPa, 1 × 10^5 cycles.

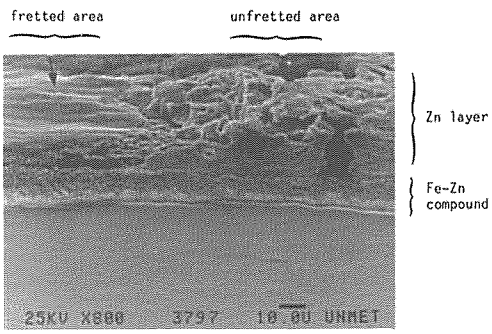


Fig. 5.13. SEM photograph of the section through the fretting scar shown in Fig. 5.10 showing severe pitting of the zinc layer due to sacrificial dissolution; in seawater, σa = 195 MPa, 1 × 10^5 cycles.

5.4 Discussion

In general, metal coatings reduce fatigue strength in air due to 1) the formation of tensile internal stress in the coatings, 2) the formation of fine cracks in the coatings, and 3) the co-deposition of hydrogen[178]. Various metals are used for coatings. A chromium coating has deleterious effects as it works in all three of the above ways. The adverse effects of a nickel coating are mainly due to the first and second reasons. In the case of galvanising, an electrodeposited coating does not reduce fatigue strength, but a hot-dipped coating has a deleterious effect. In the latter case the brittle Fe-Zn alloy formed between the steel and zinc can be the source of the initiation of fatigue cracks. This has already been shown in early investigations[172].

On the other hand, WATERHOUSE *et al.*[137] carried out fretting fatigue tests on mild steel specimens electroplated with a number of metals. They showed that the effect of electrodeposited coatings on the fatigue behaviour was dependent on the balance between the reduction of fretting damage and the deleterious effects of coatings. The metals which were relatively soft, and had a high thermal conductivity and cathode efficiency were beneficial as coatings.

The results shown in Fig. 5.3 indicate that galvanising has a significant effect in increasing the fatigue strength of wire in seawater, but reduces the fatigue strength in air. The effect of galvanising is almost as marked as the effect of applying a cathodic potential of −850 mV(SCE) which increases the fatigue strength to 200 MPa (Fig. 4.3). Zinc around the fretting scar works as an anodic electrode and suppresses the electrochemical attack occurring between the contacting surfaces (Figs 5.8 and 5.13). The slight reduction in the fatigue strength in air seems to be due to the hard Fe-Zn alloy layer in which fretting is likely to initiate cracks.

Residual stress is one of the factors which can influence fatigue behaviour. The longitudinal residual stress produced by cold drawing is generally tensile on the surface of the wire and compressive in the wire and this tensile stress reduces the fatigue performance[179]. The drawing process also produces a residual stress distribution on the circumberence of the wire. The theoretical analysis made by KNAP[180] indicated that since the wire was pulled at an angle through the final die in order to cause it to coil, the residual stress distribution was asymmetric, namely around the most lengthened fibre during the winding of the wire onto the drum the compressive residual stress was induced and the tensile stresses remained on the rest of the circumference. His analysis also showed that this distribution depended on the parameter of the drawing itself and on the winding conditions of the drum. If the hot-dip galvanising reduced the amount of tensile residual stress, the fatigue behaviour would have improved. Therefore, the axial surface residual stresses in both galvanised wire and ungalvanised (bright) wire were measured by X-ray diffraction. In the case of the galvanised wire, the coating was removed prior to the measurement by the following procedure; the wire was immersed in concentrated nitric acid (67% HNO_3) for 10 to 15 seconds to remove the zinc layer and intermetallic compound, and was washed with running water. Steel passivates in this solution. There should be no attack of the steel in a few seconds of immersion. The results are shown in Fig. 5.14. The residual stresses measured were all tensile for both the wires and there was no noticeable asymmetric distribution of the stresses on the circumference of the wire. The residual stresses in the ungalvanised wire at the points that the fretting was applied were found to be tensile stresses of 165 to 207 MPa. These were reduced to the tensile stresses of 91to 124 MPa by hot-dip galvanising. However, Figure 5.3 indicates that the deleterious effect of the Fe-Zn compound is more dominant than the effect of the residual stress altered by the galvanising.

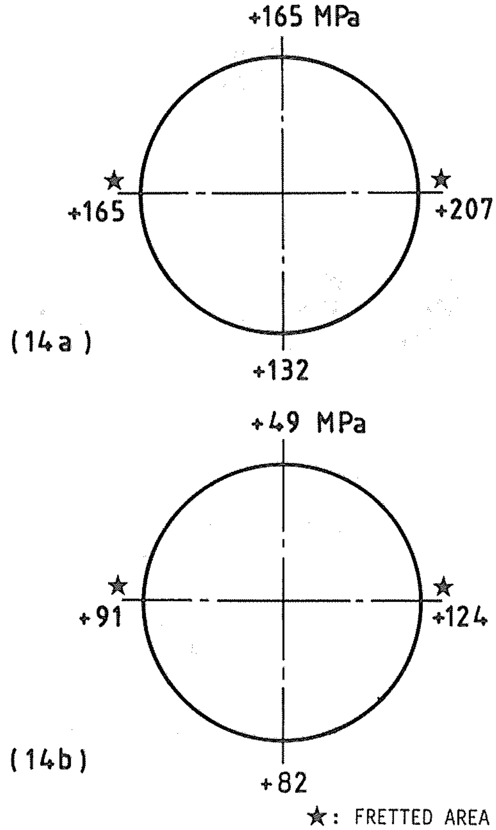
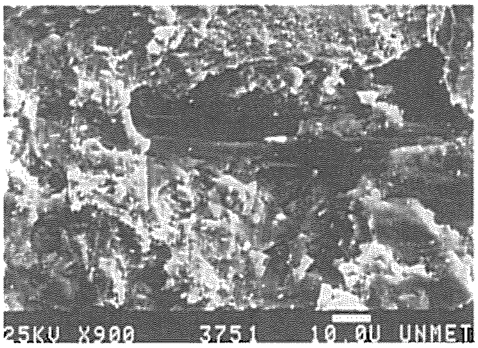
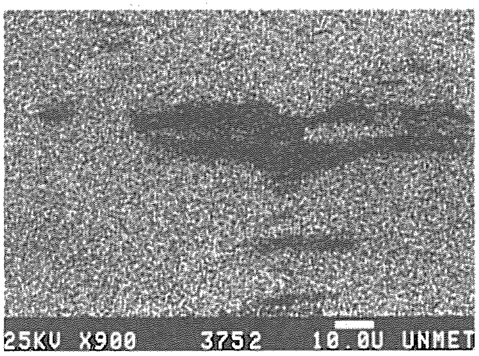


Fig. 5.14. Distribution of the residual stresses on the circumference of the cold drawn wire and the effect of the hot-dip galvanising; ungalvanised wire (14a), galvanised wire (14b).

Another interesting test is to examine the mechanical resistance of a zinc layer to fretting. The results in Fig. 5.4 indicate that galvanising does not suppress mechanical damage due to fretting in air. This is also seen in Fig. 5.11 which shows the complete extrusion of zinc from the contacting surfaces and normal fretting in steel against a steel contact. Moreover, the extrusion of the coating occurs in the early stage of fretting



(15a)



(15b) X-RAY IMAGE OF Zn-Kα

Fig. 5.15. Extrusion of the zinc layer in the early stages (5×10^3 cycles); SEM photograph showing the central region of the fretting scar (15a) and the corresponding EDAX photograph (15b).

(Fig. 5.15). However, WATERHOUSE *et al.*[67] have shown that in the fretting wear of galvanised wire vs. bright wire all the wear damage occurs on the coating and there is no damage to the bright wire. The discrepancy between their results and the present results is thought to be due to the differing severity of the fretting conditions, especially the load. The total clamping load used in the present tests is 400 N compared with 3 or 6 N used in their tests.

Figure 5.4 gives relevant information for practical applications of galvanised wire in marine environments. The importance of this is that the exhaustion of the zinc in the contact by squeezing out does not mean that its effect is lost. The result in Fig. 5.4 also suggests that to give necessary galvanic protection it is only necessary to have one of the surfaces of the contact coated with zinc or to impose sacrificial zinc around the fretting contacts.

The corrosion potential for the galvanised wire was found to be −1020 mV(SCE) (Fig. 5.2). A somewhat unexpected result is that in seawater the fatigue life for the galvanised wire is much lower than that obtained at the applied potential of −1000 mV(SCE) shown in Fig. 4.5 in the previous chapter, namely the fatigue life for the galvanised wire is 4.5×10^5 cycles at an alternating stress of 200 MPa compared with that for the bright wire at a cathodic potential of −1000 mV(SCE), which is run-out ($> 1.2 \times 10^6$ cycles) at the same stress level. Figure 5.16 shows the results for the bright wire on which pure zinc wire (0.5 mm in dia. and 40 mm in length) was wound in two places, each at a distance of 20 mm from the fretting contacts, as shown in Fig. 5.17. Two points tested at an applied potential of −1000 mV(SCE) were also plotted in the figure. The results in Fig. 5.16 indicate that the zinc gives the same effect as the application of a cathodic potential of −1000 mV(SCE) which is approximately the same as the potential of the zinc. Therefore, it is thought that the brittle Fe-Zn compound still contributes to the reduction in the fatigue strength in seawater. Another unexpected result is that although some of the zinc coating still remains on the bridge feet after the tests (this was examined in a SEM), the fatigue strength for an ungalvanised wire in contact with galvanised bridge feet is identical to that for a galvanised wire (Fig 5.4). This result suggests that the amount of the anodic metal seems to be one of the factors in providing sufficient cathodic protection.

The crack growth behaviour for an ungalvanised wire in contact with galvanised bridge feet is similar to that for an ungalvanised wire on un-

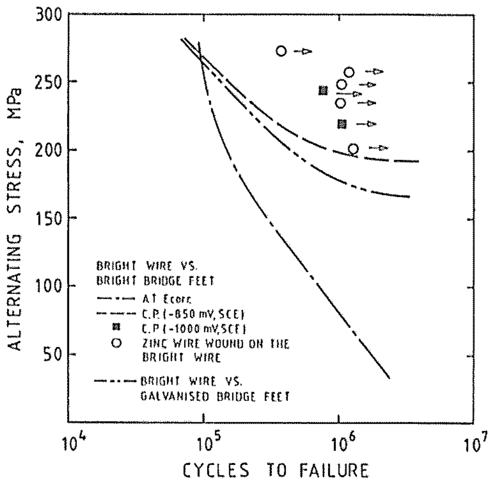


Fig. 5.16. Effects of the sacrifical zinc wire and the cathodic potential of -1000 mV(SCE) on the fretting fatigue life.

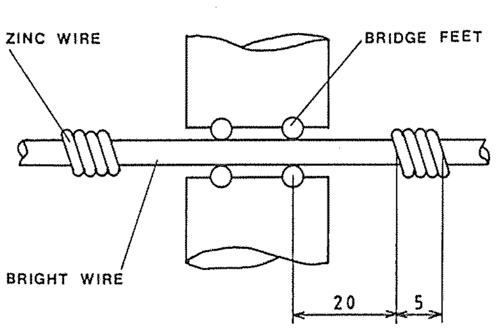


Fig. 5.17. Details of the tests with sacrificial zinc wire partially wound onto the bright wire.

galvanised bridge feet (Fig. 5.6). However, it is noted that the initial crack growth rate is greater in air than in seawater. This is likely to be due to the zinc coating which may prolong the occurrence of the direct metal to metal contact in the initial stage and also which may reduce the coefficient of friction in seawater.

5.5 Conclusions

The following conclusions can be drawn from this work.

(1) A galvanised coating on the wire increases the fatigue strength in seawater to 175 MPa compared with 50 MPa 2×10^6 cycles for an ungalvanised wire.

(2) However, in air the coating reduces the fatigue strength to 130 MPa compared with 150 MPa for the ungalvanised wire. This reduction in the fatigue strength is attributed to the existence of the brittle Fe-Zn alloy layer.

(3) The deleterious effect of the Fe-Zn alloy layer is more dominant than the effect of the residual stress which is altered by the galvanising on the fatigue performance.

(4) In air the fatigue curve for the ungalvanised wire in contact with the galvanised wire is identical to that for the ungalvanised wire. This means that a galvanised coating does not reduce the mechanical damage due to fretting.

(5) In seawater if the contacting surface is galvanised it exerts the same sacrificial protection as a galvanised wire. This indicates that in practice the protection of a steel rope is likely to be efficient even if the zinc coating is extruded or worn away in a fretting contact.

6 Summary

6.1 General conclusions

Fretting fatigue tests of a high tensile roping steel wire, 1.5 mm dia., UTS 1770 MPa grade, were carried out in fluctuating tension at a frequency of 5 Hz and a stress ratio of 0.3 in air and seawater. The effects of cathodic protection and galvanising on the fretting fatigue behaviour were investigated. The following general conclusions can de drawn from this work.

(1) Fretting fatigue in seawater has a much more serious damaging effect than corrosion fatigue. Fretting causes a much greater crack growth rate in seawater than in air in the initial stages. Chemical and electrochemical effects

play a major role in fretting fatigue failure in seawater.

(2) One technique for preventing fretting fatigue failure in marine environments is the application of cathodic protection. Cathodic protection at optimum potentials has a drametic effect in restoring the fatigue strength and also in giving longer fatigue lives than in air. The optimum cathodic potentials are found to be in the region between −950 mV(SCE) and −1000 mV. Cathodic protection has a significant effect in raducing the initial crack growth rate. However, if the crack grows out from a certain depth, the effectiveness of cathodic protection is dramatically reduced.

(3) Another beneficial measure to prevent fretting fatigue failure is the use of sacrificial metal coatings. A galvanised coating significantly improves the fatigue strength in seawater by suppressing the electrochemical attack. If the contacting surface is galvanosed it exerts the same sacrificial effect as a galvanised wire. This result is important in practice, because if the zinc coating is extruded or worn away in a fretting contact, protection of the steel rope is still likely to be efficient.

6.2 Further work

The following work is suggested to provide futher understanding of the mechanisms of fretting fatigue failure in marine enviroments and to improve techniques to prevent such failure.

(1) Machanisms of fretting fatigue failure

1-1) Details of electrochemical reactions occurring in fretting fatigue situations and the effect of calcareous depositions as the result of the electrochemical reactions on the initiation and propagation behaviour of a fatigue crack need to be investigated.

1-2) Two stage tests need to be carried out to determine fretting fatigue thresholds.

1-3) The initiation and propagation mechanisms of a fatigue crack in hot-dipped galvanised wire need to be investigated.

(2) Design data

2-1) The fretting fatigue performance of wire ropes, the effectiveness of cathodic protection by applied potentials and/or anodic coatings, and the effect of crevice corrosion need to be investigated in long-term tests, especially at much lower frequencies, e.g. 0.1 Hz.

2-2) Bending fatigue tests need to be carried out since the ropes over pullies, winch drums, and deflection rollers, etc. are possibly subjected to bending motion.

2-3) The calculation of a stress intensity factor range (ΔK) in fretting situations and an investigation of the effect of crack closure need to be carried out.

2-4) Fretting fatigue tests in seawater under high pressure might provide more useful data for a practical application in deep water.

(3) Effective prevention

3-1) The effectiveness of an electrodeposited zinc coating compared with that of a galvanised coating in increasing the fretting fatigue strength needs to be examined. It is also necessary to determine the thinkness of the coating which will give electrochemically and mechanically sufficient protection against fretting fatigue damage.

3-2) Assessments of double or more combined protections, such as lubticants plus coatings, externally applied cathodic potentials plus anodic coatings, and these protections plus improvements in the mechanical properties of the materials, especially the production of compressive residual stress in the surface, by shotpeening, heat-treatment etc., need to be carried out to provide information about more efficient methods of prevetion.

3-3) Further tests need to be carried out to investigate mechanisms of the critical crack depth at which the effectiveness of cathodic protection is dramatically reduced.

3-4) Fretting fatigue behaviour in a seawater-oil enviornment needs to be investigated since the wire ropes used in deep water are protected with heavy grease.

Acknowledgments

The author would like to express his sincere appreciation to Dr. R.B. Waterhouse, University of Nottingham (UK), for his guidance, encouragement and supervision throughout this research. Thanks are also due to Professor J.S.L. Leach, Head of the Department of Metallurgy and Material Science, for providing the facilities necessary to carry out the work.

The author wishes to thank Professor J. Sato, Tokyo University of Mercantile Marine, for his special encouragement. Thanks are also due to Professor H. Miyagawa, Oita University, Dr. A. Iwabuchi, Iwate University, Dr. Y. Mutoh, Technological University of Nagaoka, for their useful suggestions and to Dr. P.J. Boden, University of Nottingham for his advice in the field of corrosion.

The staff in the Department, University of Nottingham, particularly Mr. K. Dinsdale and Mr. H. Elliott were most helpful manufacturing the test rig and the specimens. Thanks are due to research fellows, especially Drs. R. Smallwood and A.P. Van Gool for their help. The author is also grateful to British Ropes Ltd. for providing the specimens.

The author would like to thank the staff in the Department of Marine Engineering, Shimonoseki University of Fisherises.

Finally, many thanks are extended to the author's wife, Janet, without whose support and help with English this work could not have been completed.

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海水中におけるロープ用鋼のフレッチングと疲労

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本論文は，洋上の大型構造物を係留するために使用されるワイヤロープのフレッチング疲労損傷について，その機構の解明と防止法を研究したものである。高張力鋼線のフレッチング疲労試験を海水中と大気中で行い，疲労挙動に及ぼすフレッチングと海水の影響を明らかにし，さらに疲労き裂の伝ぱ挙動，カソード電圧印加の影響，亜鉛メッキの効果等を検討した。海水中のフレッチング疲労強度は，主に化学的あるいは電気化学的作用によって著しく低下するものであり，適切なカソード電圧を印加することによって回復する。しかし，その効果は疲労き裂が30μm程度に進展すると急激に低下する。亜鉛メッキは，海水中では電気化学的損傷を抑制することにより疲労強度を増大させるが，大気中では鉄－亜鉛合金層の存在によりそれを低下させる。