

Fretting fatigue behaviour of a 2014-T6 aluminium alloy coated with an electroless nickel under rotating bending loading

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Abstract

In order to investigate the effect of electroless nickel (EN) coating on fretting fatigue, rotating bending fatigue tests were carried out by clamping contact pads to fretting fatigue specimens. Comparing with the data generated under rotating bending fatigue conditions assessed fretting behaviour of the alloy. The material for the fatigue specimens was 2014-T6 aluminium alloy, and that for the pads was AISI 4140 steel. Fretting fatigue tests were carried out at initial contact pressure of 100 MPa in air. The fretting produced a reduction in fatigue strength of aluminium alloy. Results show that EN coating could yield satisfactory improvement in fretting fatigue response of the substrate. This improvement was associated with higher strength of the coating as compared to the substrate and with the development of compressive residual stresses and beneficial effect of surface roughness on the coating.

Key words: coating, aluminium alloy, fretting fatigue properties, fractographic analysis

1. Introduction

Fretting fatigue is phenomenon that occurs in contacting parts when they are subjected to fluctuating loads and sliding movements at the same time. Shafts, bearings, riveted and bolted connections, steel cables, steam and gas turbines are typical examples of engineering applications which may be subjected to fretting fatigue damages.

Aluminium alloys are very important engineering materials widely employed in the engineering and structural applications such as automobile parts, aircraft fittings, wire ropes and overhead electrical cables due to its high strength-to-density ratio. Aluminium alloys also undergo fretting fatigue damage in these applications [1].

The resistance of the materials against fretting fatigue can be increased by improving surface conditions such as hardness, roughness and reducing friction coefficient as fretting fatigue damage originates at the surface. This is accomplished by surface coating techniques. Electroless nickel (EN) coating is an effective method to increase corrosion and wear resistance of structural materials such as steel and aluminium alloys [2, 3]. Thus, EN deposits represent extremely

functional coatings that have found very important applications in many fields of engineering including aerospace, automotive, chemical processing, oil and gas production, food processing, machinery, mining and materials handling, military, etc.

The effect of the EN coatings on fatigue behaviour of steel substrates has been investigated by several authors [4, 5]. However, there is limited information available in open literature on fretting fatigue behaviour of EN coating on aluminium substrates.

In the present investigation the fatigue behaviour of EN coating on aluminium alloy 2014-T6 substrate has been studied under rotating bending fatigue loading.

2. Experimental details

The substrate used in the present study was a 2014 aluminium alloy bar produced by direct chill casting with a diameter of 12 mm. The chemical composition of this alloy is (in wt.%) 4.51 Cu, 0.39 Mg, 0.60 Mn, 0.68 Si, 0.33 Fe, 0.05 Cr, 0.090 Zn and Al balance. The specimens were solution treated at 520 °C for 2 h and water quenched to room temperature. Subsequently

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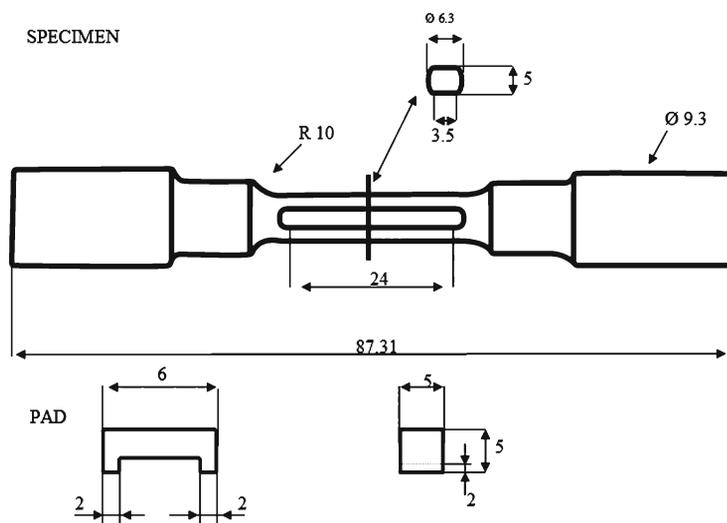


Fig. 1. Sketches of the fretting fatigue specimens and the pad employed in this study. All the dimensions are in mm.

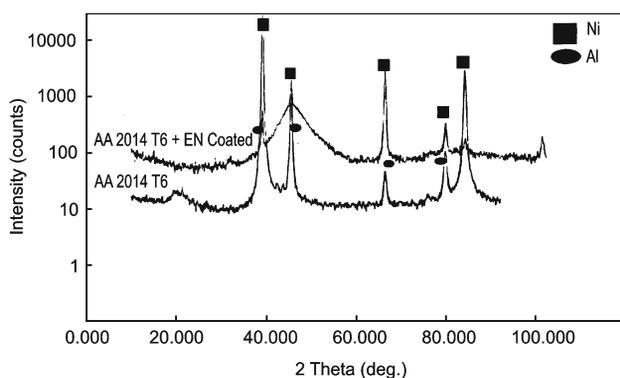


Fig. 2. X-ray diffraction pattern of the EN deposit.

they were aged at 170 °C for 10 h (referred to as T6 condition). The gauge portions of all samples were polished with SiC papers grit 800–1200, and cleaned with acetone. Such a procedure allowed the elimination of the remaining circumferential notches that could act as stress concentrators during pure and fretting fatigue tests. The residual polishing marks were oriented along the length of the specimens. Figure 1 illustrates sketches of both the fretting specimens and the fretting pads. A bridge-type flat fretting pad was made of AISI 4140 steel, and had hardness value of 339 HV, which was higher than that of specimen. The gauge parts of the fretting pads were polished with silicon carbide papers grit 800–1200 and subsequently polished with alumina. They were then degreased with acetone. The plain fatigue life data were obtained with round bar fatigue specimens whose diameter and length of the gauge section were 5 and 24 mm, respectively.

The deposition of the EN coating was carried out industrially. A proprietary EN solution was used for

the deposition of the EN coatings. The deposition process was conducted at 80–90 °C and solution pH of 5.8 ± 0.1 . The coating thickness was measured by SEM and found to be 6–8 μm .

However, both the thickness and state of the fracture surfaces in addition to fretting scars were also evaluated by means of SEM techniques. The structural condition of the coating was also analysed by means of X-ray diffraction method. The XRD spectrum is presented in Fig. 2, in which a large diffraction peak can be seen, located at values of 2θ of the order of 40–50°. Such a result is also consistent with the phosphorus content of the deposit.

The microhardness on the cross-section of samples with T6 condition, T6 + EN coating and pad material was measured with Vickers hardness, using a PC controlled Buehler-Omnimet tester. Vickers hardness numbers were obtained by averaging eight measurements on each specimen employing loads between 10–200 g.

An experimental facility, with a ring type load cell and bridge-type fretting pads, which can simulate fretting fatigue conditions, was designed and fabricated. Figure 3 shows a schematic view of fretting fatigue test set-up employed in the present study. The specimens were gripped and loaded cyclically in a rotating bending testing machine.

By adjusting the loading screw on a proving ring with a torque driver, the normal contact load between the contact pads and specimen was controlled. The fretting fatigue tests were carried out at a constant average contact pressure of 100 MPa. The average contact pressure was calculated by dividing the contact (normal) load by the apparent contact area ($= \text{pad food size} \times \text{specimen thickness} = 2 \times 3.4 = 6.8 \text{ mm}^2$). When a fatigue specimen is subjected to cyclic stresses, fretting between the contact pads

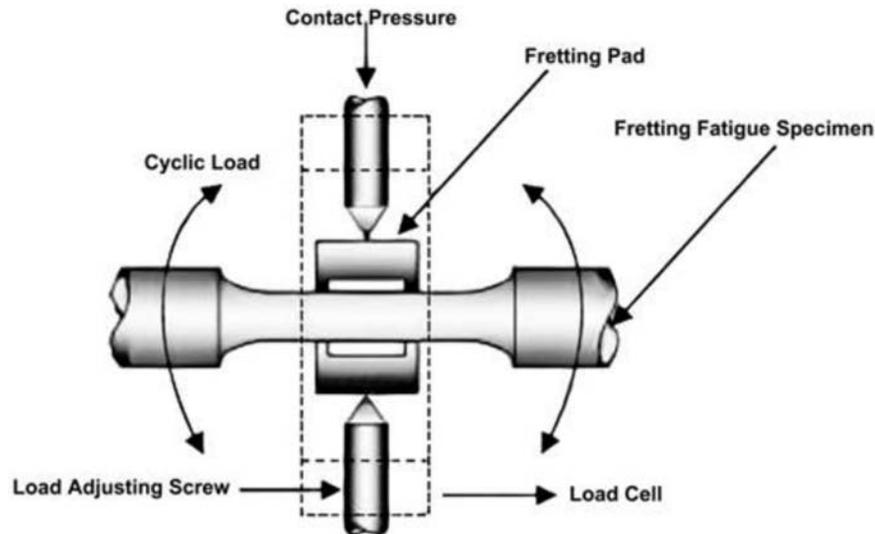


Fig. 3. The fretting fatigue test set-up used in the present study.

and the specimen is generated. Uncoated fretting pads were used for testing against coated as well as uncoated test specimens. Plane and fretting fatigue testing were carried out at room temperature in a four-point loading rotating bending machine ($R = -1$) under constant stress amplitude at a rotational speed of 5000 rpm.

Rotating bending fatigue test is a simple method of determining fatigue properties at zero mean load by applying known bending moments to rotating round specimens. The application of load is at a single point. The specimen has a continuous radius such that the maximum bending stresses are constant at all cross sections. The stress at a point on the surface of rotating bending specimens varies sinusoidally between numerically equal maximum tensile and compressive stress values in every cycle. In this test, the maximum number of cycles to failure is obtained at a given stress level. The stress S is continually reduced, and the number of cycles to failure, N_f , increases. Finally, the limiting value of stress (endurance/fatigue limit) is reached where fatigue failure will not occur [6, 7]. However, for aluminium alloys as most nonferrous materials, the $S-N_f$ curve does not approach an asymptote. In general, a fatigue limit is often arbitrarily defined as the fatigue strength at 10^7 cycles and should be experimentally determined [8].

The quantitative description of the change in the number of cycles to failure with the stress applied was carried out with a parametric relationship of the form

$$S = AN_f^b, \quad (1)$$

which involves two constants, A and b , characteristic of the materials under investigation and testing conditions that are described from the experimental data. The above relationship is similar to that advanced

earlier by Basquin [9] for the description of this kind of data.

Constant A represents the fatigue strength coefficient, that is, the stress required to produce failure of the material in a single load application, and b is the fatigue exponent, which characterizes the sensitivity of the change in the number of cycles to failure with applied stress. In addition, it is possible to evaluate the reduction in fatigue life brought about by the presence of the coating, by means of a simple relationship of the form

$$\% \text{reduction} = \frac{N_f^{\text{EN}} - N_f^{\text{subst.}}}{N_f^{\text{subst.}}} \times 100. \quad (2)$$

3. Results and discussion

Microhardness measurements (average of 10 measurements) indicate that EN coating has higher hardness than that of the substrate material (Table 1). The surface roughness parameters R_a and R_{max} were determined using a surface roughness tester. The coated surface was very rough.

Figure 4 shows the results of plain fatigue and fretting fatigue conducted on the substrate and EN coated specimens. Fretting fatigue lives of the uncoated and EN coated specimens were shorter than plain fatigue lives.

Fretting reduced the fatigue lives of the uncoated and coated specimens. This effect is much more noticeable in comparison to the substrate in particular for lower alternating stresses. Since the fretting plays a severe role in an initiation period and as crack initiation occupies a major portion of the total life, the

Table 1. Characteristics of substrate (T6 heat treated) and coating (T6 + EN coated)

Condition	Hardness HV	Roughness (μm)	
		R_a	R_{max}
T6 heat treated	175	0.42	3.25
(T6 + EN coated)	220	0.80	5.3

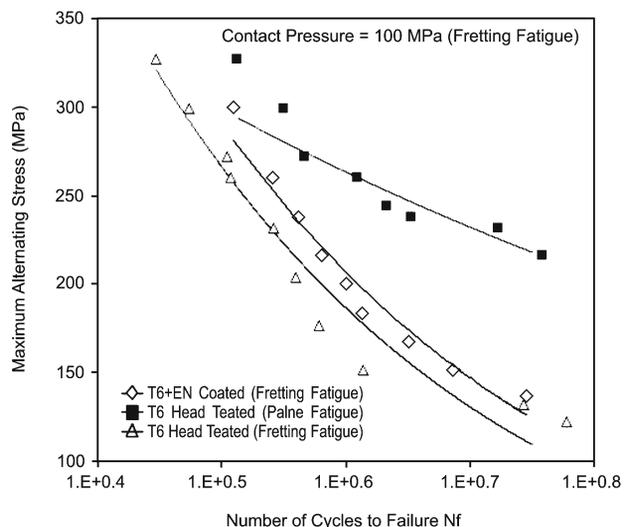


Fig. 4. Plain fatigue and fretting fatigue test results for substrate and EN coated specimens.

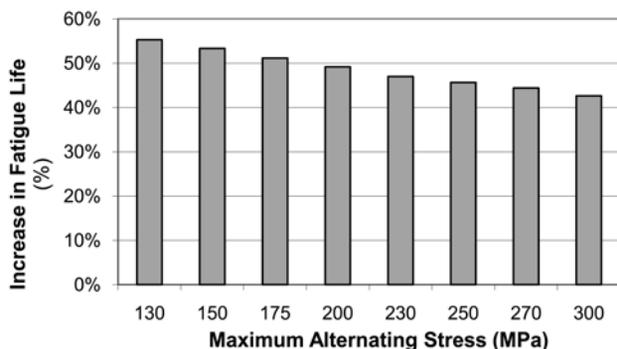


Fig. 5. Percentage increase of fretting fatigue life vs. stress.

influence of fretting on the fatigue life may be expected to be of a greater extent in the high cycle regime at lower stresses [10, 11]. The change in the % of increase in fatigue life versus stress applied, for coated specimens in comparison with the uncoated ones (substrate), is shown in Fig. 5.

The results show that the EN coating gives rise to an important increase in fretting fatigue lives. As the figure suggests, increase in fretting fatigue life rises up to more than 50 %, particularly if it is tested at low alternating stresses. However, the ap-

plied stress increases, the gain in the fatigue life decreases. Figure 4 demonstrates that EN coating also results in a significant improvement in the fretting fatigue strength at 1×10^7 cycles compared to substrate. It is about 130 MPa for substrate while the fretting fatigue strength for EN coating is a value of about 160 MPa.

An improvement in the fretting fatigue behaviour due to the EN coating could be related to the higher strength of the coating, internal stress and beneficial effect of surface roughness. A higher strength of the coating when compared to the substrate material, measured as microhardness, is one of the factors responsible for the better fatigue resistance of the coated alloy. An increase in surface hardness will prevent adhesion and abrasive wear during fretting. Thus, coating improves fretting resistance provided that it has bond strength with the substrate. Another factor, which will affect the fatigue performance, is a compressive state of the internal residual stresses in the deposit. The residual stresses are induced in EN coating presumably due to difference in the thermal expansion coefficient between the deposit and substrate during cooling from the deposition temperature (80–90°C) to the ambient temperature. In the present study, residual stress measurements have not been conducted. However, results reported by Parker and Shah [12] clearly indicate that high phosphorous EN coating on aluminium substrate can induce compressive residual stresses. The role of these compressive residual stresses is to close up fretting fatigue cracks at the surface and to prevent their propagation.

The surface roughness has a beneficial effect on fretting fatigue life [13, 14]. During fretting, hard oxide debris formed at the contact surface may cause severe abrasion. However, on a rough surface, the wear debris may escape from the contact area into the adjacent depression instead of causing abrasion damage. The beneficial effect of EN coated specimens that had very rough surfaces (R_a and R_{max}) compared to substrate may be based on this hypothesis.

While it was not possible, on the other hand, to identify the relative importance of each factor and their effect on the fretting fatigue behaviour, the first three parameters are expected to play a beneficial role.

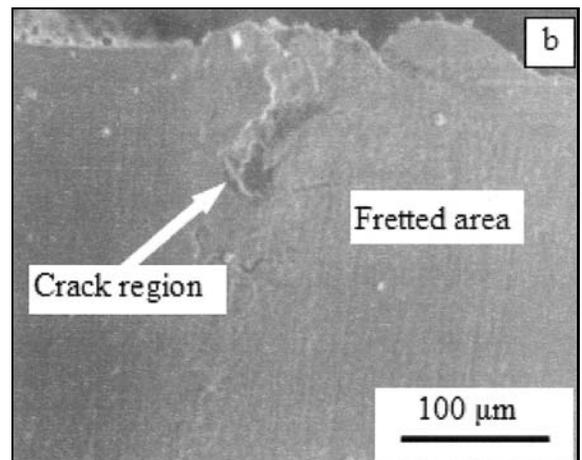
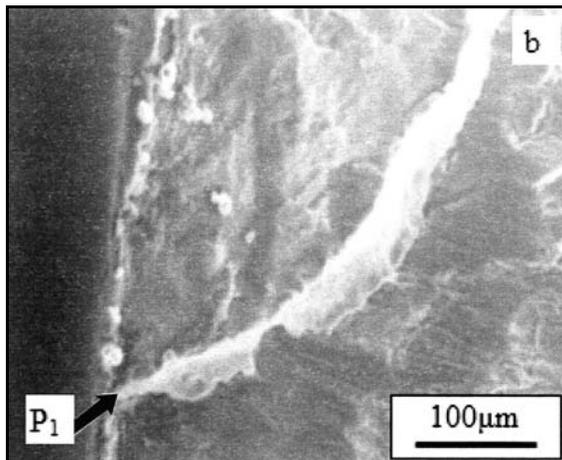
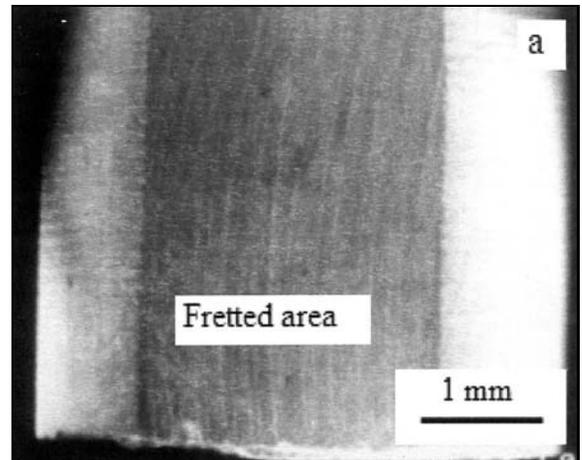
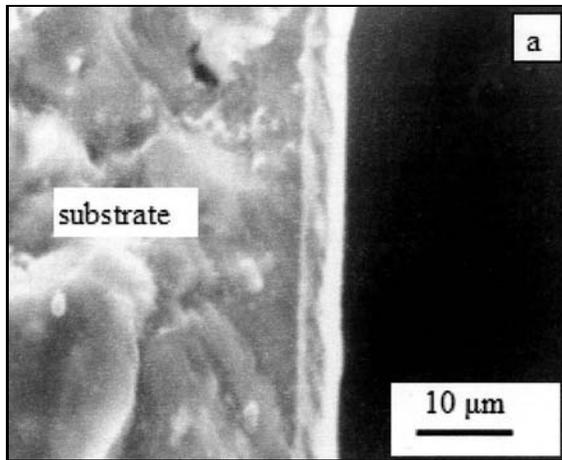


Fig. 6. a) Cross-section view of a coated sample. The thickness of the deposit and the substrate-coating interface could be observed. b) View of the crack initiation site and propagation direction. P₁ and black arrow indicate crack initiation site and propagation, respectively.

Fig. 7. Surface morphology of the fretting fatigue: a) substrate, b) EN coated specimens.

Regarding the EN coating, Fig. 6a illustrates a cross-section view of the coated samples, which indicates the deposition of a uniform film with a mean thickness of approximately 6–8 μm and a coating-substrate interface apparently free of pores and cracks. Figure 6b indicates the fracture surface of a sample. In this case, fracture of the specimen was observed to occur as a consequence of the propagation of a single crack whose origin is marked as P₁.

Figure 7 shows the SEM appearance of surface morphologies of the specimen surface of the fretting fatigue-failed specimens. The fretting fatigue scars of substrate were very clear compared to EN coated specimens. The fretting fatigue crack initiated at the surface (contact region) of the specimens due to stress concentration effect introduced by fretting for both conditions. These fracture surface morphologies were observed in all fretting fracture surfaces.

4. Conclusions

Based on the results obtained in the present study on the effect of EN coating on a T6-2014 alloy, the following conclusions were drawn:

- Fretting produced a marked reduction at the fatigue lives and strength of the substrate and coated specimens. These reductions were more severe in the low cycle region.

- EN coating can increase the fatigue life up to more than 50 % at low working stresses, while at higher stresses it may give rise to less change in fretting fatigue life.

- EN coated samples exhibited increased surface hardness and increased surface roughness with substrate. These parameters are expected to play a role to fretting fatigue behaviour.

- Due to stress concentration effect introduced by the fretting, in the EN coated samples, cracks initiated at the coating surface propagated through the coating and penetrated into substrate.

Acknowledgements

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