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Effect of friction stir processing on erosion–corrosion behavior of nickel–aluminum bronze

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ABSTRACT

In the present investigation, effects of Friction Stir Processing (FSP) on Erosion–Corrosion (E–C) behavior of Nickel–Aluminum Bronze (NAB) were studied by weight-loss measurements and surface characterization using an impingement jet test system. After FSP, the initial coarse microstructure of the cast NAB was transformed to a fine structure, and the porosity defects were eliminated. In addition, different FSP structures were produced by each rotation rate. Microhardness measurements showed a marked increase in FSP samples depending upon the FSP parameters. E–C tests were carried out by erodent at kinetic energies about 0.45 μJ and in 30°, 60° and 90° impact angles to simulate actual service conditions. The maximum weight-loss was observed in FSP samples and Scanning Electron Microscopy (SEM) results showed signs of brittle fracture mechanism in FSP samples. By gravimetric analysis, the degree of synergy was evaluated at 0.45 μJ kinetic energy at normal impact angle and negative synergy result implies the presence of a protective film on all sample surfaces.

1. Introduction

Nickel Aluminum Bronze (NAB), due to good combination of mechanical and physical properties such as strength, fracture toughness and corrosion behavior [1] is widely used in marine propellers production [2]. This is a copper based alloy with 10 percent of aluminum as main alloying element which has the biggest role in its properties [3,4]. In addition, presence of 5 percent of two elements of nickel and iron increase stability of alpha phase and prevents the formation of gamma phase which deteriorates corrosion resistance [5,6].

Erosion–Corrosion (E–C) by sand particles entrained in seawater is one of the main deterioration mechanisms of the propellers [2]. Erosion (E) is defined as the wear caused by hard particles striking a surface, carried by a gas stream or entrained in a flowing liquid medium [7,8]. Erosion when accompanied by aggressive environment such as seawater, is called E–C.

Synergy can be defined as the difference between erosion–corrosion and the sum of its two parts and can be expressed by the following relationship [7,8]:

$$S = T - (E + C) \tag{1}$$

where T is the material loss under erosion–corrosion, E is the material loss by pure mechanical erosion processes, C is the material loss by electrochemical corrosion processes and the synergy S is the combined interaction between erosion and corrosion process.

In addition, the synergistic term can further be divided into two additional components, ΔE and ΔC, where ΔE is the corrosion enhanced erosion and ΔC is the erosion-enhanced corrosion, according to the following relationship [7,8]:

$$S = \Delta E + \Delta C \tag{2}$$

Although NAB is relatively erosion–corrosion resistant material, in order to further improve its E–C performance, the use of organic and metallic coatings has been investigated [9,10]. However, the coating approach cannot enhance the mechanical properties, which could be achieved by the refinement of coarse cast structure and the elimination of porosity defects. So, a method which could improve both the mechanical and erosion–corrosion properties of the cast NAB is more desirable.

Friction Stir Processing (FSP) is a new solid-state technique based on Friction Stir Welding (FSW) which was invented in TWI of Britain in 1991 [11,12].

This technique has been used to produce fine-grained structures [13], to modify the structure of heterogeneous metallic materials [14], to produce surface composites and to synthesize composites and intermetallic compounds [15,16]. In addition, providing localized modification and control of microstructures in near surface layers of the cast components is one of the most useful application of FSP. In this way, porosities can be eliminated and the inclusions also redistributed without any change in components shape [11,12].

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Recently, US navy use FSP to increase performance of NAB propellers [17,18].

OH-Ishi et al. and Fuller et al. and Ni et al. [19–23] studied effect of friction stir processing on microstructure and mechanical properties of NAB. It was shown that coarse microstructure of cast NAB changed to fine microstructure and porosity defects were eliminated. The FSP NAB exhibited significantly improved hardness, tensile strength, and ductility compared to the base metal.

Furthermore, Zheng et al. [24] studied effect of FSP on cavitation erosion behavior of NAB which their results showed that FSP improved cavitation erosion resistance of FSP NAB by modifying its microstructure. So in this study, potential of FSP technique in improving E–C properties of NAB was studied through weight-loss and surface characterization by SEM.

2. Experimental procedure

Commercial UNS C95800 NAB alloy (chemical composition in wt.%: Al 9.22, Ni 4.81, Fe 4.34, Mn 1.11 and Cu balance) cast plates were machined to dimension of 300 mm × 80 mm × 8 mm pieces and were used in this study. Then this plates were subjected to FSP under 1000 and 2000 rpm tool rotation rates and 100 mm min^{-1} traverse speed. In this study, the sample designated as FSP-1000/100 denotes that the sample was subjected to FSP under a rotation rate of 1000 rpm and a traverse speed of 100 mm min^{-1}. A tool tilt angle of 3° was used for all FSP operations. A WC alloy tool with a concave shoulder 16 mm in diameter and a conical pin 4 mm in root diameter and 4 mm in length was used. After etching with solution of 5 g $FeCl_3$ + 2 ml HCl + 95 ml C_2H_5OH, the microstructure of the cast and FSP samples were examined using Optical Microscopy (OM). The hardness profile were measured on the surface of stirred zone along vertical direction by a micro-Vickers hardness tester with a load of 1 kg for 15 s.

Erosion (E) and Erosion–Corrosion (E–C) experiments were carried out using a slurry jet impingement rig. On entering the reservoir, the slurry was accelerated through a steel nozzle to generate a free jet. Jet velocity was controlled by the pump rotation speed. The slurry was freshly prepared for each test and consisted of 4.8 l of distilled water with 3 wt.% sand and 3.5% NaCl. All tests were carried out at the room temperature. The specimens (8 mm diameter) were held in front of the jet and stands off distance of 5 mm and at 3 impingement angle (30°, 60° and 90°). Test duration was 1 h.

The possible particle kinetic energy (assuming particle diameter of 100 μm) for a propeller is about 0.45 μJ [10]. In this study for simulating actual service condition, the particles with 250–300 μm were used so the velocity of sand particles were calculated using Eq. (3) [9]: (calculated from experimental parameters)

$$E_K = \frac{\pi \rho V^2 D_P^3}{12} \tag{3}$$

where E_K is kinetic energy of sand particles, ρ is the density of sand particles, V is the mean velocity of sand particles and D_P is the diameter of sand particles. The velocity of 8 m/s were used for each test.

The specimens were wet ground (up to grade 1200 SiC paper) and lapped (up to 3 μm diamond suspension) to a surface roughness (R) of less than 1 μm. Before and after each erosion test, specimens were washed in distilled water and degreased with ultrasonic of acetone, dried in a jet of cold air and then weighed by a precision balance with an accuracy of ±0.02 mg to obtain mass loss results. All tests were done in duplicate and the results were found to be within ±5%.

Modifications have been made to accommodate a silver/silver chloride (Ag/AgCl) reference electrode (RE) and two platinum counter electrode (CE). The ejector assembly, used for sand particle intake, was located downstream to prevent erosion damage on the counter and reference electrodes. −200 mV cathodic protection was applied to samples for erosion tests.

3. Result and discussion

3.1. Microstructure

The cast structure of the NAB was characterized by the coarse Widmanstätten α phase which was light-etching with a size of about 150 μm , the coarse martensite β′ phase which was dark-etching constituents, and fine κ phase particles and some casting porosities (Fig. 1a) [19–21]. Fig. 1b shows the types of κ particles in higher magnifications.

Fig. 2 shows the stir zone (SZ) microstructure of the upper surface of FSP-1000/100. This bandlike structure consisted of alternating light-etched primary α phase and dark-etched β′ phase that both of them are elongated and generally aligned in a horizontal direction [19–21].

Fig. 3 shows the SZ microstructure of upper surface of FSP-2000/100. This structure is consisted of equiaxed and Widmanstätten primary α phase in the continuous field of β′ phase [20,21].

The cast NAB is characterized by coarse microstructure, severe composition segregation, and shrinkage porosity defects, which reduce the mechanical properties and corrosion resistance of the NAB castings [1,19]. FSP resulted in the significant breakup and decomposition of coarse Widmanstätten α phase and β′ phases, the closure of casting porosities, and the uniform distribution of phases. Furthermore, the as-cast microstructure of the base metal was greatly refined by FSP [20,21].

In addition, different rotation rates in FSP samples resulted in different microstructures on the upper surface of SZ [20]. In fact, FSP parameters can affect peak temperatures, times at temperature,

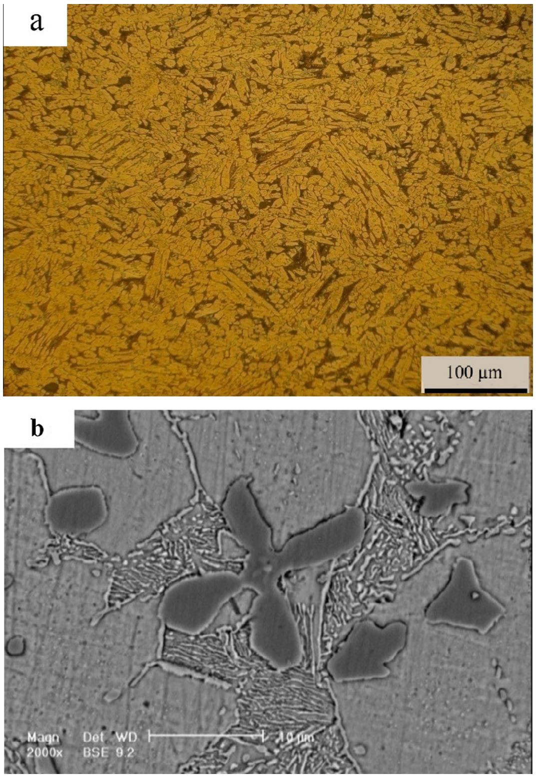

Fig. 1. Microstructure of cast NAB sample: (a) Widmanstätten morphology and porosities (b) precipitates.