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Evaluation of an electroless nickel-boron (Ni-B) coating on corrosion fatigue performance of ball burnished AISI 1045 steel

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Abstract

The aim of this research is to analyze the corrosion fatigue behaviour of the AISI 1045 steel for two different surface treatments (i.e., single ball burnishing and a duplex treatment combining ball burnishing with an electroless Ni-B coating). The tests were carried out in order to study the fatigue performance both in air and in a 5 % NaCl solution under rotating bending condition ($R = -1$). Corrosion fatigue tests were conducted at alternating stress levels ranging between 240 and 450 MPa. The results indicated that the 5 % NaCl environment reduced the fatigue life drastically, but the ball burnishing was found to increase the corrosion fatigue life. Also, the duplex treatment improved the corrosion fatigue resistance compared to the case of the ball burnishing alone. The surface morphologies after corrosion fatigue tests were studied by using a scanning electron microscopy (SEM).

Key words: corrosion fatigue, electroless nickel-boron (Ni-B) coating, ball burnishing treatment

1. Introduction

Corrosion fatigue occurs by the combined synergistic actions of cyclic loading and corrosive environment leading to premature failure of metals by cracking [1]. Corrosion fatigue behaviour of a given material/environment system refers to the characteristics of the material under fluctuating loads in the presence of a particular environment. Many mechanical, metallurgical and electrochemical variables have an effect on corrosion fatigue behaviour [2]. Many small pits occur in corrosion fatigue because of interaction of aggressive environment and surface of a metal under applied stress [3]. Many studies have shown that corrosion fatigue cracks start from corrosion pits [4–6], which can support early cracks development by acting as a high stress concentrator. Therefore, pitting can be considered as one of the most important deterioration mechanisms reducing the life of a component under corrosive environments.

Damage of a material caused by corrosion fatigue is much more severe and faster than a simple sum of damages caused separately by fatigue and corrosion, so that corrosion fatigue can cause unexpected damages in industrial sites or engineering fields [5].

Corrosion fatigue life of a metal is known to be greatly affected by the surface state of the metal [6]. A number of methods such as metallic or non-metallic coatings, the formation of surface compressive residual stresses and the elimination of stress concentrators by careful design are available for minimizing corrosion fatigue damage. The protection against corrosive attack under applied stresses can be achieved through mechanical surface enhancement methods. All currently available methods of surface enhancement develop a layer of compressive residual stress following mechanical deformation. The most commonly used treatment is shot peening [7]. Shot peening usually increases hardness and induces compressive residual stress in the material's surface. When repeated load of sufficient magnitude is applied to a material, slip bands are formed. If the material is shot-peened, a protective layer is formed on the material's surface and the resistance to corrosion fatigue increases [8, 9]. New surface enhancement technologies have recently been developed, which are superior to shot peening regarding compressive residual stress magnitudes and depths to which compression can be achieved. Ball burnish-

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ing method is relatively inexpensive and easy implement compared to other treatments such as peening, and does not require any complicated devices. Ball burnishing is a cold working, surface treatment process in which plastic deformation of surface irregularities occurs by exerting pressure through a very hard smooth ball on a surface to generate a uniform and work hardened surface. Ball burnishing (deep rolling) is one of the most effective commercially available mechanical surface treatments for the enhancement of the fatigue behaviour of metallic materials [10].

Protection of the metal from contact with the corrosive environment by metallic or nonmetallic coatings is successful provided that the coating does not become ruptured from cyclic strain [11]. Electroless nickel plating is an auto-catalytic chemical technique used to deposit a layer of nickel-phosphorus or nickel-boron alloy on a solid work piece, such as metal or plastic. Electroless deposition processes experienced numerous modifications to meet the different needs of industrial applications [12]. Electroless nickel-phosphorus (Ni-P) deposits are considered to be effective from the electrochemical point of view to steel which provides a good corrosion resistance both in water and marine environments. This was expressed very well in the literature [13, 14]. Electroless nickel (Ni-P) deposits containing approximately 10 % phosphorus and about 20 µm thickness were shown to increase the corrosion fatigue properties of the AISI 1045 steel in the stress amplitude range of 221–231 MPa, in the presence of an aqueous solution of 3 % NaCl [15].

The electroless nickel boron (Ni-B) plating is a chemical reduction process which depends on the catalytic reduction of nickel ions in aqueous solution and the subsequent deposition of nickel metal without the use of electrical energy [16, 17].

Ni-B coating being lesser corrosion resistant than Ni-P coating, an extensive study regarding the corrosion behaviour of the former has remained neglected. But Ni-B coatings are often preferred in various tribological applications due to their superior hardness and wear resistance compared to Ni-P coatings. Thus, a systematic study of the electrochemical behaviour of Ni-B coatings is necessary as the coatings in various applications would definitely encounter corrosion [18].

The corrosion behaviour of Ni-B deposits has not been extensively studied, thus only limited information is available for Ni-B deposits [18, 19]. Similar to nickel-phosphorus, the corrosion behaviour of nickel-boron deposit may depend on many parameters such as its B content, surface morphology of the deposit, the microstructure of the deposit, the nature of the substrate under the deposit, etc. [20, 21].

Results for the corrosion fatigue behaviour of a duplex treatment combining ball burnishing with an electroless Ni-B coating almost do not exist in the literature. The aim of this work was to study the influence of

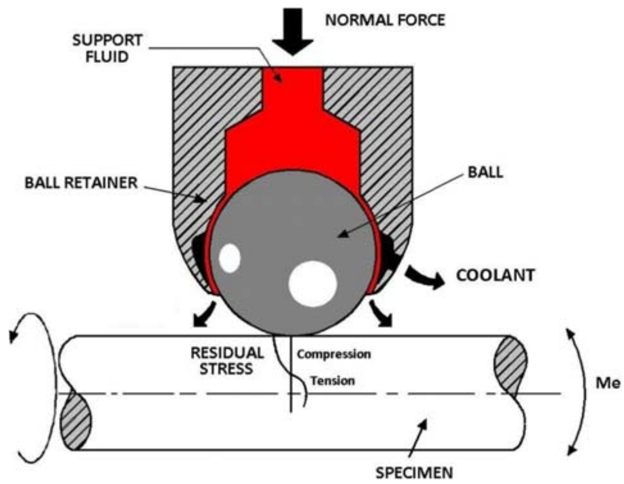

Fig. 1. Hydrostatic principle of the ball burnishing tool.

a duplex treatment combining ball burnishing with an electroless Ni-B coating on corrosion fatigue of AISI 1045 steel tested in a 5 % NaCl solution.

2. Experimental details

2.1. Materials and specimens preparation

The material used in this study is a commercial medium carbon steel (AISI 1045), which is widely used for gears and shaft manufacturing. Chemical composition of the material is (in wt.%): 0.4220 C, 0.2440 Si, 0.6070 Mn, 0.0190 P, 0.0330 S, 0.1970 Cr, 0.0332 Mo and 0.1220 Ni. The material was supplied in bars with approximate 12 mm in diameter. The fatigue samples were machined to the following dimensions: a gauge diameter of 6.3 mm and a gauge length of 40 mm. The surface of the fatigue samples was ground by using silicon carbide grit papers of 800–1200 grids, and then degreased with acetone before the ball burnishing treatment.

2.2. Ball burnishing and electroless Ni-B coating

Ball burnishing was performed by using a conventional lathe and a hydrostatically supported burnishing tool from ECOROLL Company, as shown in Fig. 1. A hard metal ball of ø 6 mm (HG6) was utilized as the burnishing element. The burnishing pressure was selected as 30 MPa. The samples were ball burnished (deep rolled) at a rotational speed of 1000 min^{-1}. The burnishing element was operated by the coolant of machine which was supplied via the tool shank. The required pressure was built up by an external hydraulic unit to the tool. This setup has several advantages, as follows:

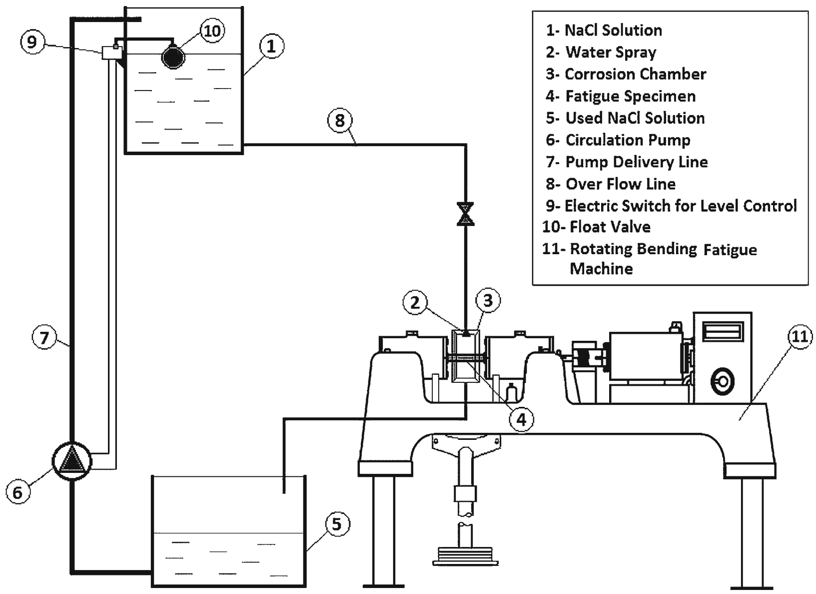

Fig. 2. Diagramatic sketch of corrosion fatigue testing.

Table 1. Bath composition and operating conditions of the reference bath

Bath composition	g l^{-1}
Concentration of $NaBH_4$	1.2
Concentration of $NiCl_2$	10
Concentration of ethylenediamine	90
Concentration of sodium hydroxide	90
Concentration of lead nitrate	0.0145
Conditions Temperature = 95 °C pH = 13.5 Time = 60 min	

1. The self-regulating following system enables the ball to follow the specimen contour within a stroke, while the rolling force remains constant.

2. The hydrostatic bearing of the ball allows it to run nearly without friction and to rotate in any direction.

3. The tool can be installed on a conventional or CNC lathe.

The deposition of Ni-B coating was applied to fatigue samples following the ball burnishing treatment. They were firstly rinsed with distilled water, and immersed in 15 % HCl for 15 s and then washed thoroughly with distilled water and dried in air with a fan. Table 1 shows bath composition and operating conditions of the reference bath for Ni-B coating. The steel substrates were mounted in this deposition bath and kept at a bath temperature of 95 °C for 60 min. The coating thickness achieved after this treatment was about 5 μm.

2.3. *Corrosion fatigue tests*

A rotating bending machine was employed for carrying out the fatigue tests, both in air and a 5 % NaCl solution environment with a pH value of 3, at a frequency of 4000 rpm and at room temperature. When testing was carried out in air, the fatigue limits of both the bulk and ball burnished samples were determined based on the standard JSME S002 with staircase method. According to the standard's recommendation, fatigue limit can be calculated with 6 samples for 50 % survival. The alternating stresses in the range of 240–450 MPa were employed for corrosion fatigue tests. A specially designed and manufactured environmental testing chamber suitable for the rotating bending fatigue testing machine was installed.

The main constituents of the chamber are a circulating pump and an electric switch for level control. This setup is used to circulate the corrosive medium around the fatigue test sample. A schematic sketch of this setup for the corrosion fatigue test under NaCl environment is presented in Fig. 2.

After all the surface treatments, the representative samples were examined by a series of material characterization techniques, including metallographic examination (SEM) and microhardness tests. The hardness test with a load of 50 g was carefully carried out for measurements on each specimen surface. The surface roughness of all the specimens was measured by a profilometry.

3. Results and discussion

The average surface roughness decreased after the

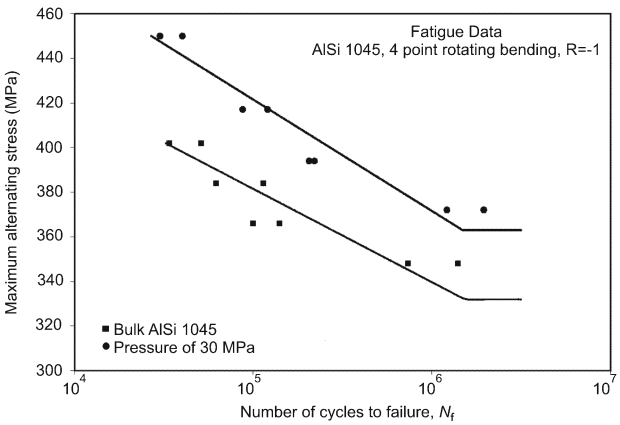

Fig. 3. Maximum alternating stress versus number of cycles to failure for bulk and a single ball burnished samples tested in air.

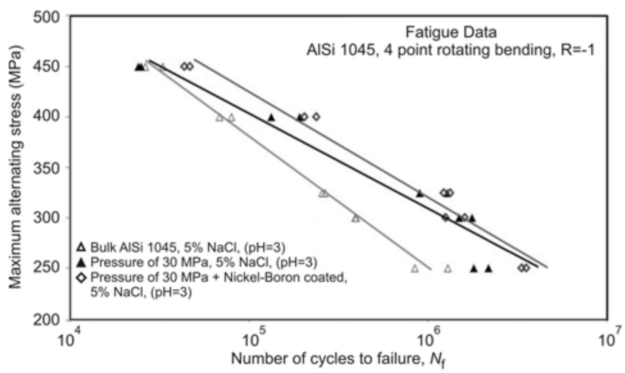

Fig. 4. Maximum alternating stress versus number of cycles to failure for bulk, a single ball burnished and duplex treated samples tested in a 5 wt.% NaCl solution.

ball burnishing treatment for the pressure of 30 MPa. The roughness for the applied pressure of 30 MPa was about 0.099 μm and that of the untreated sample was about 0.299 μm. On the other hand, the average roughness value after a duplex treatment combining ball burnishing and an electroless Ni-B coating was about 0.37 μm. This was higher than those values for the other conditions. The surface hardness of untreated sample was approximately 220 HV. There was a significant increase in the microhardness value after the ball burnishing treatment due to existence of a work hardened layer. The surface hardness corresponding to a pressure of 30 MPa was approximately 580 HV. After a duplex treatment, the average surface hardness was observed to increase to approximately 900 HV. It was much higher than those values for the untreated bulk sample and the ball burnishing sample.

Figures 3 and 4 show the results of the fatigue tests conducted in air and in the NaCl solution, respectively. It can be clearly observed from Fig. 3 that the ball burnishing treatment can give rise to a significant increase both in the fatigue life and in the fatigue limit in air. Such an increase in fatigue properties after the ball burnishing treatment would be associated with surface smoothening, the formation of strain hardened layers and exhibiting compressive residual stresses. Surface roughness is assumed as detrimental to fatigue crack nucleation due to stress concentration factor. The crack initiation in fatigue accounts for a large portion of the fatigue life and occurs through the movement of dislocation in the surface region by cyclic shear stress. Increasing hardness of the surface region makes dislocation motion more difficult, thus crack initiation is delayed and fatigue behaviour is improved. It is also expected that the residual compressive stresses shift the fatigue crack nucleation site from surface to subsurface regions as compared to untreated condition.

Thus, the superposition of residual stresses and applied stresses in bending lead to lower combined stresses in these deeper subsurface regions than nominal applied alternating stress [22, 23].

The *S-N* curves for the fatigue tests in the NaCl solution are shown in Fig. 4. The fatigue tests conducted in the NaCl solution illustrate that fatigue life tested in the NaCl solution decreased in the longer fatigue life region compared with those tested in air. It was also clear that NaCl solution environment was much more aggressive in comparison with air as can be seen in Figs. 3 and 4.

It is quite clear that the burnishing treatment provides a better corrosion life, compared with bulk samples. The reason for this increase can be explained with three properties (higher hardness, existence of cold worked layer and especially in the presence of the compressive) provided the ball burnishing treatment.

It is known that the corrosion fatigue cracks start from corrosion pits [4] and notches produced by machining, which can lead to the formation of early cracks development by acting as a high stress concentrator. Therefore, pitting and notches can be taken into consideration as one of the most important deterioration mechanisms reducing the life of a component under corrosive environments. The formation of the cold worked layer and compressive residual stresses in the substrate surface tends to prevent the opening of surface pits and notches and the access to corrosive medium. On the other hand, surface roughness similar to pits and notches can be served as potential sites for crack nucleation. In NaCl environment, the surface roughness may have a significant effect on the corrosion fatigue life. The smooth surface due to ball burnishing treatment would improve fatigue strength, as seen from Fig. 4.

Figure 4 also shows that the presence of a duplex treatment combining ball burnishing with an electroless Ni-B coating gives rise to the best corrosion fatigue life.

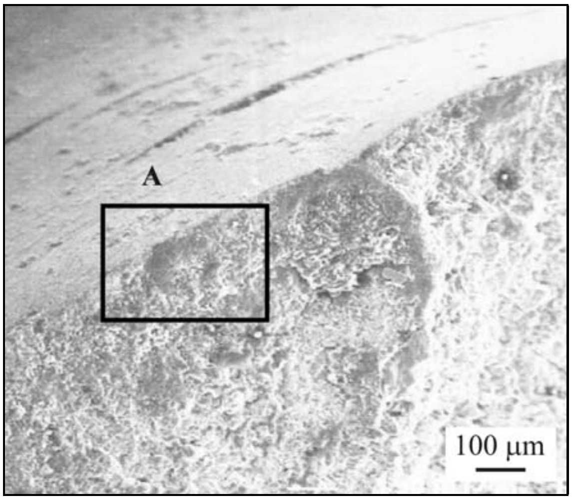

Fig. 5. SEM photomicrograph indicating a number of potential sites for the nucleation of fatigue cracks on the specimen surface, possibly generated at corrosion pits under 5 wt.% NaCl solution. A shows a possible nucleation point for fatigue crack initiation.

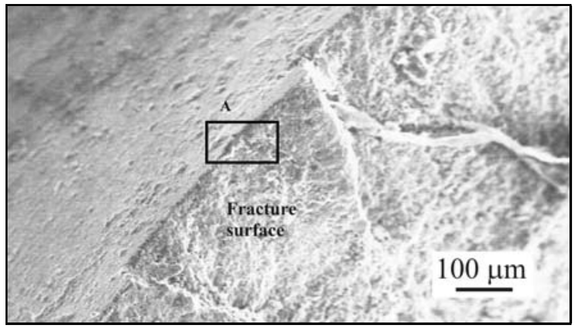

Fig. 6. SEM micrograph illustrating possibility at the crack nucleation points under the surface in 5 % NaCl environment. A shows a possible point for fatigue crack initiation. A illustrates crack growth path.

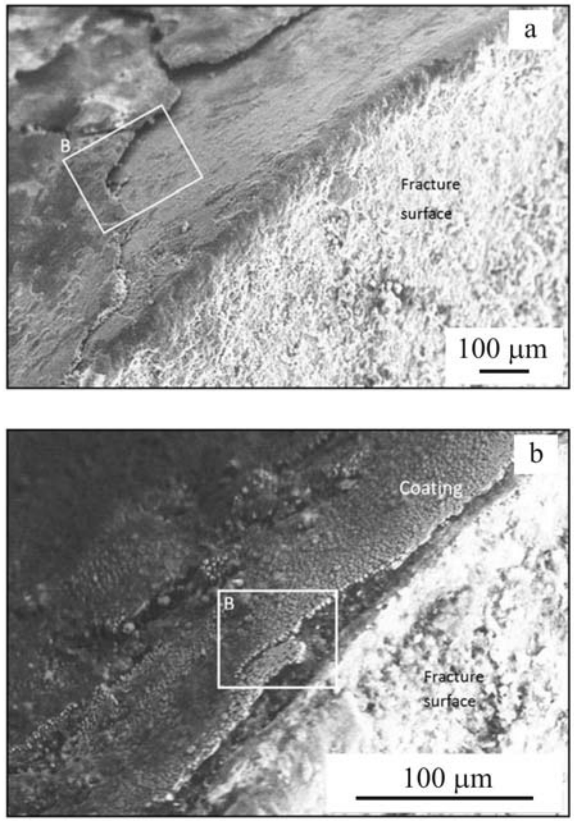

Fig. 7. (a) SEM micrograph illustrating detachment of coating on the ball burnished surface, and surface fracture region for duplex surface treatment, (b) SEM photomicrograph illustrating a partial view of the Ni-B coating. (B) shows the partial detachment of the Ni-B coating after testing in NaCl solution.

The pure corrosion behaviour of Ni-B coating has not been extensively studied, thus only limited information is available for Ni-B coatings. Ni-B coatings improve the pure corrosion resistance of steel samples [24]. The corrosion resistance of coatings depends on the physicochemical features of the coating such as the adherence, hardness and roughness of the substrate mainly. These physicochemical features of Ni-B coating with support of the ball burnished substrate may have a more pronounced effect to protect the substrate from the aggressive environment due to the properties such as high hardness, cold worked layer and surface compressive residual stresses resulting from the burnishing treatment applied before Ni-B coating in addition to their amorphous state and the formation of a passive film on the surface. Thus, it is expected to act as an effective barrier to protect the ball burnished substrate from aggressive environment.

The SEM micrograph for the bulk specimen tested under NaCl environment (uncoated substrate) is shown in Fig. 5. As seen from the figure, clear pit formation was not found on the specimen surface. However, the corrosive environment would have a significant influence on fatigue crack nucleation stage and then degrade the fatigue strength. It is known that the corrosive environment influences a fatigue crack nucleation but not a fatigue crack growth behaviour [25, 26].

Figure 6 shows possible sites of crack nucleation for a single ball burnishing treatment with 30 MPa pressure. It is clear from the figure that corrosion pits, which act as potential sites for the nucleation of fatigue cracks, are hard to observe, similar to the uncoated one.

Figure 7 represents no corrosion pits on the duplex treated surface because Ni-B coating does not passivate in NaCl solution. Also, it can be seen that coating has partially fractured and delaminated from the ball burnished substrate in some regions. Once the Ni-B coating has delaminated from the ball burnished substrate, the aggressive medium could enhance the nucleation of fatigue cracks from the intermediate between Ni-B coating and the ball burnished substrate, while this stage would be late compared to the case for the bulk specimen and the ball burnishing specimen.

4. Conclusions

The results obtained from the present investigation indicate that the ball burnishing treatment gives rise to an important increase in fatigue limit and life tested in air, in comparison with the bulk specimen. When the untreated bulk specimens were tested in NaCl solution, a significant reduction in fatigue life was observed. Under the corrosive environment, a single ball burnishing and a duplex treatment provided an effective protection against corrosion fatigue failure. However, such an improvement was more marked for a duplex treatment. The corrosion pits formation was not observed in all three kinds of specimens tested under the corrosive environment, while the corrosive environment affected fatigue process and then degraded fatigue strength at lower applied stresses.

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