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Response relationship between loading condition and corrosion fatigue behavior of nickel-aluminum bronze alloy and its crack tip damage mechanism

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ABSTRACT

Corrosion fatigue is one of the major forms for nickel-aluminum bronze alloy used in marine propeller. It is greatly important to understand the corrosion fatigue behavior of nickel-aluminum bronze alloy in seawater for the purpose of improving the service life of marine equipment. In this study, corrosion fatigue crack growth rate of nickel-aluminum bronze alloy in 3.5% NaCl solution was tested under various stress intensity factors, stress ratios and loading frequencies to reveal its corrosion fatigue mechanism. The results show that corrosion environment significantly accelerates the crack growth and decreases the corrosion fatigue threshold, which is attributed to the corrosion reactions between the metals of crack tip and corrosive medium. Among the various factors, loading frequency has more predominant influence on the corrosion fatigue crack growth rate of nickel-aluminum bronze alloy, which can be rationally explained by the hydrogen embrittlement mechanism. Additionally, in the process of corrosion fatigue crack growth, the acidification and the dealumination would occur at the crack tip, resulting in the corrosion dissolution of κ phases and the deterioration in mechanical properties of crack tip.

1. Introduction

Nickel-aluminum bronze (NAB) is a kind of copper based multi-component alloy containing Al, Ni, Fe and Mn as the major alloying elements [1]. The typical as-casted NAB microstructure includes Cu-rich Widmanstatten α phase, retained martensitic phase (β′ phase) and several forms of κ phases ($κ_I$, $κ_{II}$, $κ_{III}$ and $κ_{IV}$) [2, 3]. It is widely used for marine components especially for propeller materials due to the good combination of strength, fracture toughness and corrosion resistance [3–5]. With the development of ocean transportation and industry around the world, NAB alloy, a kind of important ocean material, has attracted more and more attention from material scholars [6–8]. In recent years, considerable researches have been performed to investigate the corrosion behavior and fatigue properties of NAB alloy, aiming at further improving the properties of marine propeller in the harsh service condition. S. Neodo et al. [9] reported that the selective phases corrosion occurred commonly in NAB alloy and the lamellar α phases in α + $κ_{III}$ eutectoid structures were preferentially corroded. The protective oxide film was formed on the κ phases surface, by which the κ phases became the cathode compared to α phases in a neutral environment. J. A. Wharton et al. [10] found that the micro-cracks with hundred micrometers scale were formed easily at the smooth surface of NAB alloy after immersion test in seawater for one month. Xu et al. [11] studied the fatigue crack growth rate of different heat treated NAB alloys in air and concluded the effects of secondary phases in microstructure for fatigue behavior of alloys. In addition, they also refined and homogenized the microstructure by using friction stir processing to improve the fatigue properties of NAB alloy [12].

Many experiments and numerical simulations suggested that for the practical application of NAB alloy, the marine propeller usually served under cyclic loading with different amplitude and frequency. Thus, the corrosion fatigue failure was treated as one of the main forms for NAB alloy [13–15]. In general, the corrosion fatigue failure of metals consists of three main stages: crack initiation, crack propagation and final fracture. Previous results indicated that it was easy to initiate the corrosion fatigue cracks in marine environment because of the occurrence of pitting or selective phases corrosion on NAB alloy surface [10, 16–18]. The stage of crack propagation is the main part of fatigue life

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and the crack growth behavior becomes more dominant. Therefore, the investigation on the corrosion fatigue crack growth rate in NAB alloy is essential for engineering design and service, and the features and mechanisms of corrosion fatigue are necessary to be fully understood.

Czyryca et al. [19] investigated the corrosion fatigue crack growth of as-casted and welded NAB metal at various service frequency in artificial seawater. They reported that both as-casted and welded NAB showed large closure loads, but higher crack growth threshold and closure levels were presented in welded NAB than that in as-casted NAB, which could result from the residual stress and the grain refinement in weldment. In addition, Denoh et al. [20] tested the corrosion fatigue properties of different locations in real large-scale propeller blades and they obtained some engineering data about the fatigue crack growth threshold and crack growth rate of NAB alloy in certain service condition. They found that the different locations of propeller with different microstructure presented different fatigue performance. However, the existing researches about corrosion fatigue of NAB alloy generally concentrated on collecting crack growth rate and evaluating the component service life, which ignored investigating the processes and features of the corrosion fatigue. It is not conducive to demonstration of corrosion fatigue mechanism of NAB alloy and makes performance improvement to be difficult. Besides, differing from the fatigue in air, the corrosion fatigue is a kind of metal failure form coupling the effects of corrosive medium and cyclic loading. There are many influential factors of corrosion fatigue for NAB alloy, such as corrosion environment and stress loading condition, which are also of importance to investigate.

Therefore, in the present work, corrosion fatigue crack growth rate of NAB alloy in 3.5% NaCl solution was conducted under various stress intensity factors, stress ratios and loading frequencies. Corrosion fatigue behavior of NAB alloy was systematically studied via detailed observation of fatigue fracture and crack propagation path. Some advanced technologies, such as electron back scattered diffraction (EBSD), focus ion beam (FIB) and nano-indentation, were adopted to analyze the properties of crack tip and reveal the corrosion fatigue crack propagation mechanism.

2. Experimental Procedures

2.1. Material

The material used in this study was cut from the NAB cast ingot prepared by vacuum melting according to ASTM B148 standard, with a dimension of 180 mm in diameter and 240 mm in length. The initial NAB alloy was annealed at 675 °C for 6 h and cooled with furnace in order to relieve the residual stress, which could eliminate or lessen the errors of measurement in fatigue crack growth test. The chemical composition of NAB alloy was determined by X-ray fluorescence spectrophotometer (XRF), as shown in Table 1. The basic mechanical properties of the annealed NAB were listed in Table 2.

Fig. 1 shows the microstructure of the annealed NAB alloy, which consists of copper-rich α phase, retained β phase with a martensitic structure (β′ phase), and a series of intermetallic phases (κ_{II}, κ_{III} and κ_{IV} phases). The chemical composition of various constituent phases in NAB alloy are measured by energy dispersive X-ray spectroscopy (EDS) and the results is listed in Table 3, which coincides well with the former literature values [6, 21]. Because of the resolution limitations, the fine particle κ_{IV} cannot be measured accurately by EDS. Therefore, it has not been shown in Table 3.

Table 1
The nominal and experimental chemical composition of NAB alloy (wt%).

	Cu	Al	Fe	Ni	Mn
Nominal	81.1	9.5	4.0	4.2	1.2
Experimental	81.7	8.8	4.4	3.6	1.5

Table 2
The basic mechanical properties of annealed NAB alloy.

Material	Elastic modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
Annealed NAB	146	282	679	26.2

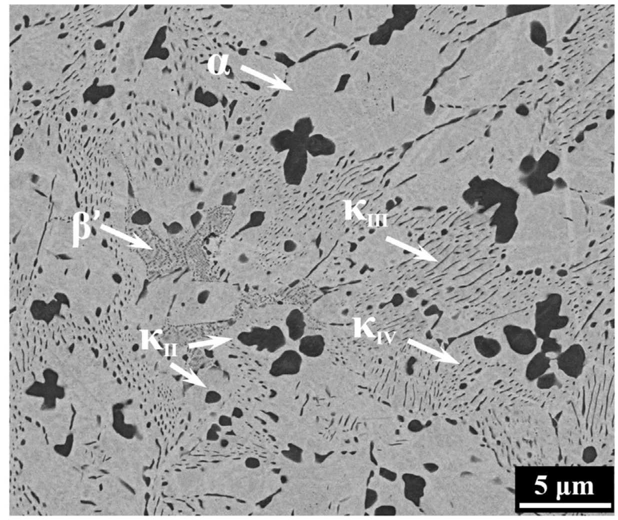

Fig. 1. Microstructure of the annealed NAB alloy.

Table 3
The chemical composition of each phases in NAB alloy (wt%).

Phase	Cu	Al	Fe	Ni	Mn
α	84.7	8.3	2.6	3.1	1.3
β′	83.4	9.6	3.2	2.7	1.1
κ_{II}	23.9	17.7	34.7	21.8	1.9
κ_{III}	28.1	16.5	21.7	32.5	1.2

2.2. Experimental Methods

2.2.1. Fatigue Crack Growth Test

The fatigue crack growth tests were conducted on a DLU-50 Hydraulic servo testing machine in air and in 3.5% NaCl solution at room temperature (25 ± 2 °C). Standard 12.7-mm thick compact tension (CT) specimens were used for this test according to ASTM E647 standard [22]. Fig. 2 illustrates the detailed dimensions of the CT specimen. The crack length in its propagation was continuously monitored by the reversed direct current potential drop (DCPD) measurement system, which is based on the adopted variation of main voltage drop at the tested specimens. The specific conversion relationship between main voltage drop and crack length has been described in elsewhere [11]. The stress intensity factor ΔK for CT specimen was calculated by the equations according to ASTM E647, which can be presented as follow [22]:

$$\Delta K = \Delta P\,[f(a/w)]/B\sqrt{w} \tag{1}$$

where

$f(a/w) = \frac{2+\alpha}{(1-\alpha)^{3/2}}(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4)$ and

ΔP = maximum load (1-R),

R = the minimum peak force divided by the maximum peak force,

a = crack length,

w = specimen width,

B = specimen thickness,

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