A higher corrosion resistance for a bainitic steel with Al instead of Si

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Abstract: The stress corrosion and neutral salt spray corrosion behaviours of two bainitic steels, with Si and/or Al respectively, were studied. Results show that adding Al instead of Si in steel, not only notably reduces stress corrosion cracking susceptibility which efficiently suppresses the occurrence of cracking for stress corrosion, but reduces the corrosion rate of steel in neutral salt spray condition, referring to the weight loss and thickness of rust layer. Phase composition reveals that more β -FeOOH and Si in the rust layer of steel with Si makes the rust layer loose and increases corrosion rate, and more α -FeOOH in the rust layer of steel with Al improves the corrosion resistance of the steel. Also, Al facilitates the formation of a compact oxide layer which can increase the corrosion resistance.

Keywords: Metals and alloys; Corrosion; Stress corrosion cracking; Rust layer; Phase composition

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1 Introduction

Bainitic steel has been widely applied in modern industries, such as energy generation industry, bearing and railway system (including rail and crossing), for its high strength and high toughness [1–3]. Silicon is an important alloying element in

bainitic steel, which not only can strengthen the ferrite phase, improve the hardenability and temper resistance, but can suppress the carbide precipitation [4,5]. However, there are some disadvantages for a high Si content, such as retarding the bainite phase transformation [6], reducing the surface property of hot rolled plates [7]. Al alloying element, which also can suppress the carbide precipitation in ferrite, has been introduced into bainitic steel for it can accelerate the bainite phase transformation [8] and improve the formability of steel [7]. Therefore, the Al can substitute for the Si in some bainitic steels. The mechanical properties and the microstructure of bainitic steel with Si and/or Al have been widely studied [3-8].

Corrosion process is inevitable during the service life of a steel product. And the variation of alloying element changes the corrosion resistance of steel. Previous studies showed that both Si and Al played a positive effect on the corrosion behaviour of steel. Wang et al. found adding Al improved the corrosion resistance of J55 carbon steel [9]. Li et al. considered that Si promoted the formation of thin oxide films containing Cr, and then improved the corrosion resistance of Cr steel in salt water [10]. They also found the combination of Al and Si made the Cr steel exhibits an excellent corrosion resistance in KCl solution. Nishimura reported that in the rust layer, Al existed in the form of Al^{3+} in complex oxides of $Fe-Al^{3+}-O$, which fills up the voids and cracks in the rust layer, and then improved the corrosion resistance of the steel [11]. Several researchers also pointed out that the compact and dense amorphous oxide layer could protect the steel from weathering [12,13]. However, for bainitic steel, how the corrosion behaviour changes when substitute Al for Si is still unknown.

The aim of this study is to investigate the corrosion behaviour of two bainitic steels with different contents of Si and Al, with a hope of further improving the understanding

of Al on the bainitic steel. In this paper, the stress corrosion and neutral salt spray corrosion were introduced.

2 Material and methods

The chemical compositions of studied steels were 0.30C-1.62Mn-2.23Si-1.20Cr-0.41Ni-0.39Mo-0.006S-0.008P (steel 1) and 0.29C-1.62Mn-0.11Si-1.20Cr-0.41Ni-0.38Mo-1.77Al-0.006S-0.008P (wt%) (steel 2). The as-received steels were heated to 930°C for 45 min, then isothermal treated at 345°C for 1 h to obtain bainite microstructure, and then air-cooled to room temperature. Finally, the steels were tempered at 320°C for 1 h.

The stress corrosion cracking (SCC) properties of steels were studied via slow strain rate tensile tests. The notch specimens showed in Fig. 1 were tensiled at room temperature with a strain rate of $1.67 \times 10^{-6} \text{ s}^{-1}$, and in a medium of atmosphere and 3.5% NaCl solution, respectively. The neutral salt spray (NSS) tests were carried out in a salt spray test machine (BY-120A). The polished specimens with a size of 10 mm × 10 mm × 5 mm were cleaned and weighed. The specimens were removed from machine after different exposure time. Then, these specimens were cleaned and weighed again.

The morphology of the cross section of the corrosion specimens were characterised via scanning electron microscopy (SEM). The phase constitutions and chemical composition of the rust layer were examined via X-ray diffraction (XRD) and energy dispersion spectrometry (EDS), respectively.

3 Results and Discussion

3.1 Stress corrosion cracking behaviour

Fig. 1 shows the stress-strain curves of specimens in atmosphere and 3.5% NaCl solution, respectively. One can see that the peak-stress values of steel 1 are notably higher than that of steel 2, due to high Si content in steel 1. Si possesses a higher

solution strengthening effect than Al. However, the reduction amplitude of peak-stress is obviously smaller in steel 2.

Fig. 1 Stress-strain curves of steels. *Note:* the inset is the specimen size with a thickness of 3 mm.

The SCC susceptibilities of the two steels are evaluated according to the following equations: $F_I = (\sigma_{air} - \sigma_{sol}) / \sigma_{air}$ and $F_A = (A_{air} - A_{sol}) / A_{air}$, where σ_{air} and σ_{sol} are the peak stress in air and in 3.5% NaCl solution, respectively, and A_{air} and A_{sol} are the fracture energy values. The results are summarized in Table 1. Obviously, the SCC susceptibility of steel 2 is significantly lower than that of steel 1. When F is greater than 35%, the occurrence of SCC is inevitable in a certain environment, and when F is below 25%, the material is safe and no SCC occurs [14]. It can be seen that the SCC susceptibility of steel 2 is below 25%, and the SCC susceptibility of steel 1 is above 35%. Undoubtedly, adding Al instead of Si in the bainite steel efficiently suppress the occurrence of SCC.

Table 1 SCC susceptibility of the two steels

Steel	Corrosion medium	σ_{max}/MPa	$F_I/\%$	$A/\text{MPa}\cdot\text{mm}$	$F_A/\%$
1	3.5% NaCl	590	68.4	296	88.8
	air	1866		2659	
2	3.5% NaCl	1290	11.1	1324	21.3
	air	1451		1682	

3.2 Neutral salt spray corrosion behaviour

The weight loss per unit surface area ΔW (mg/cm^2) of the two steel specimens undergone different exposure time are measured according to the equation of $\Delta W = (W_1 - W_2) / S$, where W_1 and W_2 are the average weight of specimens before and after exposure, respectively, and S is the exposure area of the specimens. The variation of ΔW with exposure time is showed in Fig. 2. It can be seen that with increasing exposure time, ΔW increased monotonously for both steels, with a fast increase at earlier 160 h. The ΔW value of steel 2 is smaller than that of steel 1, revealing a better corrosion resistance for steel 2 than steel 1.

Fig. 2 Variation of ΔW with exposure time t

Fig. 3a-d shows SEM micrographs of the cross-sections of the two steels after different exposure time. It can be seen that the rust layer is much thinner and denser for steel 2 than steel 1, and the interface between the rust layer and the matrix is more flat for steel 2. Thickness measurement on rust layer shows that with increasing exposure time from 72 to 360 h, the thickness increased from 26 to 50 μm and from 6 to 11 μm , respectively for steel 1 and steel 2, also stating a better corrosion resistance of steel 2.

Zhang et al. has demonstrated that in steel, Si can increase the thickness of rust layer,

make the rust layer become loose, and reduce the adhesion of the rust layer to the matrix [15], which is similar to our results.

Fig. 3 SEM micrograph of cross-section of Steel 1 in first row and Steel 2 in second row after 72 h (a,c) and 168 h (b,d) accelerated corrosion, and the two corresponding XRD patterns and EDS results of rust layer in the right. *Note:* the red ellipse and arrows in (b) are peeling and caverns, respectively, and the insets in XRD patterns are before corrosion test.

The denser rust layer can effectively prevent the penetration of chloride solution into the matrix, which in turn results in a slower corrosion rate. The phase composition of the rust layer in two steel specimens, analyzed via XRD in Fig. 3, shows that there are magnetite (Fe_3O_4), goethite ($\alpha\text{-FeOOH}$), akaganeite ($\beta\text{-FeOOH}$), and lepidocrocite ($\gamma\text{-FeOOH}$) in the rust layer. One can see that a mountain of $\beta\text{-FeOOH}$ presents in the rust layer of steel 1, which can weaken the protective property of rust layer [16]. And for steel 2, more $\alpha\text{-FeOOH}$ exists in the rust layer. Previous reports have pointed out that the primitive corrosion product on steel was micaceous and porous $\gamma\text{-FeOOH}$, which would gradually transform to the $\alpha\text{-FeOOH}$ with a compact and clubbed structure [17,18]. The $\alpha\text{-FeOOH}$ is beneficial to improve the corrosion resistance of the steel. Moreover, plentiful Al alloying element within the rust layer demonstrated by EDS

results facilitates the formation of a compact oxide layer, such as Fe-Al³⁺-O [11], which can inhibit the penetration of chloride solution into the matrix, and then increase the corrosion resistance.

4 Conclusions

In summary, the stress corrosion and neutral salt spray corrosion behaviours of two bainitic steels, with Si and/or Al respectively, were studied. Adding Al instead of Si in bainite steel notably reduces SCC susceptibility from 88.8% and 68.4% to 21.3% and 11.1%, respectively, which can efficiently suppress cracking resulted from stress corrosion. Also, the steel with Al shows a much smaller corrosion rate in neutral salt spray condition, including a smaller weight loss and a thinner rust layer, as compared with the steel with Si. Analyses on phase composition of rust layer shows more β -FeOOH in the rust layer of steel with Si and more α -FeOOH in the rust layer of steel with Al. β -FeOOH increases the corrosion rate, and to the contrary α -FeOOH is beneficial to improving the corrosion resistance of the steel. Moreover, the Al facilitates the formation of a compact oxide layer which increases the corrosion resistance. Then it can be concluded that the Al element can effectively improve the corrosion resistance for bainitic steel.

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References

- [1] Bhadeshia HKDH. Bainite in Steels. 3rd ed. UK: Maney; 2015.
- [2] Hu F, Hodgson PD, Wu KM. Mater Lett 2014; 122: 240-3.
- [3] Zhang FC, Wang TS, Zhang, Zheng CL, Lv B, Zhang M, Zheng YZ. Scripta Mater

2008; 59:294-6.

[4] Bhadeshia HKDH, Edmonds DV, Bainite in silicon Steels: New Composition-property-approach, Part1. Metal Sci 1983; 17: 411-9.

[5] Long XY, Zhang FC, Kang J, Lv B, Shi XB. Mater Sci Eng A 2014; 594:344-51.

[6] Sourmail T, Smanio V, Acta Mater 2013; 61: 2639-48.

[7] Meyer M De, Vanderschueren D, Cooman BC De. ISIJ Int 1999; 39: 813-22.

[8] Garcia-Mateo C, Caballero FG, Bhadeshia HKDH. ISIJ Int 2003; 43: 1821-5.

[9] Wang R, Luo SJ, Liu M, Xue YN. Corros Sci 2014; 85: 270-9.

[10] Li YS, Spiegel M, Shimada S. Mater Lett 2004; 58: 3787–91.

[11] Nishimura T. Corros Sci 2008; 50: 1306-12.

[12] Asami K, Kikuchi M. Corros Sci 2003; 45: 2671-88.

[13] Siddique M, Anwar-ul-Islam M, Butt NM, Hussain N, Rehman S, Arshed M, J Radioanal Nucl Chem 1999; 241: 239-40.

[14] Dong YX, Zhang W, Yang TC. Corros Sci Protec Tech 2011; 23: 427-30.

[15] Zhang QS, Wang XD, Yu YS, Jiang SM, Chen XP. Mater Protec 2007; 40: 21-3.

[16] Ma YT, Li Y, Wang FH. Mater. Chem. Phys. 2008; 112:844-52.

[17] Smith DC, Mcenaney B. Corros Sci 1979; 19: 379-94.

[18] Oh SJ, Cook DC, Townsend HE. Corros Sci 1999; 41:1687-702.

Figure captions

Fig. 1 Stress-strain curves of steels. Note: the inset in the bottom right corner is the specimen size with a thickness of 3 mm.

Fig. 2 Variation of ΔW with exposure time t .

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