



# Hot corrosion behaviour and its mechanism of a new alumina-forming austenitic stainless steel in molten sodium sulphate



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## ABSTRACT

Hot corrosion behaviour and related mechanism of an alumina-forming austenitic (AFA) stainless steel at 1173 K in molten sodium sulphate were investigated. Compared with the Ni-based super-alloy K438, K417 and the commercial steel 316L, the current AFA steel exhibited a high hot-corrosion resistance with less internal sulphidation. It was found that a dense, continuous Al<sub>2</sub>O<sub>3</sub> scale created at the early corrosion stage enabled formation of a compact Cr<sub>2</sub>O<sub>3</sub> scale on it in the subsequent corrosion. Such dual layers effectively suppressed the sulphur penetration and protected the matrix from the hot corrosion.

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## 1. Introduction

Commercial austenitic stainless steels are primarily utilised as construction materials for high-temperatures components because of their good high-temperature creep strength and oxidation resistance at a relatively low cost. Conventional austenitic stainless steels form a Cr<sub>2</sub>O<sub>3</sub>-based protective scale at high temperatures, however, such scale would lose its protectiveness when the service temperature is higher than 600 °C in harsh environments with water vapour or other aggressive species, resulting in accelerated oxidation rates and shortened material life [1–3]. Recently, alumina-forming austenitic (AFA) steels which can achieve fine high-temperature oxidation resistance in both dry air and air with 10% water vapour between temperatures of 650 and 900 °C due to formation of a much stable Al<sub>2</sub>O<sub>3</sub> scale were successfully developed [4–12]. These new austenitic steels have great potential to be utilised as engineering components serviced in harsh environments, particularly with presence of water vapour.

In industrial and marine gas turbines, sulphur from the fuel reacts with sodium chloride from ingested air at elevated temperatures to form sodium sulphate during combustion. The sodium sulphate then deposits on the hot-section components, resulting in accelerated oxidation (or sulphidation) attack and the materials prone to so-called ‘hot corrosion’ [13]. Reaction kinetics of the hot corrosion has been traditionally characterised by an initial incubation stage with a relatively low reaction rate, followed by a propagation stage with rapid material degradation [14]. In order to

improve application range and service life of the newly developed AFA stainless steels, characterisation of their hot corrosion behaviour and understanding of the related mechanism are urgently needed. Nevertheless, limited work in this regard has been conducted. In this paper, we present hot corrosion behaviour of the AFA stainless steel recently developed on a basis of the commercial heat-resistant steel NF709 [9]. The underlying reasons about why this AFA alloy possessed a high resistance to the hot corrosion will also be discussed in detail.

It is known that the component and velocity of cover gases in hot corrosion experiments have a great influence on the hot corrosion behaviour and mechanism. In early hot corrosion simulation experiments for aircraft engines, only air was used as the cover gas. However, it was found that for industrial and marine turbines, using air alone could not well simulate hot corrosion attack unless some SO<sub>2</sub> gas was also included [15]. In this paper, it was the first screening attempt for characterising hot corrosion resistance of the newly developed AFA steels and only air was used as cover gas for baseline. In future work, SO<sub>2</sub> and other gases would be considered as cover gases for better evaluation.

## 2. Experimental

### 2.1. Material preparation

In this study, the AFA stainless steel developed recently by our group [9] was selected as the base alloy. In order to compare the hot corrosion performance of our AFA stainless steel with other materials, we also chose the nickel-base super-alloy K438 (grain size about 30–40 μm), nickel-base super-alloy K417 (grain size

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**Table 1**

Alloy compositions (wt.%) of representative alloys investigated.

Elements	AFA Alloy		K438		K417		316L	
	Nominal	Actual	Nominal	Actual	Nominal	Actual	Nominal	Actual
Ni	25	25.2	Bal.	Bal.	Bal.	Bal.	10	10.1
Cr	18	17.9	16	15.9	9	8.9	16	15.8
Al	3	3	3.5	3.4	5.2	5.2	–	–
Si	0.15	0.15	–	–	–	–	1	0.95
Mo	1.5	1.4	1.8	1.7	3	2.9	2	1.9
Nb	1.5	1.5	0.6	0.6	–	–	–	–
C	0.08	0.07	0.15	0.14	0.15	0.15	0.03	0.04
B	0.01	0.008	0.01	0.009	0.016	0.015	–	–
P	0.04	0.03	–	–	–	–	0.045	0.03
Ti	–	–	3.2	3.2	4.8	4.8	–	–
Co	–	–	8.5	8.4	15	14.9	–	–
W	–	–	2.5	2.5	–	–	–	–
Ta	–	–	1.8	1.7	–	–	–	–
V	–	–	–	–	0.6	0.61	–	–
Zr	–	–	0.1	0.1	0.06	0.06	–	–
Mn	–	–	–	–	–	–	2	1.8
Hf	0.15	0.14	–	–	–	–	–	–
Y	0.01	0.008	–	–	–	–	–	–
Fe	Bal.	Bal.	–	–	–	–	Bal.	Bal.

about 30–50  $\mu\text{m}$ ), and 316L stainless steel (grain size about 20–30  $\mu\text{m}$ ) for comparison. Table 1 lists target and actual compositions of all the alloys investigated. Alloy ingots were prepared by arc-melting a mixture of commercially-pure elements. The ingots were remelted and then cast into a 10  $\times$  10  $\times$  100 mm copper mould. The as-cast bars were homogenised at 1200–1250  $^{\circ}\text{C}$  for 24 h, cold rolled 30–40%, then recrystallised at 1200–1250  $^{\circ}\text{C}$  for about 5–10 min to control grain size (about 20–30  $\mu\text{m}$ ), and subsequently water-quenched to eliminate precipitation of second phases.

## 2.2. Hot corrosion testing

Corrosion specimens with a dimension of 8  $\times$  8  $\times$  1.2 mm were ground to a 2000-grit surface finish using emery papers. Then the specimens were cleaned subsequently in de-ionised water, acetone, and alcohol. Hot corrosion tests were performed in an open-ended tube furnace at 1173 K. The specimens were pre-heated and then were coated with a saturated aqueous solution of sodium sulphate. Amount of the salt layer was controlled within the range of 2–3  $\text{mg}/\text{cm}^2$  after evaporating water. The hot corrosion tests were conducted in static air at 1173 K, and the specimens were circularly taken out of the furnace to cool, wash to remove loose corrosion product, dry, weight and re-coat salt. The total testing time was 100 h, while the actual time span for all 9 cycles is 1, 11, 8, 13, 9, 13, 8, 17 and 20 h, respectively.

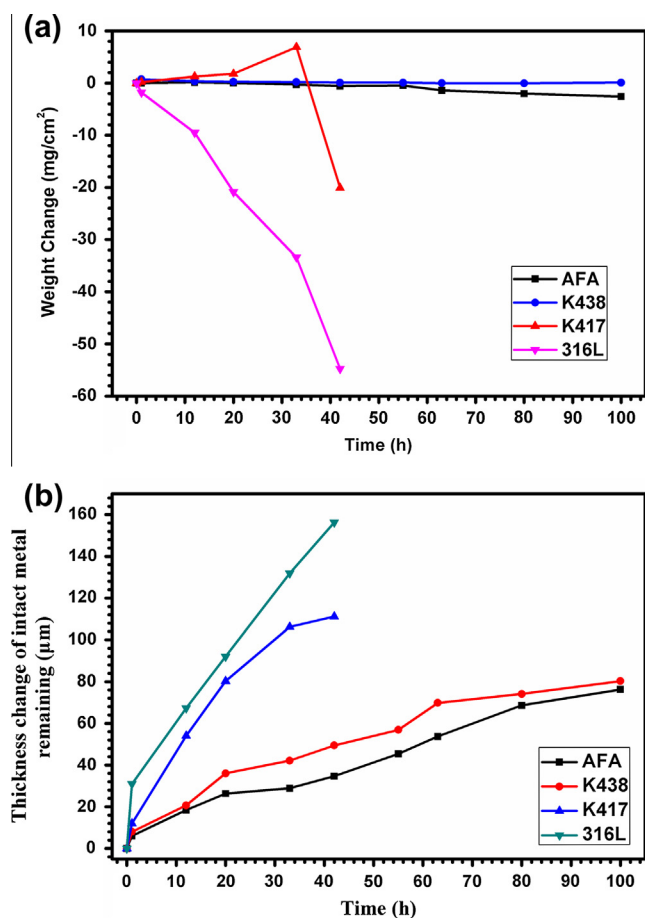
## 2.3. Corroded specimen characterisation

Mass change after each cycle was measured by an electronic balance with a sensitivity of 0.01 mg, and the corrosion products were analysed by X-ray diffraction (XRD) using  $\text{Cu K}\alpha$  radiation. Morphology and compositions of the tested specimens were characterised through field emission scanning electron microscopy (SEM) with an energy dispersive X-ray spectrometry (EDS). All the corroded samples were electrodeposited with a Ni layer on their surfaces before the SEM observation to keep the corrosion scale intact.

## 3. Results

### 3.1. Hot corrosion kinetics

Corrosion kinetics of the AFA steel at 1173 K in the molten sodium sulphate is illustrated in Fig. 1. The corresponding data of



**Fig. 1.** (a) Weight change of the specimens hot-corroded at 1173 K in molten sodium sulphate, and (b) thickness change of intact metal remaining in the specimens hot-corroded at 1173 K in molten sodium sulphate.

the nickel base super-alloy K438, K417 and 316L stainless steel were also included for comparison. As can be seen in Fig. 1a, the 316L stainless steel underwent a fast mass loss up to 42 h (about 56  $\text{mg}/\text{cm}^2$ ) without an evident incubation period. The super-alloy K417 showed a weight gain until 33 h and then bubbled seriously, resulting in a large weight loss. These results indicated that the hot

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