Corrosion and Cavitation Erosion Behaviors of Two Marine Propeller Materials in Clean and Sulfide-Polluted 3.5% NaCl Solutions

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Abstract The corrosion and cavitation erosion behaviors of two main materials for ship propellers, i.e., nickel–aluminum bronze (NAB) and manganese–nickel–aluminum bronze (MAB) were investigated in a clean and sulfide-polluted 3.5% NaCl solutions. The presence of sulfide increased the corrosion damage of both NAB and MAB by rendering the corrosion product film thicker, more porous and less protective. For MAB, the formation of Fe oxides/sulfides within the corrosion product film may reduce the film compactness and responsible for the lower corrosion resistance, compared with NAB. The presence of sulfide caused the occurrence of more severe corrosion on the surface and therefore further enhanced the cavitation erosion damage. Compared with the result in the clean solution, the cavitation–erosion mass loss rate was raised by a factor of about 11.88% for MAB, and 58.6% for NAB. For NAB, the mechanical erosion dominated the damage in the clean solution, while the cavitation erosion synergy made a significant contribution to the overall damage in the sulfide-polluted solution. For MAB, it was the mechanical damage that contributed mainly to the cavitation erosion damage in both solutions. The exfoliation of large-sized κ phase and the cleavage rupture of β phases resulted in lower cavitation erosion resistance of MAB, compared with NAB.

KEY WORDS: Copper alloy; Cavitation erosion; Corrosion; Sulfide

1 Introduction

Aluminum bronze is a copper alloy with aluminum as the major alloying element (<14 wt%). It possesses high strength and excellent resistance to corrosion, biofouling,

erosion and impingement attack [1–3]. Therefore, it is widely used for making marine components, including valves, pumps and ship propellers. Nickel–aluminum bronze (NAB) and manganese–nickel–aluminum bronze (MAB) are two main aluminum bronzes used for making ship propellers, which are designated as UNS C95800 and 95700, respectively. NAB mainly contains 9–12% Al, about 6% each of Fe and Ni and 1% Mn, and MAB mainly contains 11–14% Mn, 7–9% Al, about 3% Fe and 2% Ni.

Cavitation erosion is a typical degradation mode for hydraulic components, including ship propellers [4]. It is related to the generation and collapse processes of bubbles caused by the pressure fluctuation in liquids. The adjacent liquid with the collapsing energy of the bubbles impacts on the components as a micro-jet or shock wave, and consequently causes deformation and mass loss. Many researches have been conducted on the corrosion and cavitation erosion behaviors of NAB and MAB in seawater [4–8], and

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the modifying methods have been also explored in order to further extend the lifetime of ship propellers [9–12].

It is noteworthy that various pollutants are often introduced in seawater by the industrial waste discharge and metabolism process of marine creature. The biological and bacteriological processes, such as the decomposition of seaweed, marine organisms, microorganisms and sulfide-reducing bacteria (SRB), will result in sulfide pollution and consequently accelerate the degradation of marine components. The corrosion behaviors of copper and its alloys, such as pure copper [13–15], Cu–Zn alloy [16, 17], Cu–Ni alloy [16, 18, 19] and Al bronze [20, 21] in sulfide-polluted chloride solutions have been studied by many researchers. It was reported that the sulfide shifted the corrosion potential of copper and its alloys toward more negative values and significantly increased the corrosion rate. The sulfide ions acted as a catalyst to accelerate the cathodic and anodic processes and interfered with the normal growth of the protective oxide films [19]. A mixture of sulfides (such as Cu_2S) and oxides with porous and defective structure formed on the surface and decreased the corrosion resistance of copper alloys [15, 16, 18]. The susceptibility of Al bronze to stress corrosion cracking increased with the sulfide concentration, and the presence of sulfide changed the fracture mode from ductile to brittle transgranular [20]. Schussler *et al.* [22] investigated the corrosion mechanism of NAB in sulfide-polluted seawater and reported that the formation of highly porous copper sulfide in the corrosion product film increased the corrosion rate of NAB. Recently, Hazra *et al.* [23] reported that the highly polluted seawater with sulfide was a main factor leading to the failure

of a NAB canned motor pump impeller, and the sulfur reacted with the oxides to form Cu–S–O corrosion products. However, in these researches, it was the stagnant corrosion behavior that was mainly investigated for copper and its alloys. Ship propellers rotate at a high speed and suffer both corrosion and cavitation erosion. The increased corrosion damage caused by the sulfide ions will also enhance the cavitation erosion degradation. To the current, few studies have been conducted on the effect of sulfide on the cavitation erosion behavior of both NAB and MAB.

In this study, the corrosion and cavitation erosion behaviors of NAB and MAB in clean and sulfide-polluted 3.5% NaCl solutions were evaluated and compared by conducting gravimetric measurements and ultrasonically vibrating cavitation erosion tests. The effect of sulfide on the corrosion product film and the synergy between cavitation erosion and corrosion was also discussed.

2 Experimental

2.1 Materials

The materials investigated were cast NAB and MAB, and their chemical compositions are listed in Table 1. The NAB and MAB samples were ground with abrasive papers successively to 2000 grits, polished using diamond paste to $0.5\ \mu\text{m}$ and etched with a solution of $5\ \text{g FeCl}_3 + 2\ \text{ml HCl} + 95\ \text{ml C}_2\text{H}_5\text{OH}$. An optical microscope was used to observe the microstructure.

2.2 Gravimetric Measurements

Gravimetric measurements were taken on the samples with a dimension of $14\ \text{mm} \times 10\ \text{mm} \times 2\ \text{mm}$. Each sample was ground with abrasive papers successively to 1000 grits,

Table 1 Chemical composition of the as-cast MAB and NAB

Element (wt%)	Al	Ni	Fe	Mn	Cu
MAB	7.28	2.10	3.62	12.35	Bal.
NAB	9.30	4.50	4.88	0.97	Bal.

Fig. 1 Optical microstructures of the cast NAB and MAB

Fig. 2 Mass loss and film weight results of the cast NAB and MAB after immersion in clean and sulfide-polluted 3.5% NaCl solutions for 10 days

ultrasonically cleaned in ethanol and dried with blowing air. The initial weight was recorded as m_1 . Then, it was immersed in a 1.5 l aerated clean or sulfide-polluted 3.5% NaCl solution at room temperature (i.e., about 25 °C). The sulfide-polluted solution was replaced every day since the sulfide concentration would decrease when exposed to the

air. At the end of the immersion duration (i.e., 10 days), the sample was taken out, rinsed with distilled water and dried, and its weight was noted as m_2 . Finally, the sample was immersed in a pickling solution of 500 ml HCl + 500 ml distilled water for 2 min to remove the corrosion product films, and the weight was noted as m_3 . This pickling solution was proved to cause negligible mass loss of the MAB and NAB substrate. The mass loss of the sample was noted as $m_1 - m_3$, and the corrosion product film weight was noted as $m_2 - m_3$ [1]. Gravimetric measurements were taken in triplicates in each solution.

2.3 Cavitation Erosion Tests

Cavitation erosion tests were carried out using an ultrasonically vibrating device according to the ASTM G32 standard [24]. The frequency and amplitude of the vibrating horn were 20 kHz and 60 μm , respectively. The test sample was held 0.5 mm right below the horn and immersed 15 mm below the liquid level of the medium. The medium was kept at about 20 °C by cycling cooling water. The weight of the sample was recorded initially and after cavitation erosion for a certain period.

Fig. 3 Surface morphologies of the cast NAB and MAB after immersion in a, b clean; c, d sulfide-polluted 3.5% NaCl solutions for 10 days: a, c for NAB; b, d for MAB

The surface morphologies of the corroded and eroded samples were observed by scanning electron microscopy (SEM, JEOL ISM-6480, acceleration voltage 20 kV), and the composition of the corrosion product film was characterized by energy-dispersive spectroscopy (EDS, OXFORD x-act) for the cast NAB and MAB.

3 Results and Discussion

3.1 Microstructure

Since both NAB and MAB contain various alloying elements, their microstructures were complex and heterogeneous. Figure 1 presents their microstructures. The cast NAB consists of lightly etched coarse α phase, gray κ phase and darkly etched β' phase. The κ phases are intermetallic compounds including globular κ_I , κ_{II} , lamellar κ_{III} and fine κ_{IV} phases as shown in Fig. 1a. The κ_I , κ_{II} and κ_{IV} are Fe_3Al -based intermetallics, while the κ_{III} phase is based on NiAl [25]. The cast MAB is composed of α , β and rosette-shaped κ phases in large size. The κ phases are embedded inside α as shown in Fig. 1b.

3.2 Gravimetric Results

Figure 2 shows the mass loss and corrosion product film weight results of the cast NAB and MAB after immersion in clean and sulfide-polluted 3.5% NaCl solutions for 10 days. The following points can be obtained. Firstly, for both NAB and MAB, the mass loss in the sulfide-polluted solution was higher than that in the clean one. The corrosion rate of NAB in the clean and sulfide-polluted solution was 0.0017 and $0.0054 \text{ mg cm}^{-2} \text{ h}^{-1}$, respectively. For MAB, the corrosion rate was $0.0034 \text{ mg cm}^{-2} \text{ h}^{-1}$ in the clean solution, while $0.0066 \text{ mg cm}^{-2} \text{ h}^{-1}$ in the sulfide-polluted solution. Secondly, the film weight in the sulfide-polluted solution was much higher, indicating that a much thicker corrosion product film formed on the surface. Thirdly, the mass loss of MAB was higher than that of NAB in both solutions, and this demonstrated that MAB possessed lower corrosion resistance than NAB.

Figures 3 and 4 show the surface and cross-sectional morphologies of the cast NAB and MAB after immersion in clean and sulfide-polluted 3.5% NaCl solutions after 10 days, respectively. The chemical composition results of the corrosion product films are listed in Table 2. Evidently,

Fig. 4 Backscattered electron (BSE) images in the cross section of the cast NAB and MAB after immersion in **a, b** clean, **c, d** sulfide-polluted 3.5% NaCl solutions for 10 days: **a, c** for NAB; **b, d** for MAB

the corrosion product formed in the presence of sulfide is much thicker and more porous for both NAB and MAB. In Fig. 3c, crumb-shaped corrosion products are dispersed on the outer layer of the surface for NAB, and loose and large-sized corrosion products nearly cover the entire surface of MAB as shown in Fig. 3d. According to the EDS results, the corrosion product formed in the clean solution mainly contained oxides. While in the sulfide-polluted solution, the sulfur element was detected in the corrosion product film of MAB and NAB, indicating the existence of sulfide compounds. For copper and its alloys, the corrosion product film formed in clean chloride solution mainly contained Cu_2O and other oxides of the alloying elements. This film acted as an insulating barrier and maintained the corrosion rate of copper alloys at a very low value [26–28]. However, in addition to the oxides, the sulfide compounds also formed in the sulfide-polluted solution. It was also reported that the film formed on copper alloys in the presence of sulfide contained a mixture of oxides and sulfides, including Cu_2O , CuS and Cu_2S . The formation of sulfide compounds induced the film porous and defective in structure [16, 19, 22]. Therefore, the corrosion attack of MAB and NAB increased in the presence of sulfide due to the formation of a less-protective film. As indicated in Fig. 4, both NAB and MAB suffered general corrosion in the clean solution (Fig. 4a, b), while much severe corrosion damage occurred in the sulfide-polluted solution, and large and deep corrosion pits were found beneath the surface (Fig. 4c, d).

It is also noted in Fig. 3 that the corrosion product films on MAB are much thicker than that on NAB, as also indicated by the film weight results (Fig. 2). According to the EDS results shown in Table 2, the Fe content in the outer layer of the film on MAB reached about 40% in both the clean and sulfide-polluted solutions, while it was only about 4% in the MAB substrate. The oxides or sulfides of Fe probably formed inside the corrosion product film of MAB. A mismatch was expected between different corrosion products with different structures, such as the Fe

oxides/sulfides and Cu oxides/sulfides. The mismatch reduced the film compactness and made the film less protective. Therefore, MAB was less corrosion resistant than NAB.

3.3 Cavitation Erosion

Figure 5 shows the variation of the mass loss with cavitation erosion time for the cast NAB and MAB in clean and sulfide-polluted 3.5% NaCl solutions. At the end of the test duration, the mass loss rate of MAB in the clean and sulfide-polluted solutions was 2.6167 and 2.9275 $\text{mg cm}^{-2} \cdot \text{h}^{-1}$, respectively. While for NAB, the mass loss rate was 1.3750 $\text{mg cm}^{-2} \cdot \text{h}^{-1}$ in the clean solution and 2.1808 $\text{mg cm}^{-2} \cdot \text{h}^{-1}$ in the sulfide-polluted solution. Evidently, the addition of sulfide increased the cavitation erosion damage for both MAB and NAB. The presence of sulfide increased the mass loss rate by a factor of 11.88% for MAB, and up to 58.6% for NAB, compared with the results in the clean solution. Li *et al.* [29] also reported that

Fig. 5 Cumulative mass loss as a function of cavitation erosion time for the cast NAB and MAB in clean and sulfide-polluted 3.5% NaCl solutions

Table 2 Composition results of the corrosion products located on different areas in Fig. 4

Element (wt%)	O	Al	Ni	Fe	Mn	Cu	Cl	S
<i>Areas</i>								
1	23.08	8.75	7.46	5.52	—	54.55	0.65	—
2	40.20	1.61	1.55	49.76	2.79	4.08	—	—
3	30.64	4.47	1.90	9.89	7.57	45.53	—	—
4	33.55	6.27	10.55	2.19	—	41.22	0.52	5.69
5	18.93	8.18	4.08	4.35	—	61.26	0.59	2.61
6	41.90	3.22	1.07	34.95	4.16	13.07	—	1.62
7	16.28	5.04	0.63	5.70	9.45	61.32	—	1.58

the presence of sulfide ions in seawater increased the corrosion wear damage of copper alloys and the worn surface exhibited a microfracture-dominant mode. Moreover, the mass loss rate of MAB was about 1.9 times that of NAB in the clean solution, and 1.34 times in the sulfide-polluted solution. This demonstrated that NAB possessed higher cavitation erosion resistance in both solutions. It was also worth mentioning that NAB was more sensitive to the presence of sulfide in cavitation erosion conditions.

When cavitation erosion occurred in a corrosive medium, the mechanical erosion and corrosion coexisted and interacted with each other synergistically. The weight loss caused by cavitation erosion–corrosion was usually larger

than the sum of pure cavitation erosion and pure corrosion. This synergy can be calculated from the following equation:

$$T = E + C + S, \quad (1)$$

where T is the total mass loss obtained in a specific corrosion medium, E is the pure cavitation erosion mass loss which was obtained through conducting the cavitation erosion tests in distilled water in the present study, C is the corrosion rate which was obtained through the gravimetric measurements and S is the mass loss caused by the synergism. As shown in Table 3, a positive synergy existed between corrosion and cavitation erosion for NAB and

Table 3 Mass loss results for the cast NAB and MAB in clean and sulfide-polluted 3.5% NaCl solutions

Material/solution	Mass loss rate ($\text{mg cm}^{-2} \text{h}^{-1}$)					Percentages (%)	
	T	E	C	$E + C$	S	E/T	S/T
NAB/clean	1.3750	0.9912	0.0017	0.9929	0.3821	72.09	27.79
NAB/sulfide	2.1808	0.9912	0.0054	0.9966	1.1842	45.45	54.30
MAB/clean	2.6167	1.7225	0.0034	1.7259	0.8908	65.83	34.04
MAB/sulfide	2.9275	1.7225	0.0066	1.7291	1.1984	58.84	40.94

Fig. 6 Surface morphologies of the cast NAB after cavitation erosion in **a, b** clean, **c, d** sulfide-polluted 3.5% NaCl solutions for different time: **a, c** 1 h; **b, d** 3 h

MAB in both solutions. The synergy contained two parts, i.e., the enhancement effect of corrosion on cavitation erosion and the enhancement effect of cavitation erosion on corrosion. For NAB, in the clean solution, the E/T value reached 72.09%, indicating that the majority of material loss under cavitation erosion resulted from the mechanical damage. With the addition of sulfide ions, the S/T value increased from 27.79 to 54.30%, namely the erosion–corrosion synergy made a significant contribution to the overall cavitation erosion–corrosion damage. The presence of sulfide ions remarkably accelerated the corrosion rate of NAB, and this would roughen the surface, increased the cavitation erosion–corrosion synergy and therefore caused larger mass loss. For MAB, in both solutions, it was the mechanical damage that mainly contributed to the mass loss. In the sulfide-polluted solution, the synergy percentage slightly increased since the accelerated corrosion further promoted the cavitation erosion damage. By comparison, NAB was more sensitive to the presence of sulfide ions in cavitation erosion conditions.

Figure 6 shows the surface morphologies of the cast NAB after cavitation erosion in clean and sulfide-polluted 3.5% NaCl solutions for different times. In the clean

solution, as presented in Fig. 6a, cracks initially originated along the α/κ phase boundaries since α and κ possessed different structures and acted differently to the cavitation stress [25]. This finding was consistent with the research of Alhashem *et al.* [4]. The κ phases would fall off from the substrate with increasing the cavitation erosion time. After cavitation erosion for 3 h, the soft α matrix was seriously damaged, while the hard lamellar eutectoid suffered less severe attack and remained on the surface as shown in Fig. 6b. However, in the sulfide-polluted solution, as shown in Fig. 6c, the entire surface of NAB was rougher because of the occurrence of severe corrosion, and the surrounding α matrix around κ phase dissolved. This promoted the decohesion of the α/κ interface and exfoliation of the κ phases. With the cavitation erosion time extending, the entire NAB surface was attacked and the microstructure was hardly recognized as shown in Fig. 6d.

Figure 7 shows the surface morphologies of the cast MAB after cavitation erosion in clean and sulfide-polluted 3.5% NaCl solutions for different time. As presented in Fig. 7a, cracks initiated at the α/β phase boundaries. The soft α phase suffered more severe attack, while the hard β phase maintained its original morphology. The cavity

Fig. 7 Surface morphologies of the cast MAB after cavitation erosion in **a, b** clean, **c, d** sulfide-polluted 3.5% NaCl solution for different time: **a, c** 1 h; **b, d** 3 h

indicated by a white arrow was speculated to result from the exfoliation of the embedded large-sized κ phases from the α matrix. Similar observation was reported in the research of Yu *et al.* [30]. Tang *et al.* [12] also found that under cavitation erosion, the hard κ phase sank into the soft α phase, resulting in decohesion of the α/κ interface, the erosion damage propagated into the surrounding α matrix by ductile tearing, and the κ phases underwent brittle fracture. After 3 h, as presented in Fig. 7b, some of the β phases still remained on the MAB surface and a large number of cavities appeared. The cleavage-like facets were also found at the β phases as shown in Fig. 7b. Similar findings were also reported by Li *et al.* [6]. In the sulfide-polluted solution, after 1 h, nearly all α phases were erosion-attacked and the β phases suffered corrosion as shown in Fig. 7c. As cavitation went on, severe cavitation erosion damage spread all over the entire surface. A large number of large and deep cavities dispersed on the surface. Cleavage-like facets and long cracks were found at the β phases, as demonstrated in Fig. 7d.

Evidently, the presence of sulfide aggravated the cavitation erosion damage for both MAB and NAB. In the sulfide-polluted solution, the occurrence of much more

severe corrosion increased the surface roughness and decreased the cohesion between different phases, consequently the synergy between corrosion and cavitation erosion was enhanced and the cavitation erosion damage increased. The exfoliation of the large-sized κ phase and the cleavage fracture of β phase were responsible for the larger mass loss of MAB, compared with NAB.

For MAB, in both the clean and sulfide-polluted solutions, cracks originated at the α/β and α/κ boundaries under the cavitation stress. With the gradual damage of the surrounding α phase, κ phase fell off from the surface of the alloy. The existence of the cleavage facets at the β phases in both solutions showed a brittle fracture, in addition to the ductile fracture as shown in Fig. 8a, b. It was the mechanical deterioration factor that dominated the cavitation erosion damage, and the corrosion-cavitation erosion synergy increased slightly in the presence of sulfide. While for NAB, it was noted that in the clean solution, some eutectoids were still left on the surface because of their higher hardness. However, the addition of sulfide accelerated the galvanic corrosion between the α and κ phases, and promoted the collapse of the eutectoids under the cavitation stress. Furthermore, the addition of sulfide

Fig. 8 Surface morphologies after cavitation erosion in **a, c** clean; **b, d** sulfide-polluted 3.5% NaCl solution for 10 h: **a, b** for the cast MAB; **c, d** for the cast NAB

seemed to facilitate the brittle fracture of NAB and a large area of the NAB surface was eroded, leaving groove-shaped and large-sized cavities as shown in Fig. 8d. Similar phenomenon was not observed on the NAB surface in the clean solution as shown in Fig. 8c. Li et al. [29] also reported that the sulfide promoted the microfracture-dominated wear damage for Al bronze. Thus, in the presence of sulfide, a remarkable synergy between corrosion and cavitation erosion occurred and significantly increased the erosion damage. Namely, NAB was more sensitive to the presence of sulfide in cavitation erosion condition, compared with MAB.

4 Conclusions

1. For both NAB and MAB, the addition of sulfide in 3.5% NaCl solution made the corrosion product film become thicker and more porous, and therefore increased the corrosion rate. For MAB, the formation of Fe oxides/sulfides inside the corrosion product reduced the film compactness and was responsible for the lower corrosion resistance of MAB in both solutions, compared with NAB.
2. The presence of sulfide increased the cavitation erosion mass loss rate by a factor of 11.88% for MAB, and up to 58.6% for NAB, compared with the results in the clean solution. NAB exhibited mechanical erosion-dominated damage mode in the clean solution, while the presence of sulfide significantly enhanced the cavitation erosion–corrosion synergy. For MAB, mechanical erosion contributed mainly to the cavitation erosion damage in both solutions. The exfoliation of the large-sized κ phase and the cleavage fracture of β phase were responsible for the lower cavitation erosion resistance of MAB, compared with NAB. It is noteworthy that necessary protective methods need to be used for NAB ship propellers in sulfide-polluted seawater.

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References

- [1] B.G. Ateya, E.A. Ashour, S.M. Sayed, J. Electrochem. Soc. **141**, 71 (1994)
- [2] X.F. Zhang, L. Fang, Wear **253**, 1105 (2002)
- [3] A.H. Tuthill, Mater. Perform. **26**, 12 (1987)
- [4] A. Alhashem, P.G. Caceres, W.T. Riad, H.M. Shalaby, Corrosion **51**, 331 (1995)
- [5] D.T. Zhang, R.P. Chen, W.W. Zhang, Z.G. Luo, Y.Y. Li, Acta Metall. Sin. (Engl. Lett.) **23**, 113 (2010)
- [6] X.Y. Li, Y.G. Yan, L. Ma, Z.M. Xu, J.G. Li, Mater. Sci. Eng. A **382**, 82 (2004)
- [7] M. Lotfollahi, M. Shamanian, A. Saatchi, Mater. Des. **62**, 282 (2014)
- [8] Z. Wu, Y.F. Cheng, L. Liu, W. Lv, W. Hu, Corros. Sci. **98**, 260 (2015)
- [9] Q.N. Song, Y.G. Zheng, S.L. Jiang, D.R. Ni, Z.Y. Ma, Corrosion **69**, 1111 (2013)
- [10] B. Sabbaghzadeh, R. Parvizi, A. Davoodi, M.H. Moayed, Mater. Des. **58**, 346 (2014)
- [11] R. Cottam, V. Luzin, H. Moody, D. Edwards, A. Majumdar, Y.C. Wong, J. Wang, M. Brandt, Wear **317**, 56 (2014)
- [12] C.H. Tang, F.T. Cheng, H.C. Man, Surf. Coat. Technol. **182**, 300 (2004)
- [13] J. Chen, Z. Qin, T. Martino, D.W. Shoesmith, Corros. Sci. **114**, 72 (2017)
- [14] T. Martino, R. Partovi-Nia, J. Chen, Z. Qin, D.W. Shoesmith, Electrochim. Acta **127**, 439 (2014)
- [15] K. Rahmouni, M. Keddami, A. Shhiri, H. Takenouti, Corros. Sci. **47**, 3249 (2005)
- [16] N.K. Awad, E.A. Ashour, N.K. Allam, Appl. Surf. Sci. **346**, 158 (2015)
- [17] Z. Mountassir, A. Shhiri, Corros. Sci. **49**, 1350 (2007)
- [18] A.A. Nazeer, A.S. Fouda, E.A. Ashour, J. Mater. Environ. Sci. **2**, 24 (2011)
- [19] S.J. Yuan, S.O. Pehkonen, Corros. Sci. **49**, 1276 (2007)
- [20] E.A. Ashour, L.A. Khorshed, G.I. Youssef, H.M. Zakria, T.A. Khalifa, Mater. Sci. Appl. **5**, 10 (2014)
- [21] A.A. Nazeer, E.A. Ashour, N.K. Allam, Mater. Chem. Phys. **144**, 55 (2014)
- [22] A. Schussler, H.E. Exner, Corros. Sci. **34**, 1803 (1993)
- [23] M. Hazra, K.P. Balan, Eng. Fail. Anal. **70**, 141 (2016)
- [24] ASTM International, G32-03, Standard Test for Cavitation Erosion Using Vibratory Apparatus, West Conshohocken (2003)
- [25] F. Hasan, A. Jahanafrooz, G.W. Lorimer, N. Eidle, Metall. Trans. A **13A**, 1337 (1982)
- [26] F.L. Sun, X.G. Li, L. Lu, H.X. Wan, C.W. Du, Z.Y. Liu, Acta Metall. Sin. **49**, 1211 (2013)
- [27] A. Schussler, H.E. Exner, Corros. Sci. **34**, 1793 (1993)
- [28] C. Kato, J.E. Castle, B.G. Ateya, H.W. Pickering, J. Electrochem. Soc. **127**, 1897 (1980)
- [29] S.Z. Li, X.X. Jiang, H.Y. Bi, S. Li, Wear **225–229**, 1025 (1999)
- [30] H. Yu, Y.G. Zheng, Z.M. Yao, J. Mater. Sci. Technol. **25**, 758 (2009)