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Bull. Mater. Sci. (2020) 43:11 © Indian Academy of Sciences https://doi.org/10.1007/s12034-019-1984-0 High-temperature corro sion of aluminized-AISI 1020 steel with N a C l a n d Na 2 SO 4 deposits M BADARUDDIN 1,* , SUGIYANTO 1 and D A SMI 2 1Department of Mechanical Engineering, Faculty of Engineering, Universitas Lampung, Bandar Lampung 35145, Indonesia 2Department of Physics, Faculty of Mathematics and Natural Science, Universitas Lampung, Bandar Lampung 35145, Indonesia *Author for correspondence (mbruddin@eng.unila.ac.id) MS received 27 August 2018; accepted 10 July 2019 Abstract.

High-temperature corrosion of aluminized-American Iron and Steel Institute (AISI) 1020 steel with sodium chloride (NaCl) and sodium sulphate (Na2SO4) deposits was studied using isothermal oxidization in a dry air environment at 700?C for 49 h. NaCl and Na2SO4 deposits on the aluminide layer interfered with protective alumina/aluminium oxide (Al2O3) scale formation on the steel substrate.

Chlorine and sulphur gases (Cl2g and Sg, respectively) released into the atmosphere corroded the protective Al2O3 layer. Corrosion of the Al2O3 layer was also due to local formation of iron oxide (Fe2O3). Fe2O3 growth is attributed to ferric chloride (FeCl3) vaporization. Sg diffusion into the Al2O3 scale via Al3+ vacancy defects led to the formation of aluminium sulphide on the aluminide layer surface.

Cl and S consequently induced hot corrosion of the aluminized steel, thereby increasing cyclic oxychloridation and sulphidation rates at high temperatures. Keywords. Aluminized 1020 steel; hot corrosion; oxychloridation; sulphidation; alumina/aluminium oxide (Al2O3). 1. Introduction Cold-rolled American Iron and Steel Institute (AISI) 1020 steel is a material suitable for engineering components because of its relatively low cost

compared with that of high- alloy steel.

This steel is used in heat exchangers, oil gas tanks, high-pressure water pipes and other equipment for fossil fuel power plants. Alkali metal sulphates produced by low-grade fuel combustion react with sodium chloride (NaCl) from ocean breezes at elevated temperatures, form- ing sodium sulphate (Na_2SO_4), which severely corrodes the material by oxidation, sulphidation or chloridation, thus ren- dering it prone to hot corrosion [1–3].

Therefore, the presence of NaCl and Na_2SO_4 deposits on engineering material components at high temperatures causes rapid degradation of the material [4,5]. In this regard, hot-dipped aluminide steel has great potential in engineering components for harsh environ- ments. Several studies have reported that the aluminium (Al) coating and its alloys can improve carbon steel resistance to oxidation at high temperatures [6–8].

The aluminide layer on steel can supply Al atoms and form a protective aluminium oxide (Al_2O_3) layer. To widen the application range and service life of aluminide steel, hot-corrosion behaviour and its related mechanism must be characterized. Therefore, we studied the effects of NaCl and Na_2SO_4 deposits on the surfaces of aluminized and bare steel (AS and BS) by isothermally oxidizing them at 700?C for 49 h in a static-air environment. The corrosion kinetics was analysed to determine the parabolic rate constant of cor- rosion (kp).

Oxidized AS samples were characterized by both optical and scanning electron microscopy (OM and SEM, respectively), energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) to determine the possible corro- sion causing mechanisms. 2. Experimental 2.1 Specimen preparation A commercial cold-rolled AISI 1020 steel plate with a chem- ical composition of 0.2C–0.05P–0.05S–0.5Mn (wt%; iron [Fe]-balanced) was cut into specimens with dimensions of 20×10×2mm 3.

Before Al deposition, all specimens were ultrasonically cleaned with a solution of 5% sodium hydrox- ide (NaOH) and 10% phosphoric acid (H_3PO_4) and then covered with Al welding ?ux pasta. Commercial Al–0.5 wt% silicon (Si) was melted in an alumina (Al_2O_3) crucible at 700?C, and the specimens were then dipped for 16 s in a molten Al bath.

After the aluminizing process, oxide ?ux deposited on the surface of the aluminized specimens was 0123456789().: V,-vol 11 Page 2 of 8 Bull. Mater. Sci. (2020) 43:11 Figure 1. SEM and EDS results: (a) cross-sectional micrograph and (b) iron (Fe) and aluminium (Al) element line-scan results for aluminized AISI 1020 steel.

cleaned with a solution of nitric acid, H3PO4 and water (1:1:1, v/v) at room temperature. 2.2 Corrosion t esting and characterization of s amples A saturated NaCl and Na2SO4 solution was sprayed onto the largest surface of each specimen placed on a 200?C hot plate to form deposits at a concentration of 2 mg cm-2.AsaltofNaCl and Na2SO4 at a concentration of 2 mg cm-2 was similar to that reported in the literature [9,10].

All BS and AS specimens with NaCl and Na2SO4 coatings were isothermally oxidized at 700?C for 1–49 h. In the present investigation, a temperature of around 700?C is referred to as type-II hot corrosion, which occurs at temperatures below that of salt melting [11]. After a given isothermal oxidation time, the specimens were removed and cooled in air at room temperature.

Each data point for corrosion kinetic-related weight gain was obtained from a different specimen. Linear and parabolic plots of the weight gain (mg cm-2) vs.oxidation time (h) were con- structed. The aluminide layer thickness and microstructures of aluminized specimens were observed by OM. The phases formed on steel were identi?ed by XRD using monochro- matic Cu Karadiation at 40 kV and 100 mA.

The surface and cross-sectional morphologies of AS were examined by SEM and EDS, respectively. 3. Results and discussion 3.1 Examination of t he coated specimen An SEM cross-sectional micrograph and EDS element line scan for the aluminide coating and the steel substrate after the aluminizing process are displayed in ?gure 1a and b, respectively.

When low-carbon steel and molten Al came into contact with each other during the hot-dipping process, a thin intermetallic compound (IMC) formed between the steel and aluminide layer. However, not all of the IMCs formed during the aluminizing hot-dip coating, except for the Fe2Al5 and FeAl3 phases, could be con?rmed [12]. The formation of the IMCs in the Al-rich zone suggests that inward diffusion of Fe and outward diffusion of Al pre- dominantly controlled the phase transformation and formed an aluminide layer on the steel substrate.

The thickness of the aluminide layer consisting of the Al and FeAl3/Fe2Al5 intermetallic layers was about 50μm (FeAl3: 5.403μm and Fe2Al5: 17.401μm). This coating layer showed no cracks and voids at the interface between the aluminide layer and steel substrate. In addition, an EDS element line scanning showed that the Fe content of the Al coating was much less than that of the intermetallic layer.

This may have been caused by the lower diffusion rate of Fe atoms in molten Al compared with that of Al atoms in Fe [13]. The Al content decreased while the FeAl3 and

Fe2Al5 content increased towards the steel sub- strate after formation of the aluminizing coating by the hot-dip process (?gure1b). 3.2 Corrosion kinetics Figure 2a shows the corrosion kinetics of AS after oxidation at 700?C for 49 h in various environments.

Corresponding data for BS are also included for comparison. As seen in ?gure 2a, BS showed a rapid weight gain for up to 49 h. As weight gain caused by NaCl deposits was slow dur- ing the initial corrosion stage (up to 9 h; 2.5mgcm -2), the rate gradually decreased to 2.1mgcm -2 after 49 h of corrosion. Similarly, AS with Na2SO4 deposits showed a slow weight gain at 1.4mgcm -2 after 49 h of corrosion.

AS showed weight gains lower than those of AS specimens with NaCl and Na2SO4 deposits oxidized at 700?C in dry air. Bull. Mater. Sci. (2020) 43:11 Page 3 of 8 11 Figure 2. Corrosion kinetics of BS and aluminized AISI 1020 steel at 700?C: (a) linear plot at 49 h and (b) parabolic plot at 9 h. Pieraggi [14] suggested that plots of a weight gain (_ W) vs.

t 1/2 may be a more useful and accurate analysis for the real effect on the oxidation kinetics of pure metals due to pri- mary oxide scale growth. Therefore, plots of weight gain and square roots of time for all specimens undergoing oxidation for 9 h in the parabolic regime are displayed in ?gure 2b, and the parabolic rate constant (kp) was determined by lin- ear regression. The kp values for BS with NaCl and Na2SO4 deposits were 3.721× 10-9 and 4.122× 10-9 g2 cm-4 s-1, respectively; the kp value for BS without NaCl or Na2SO4 deposits oxidized in dry air was 2.735× 10-9 g2 cm-4 s-1.

The kp values for AS with NaCl and Na2SO4 deposits were 1.082× 10-10 and 3.204×10-12 g2 cm-4 s-1, respectively, and that for AS in dry air was 7.517× 10-13 g2 cm-4 s-1. According to the kp values, the aluminide layer on AISI 1020 steel appears to play an important role in forming a protective alumina/aluminium oxide (Al2O3) scale [8,15]. Consequently, kp values for AS with NaCl and Na2SO4 coatings decreased by one and three orders of magnitude, respectively.

These reductions are attributed to the growth of an Al2O3 layer, which led to the establishment of a barrier at the Al2O3/aluminide layer interface [16]. The oxidation rates for AS with NaCl and Na2SO4 deposits were three and one order(s), respectively, of magnitude higher than those of AS in dry air (?gure 2b). This enhance- ment is attributed to the presence of gaseous chlorine (Cl2g) and sulphur (Sg) from NaCl and Na2SO4 decomposition [1,5,7,17,18] via the metal-oxide reaction with Cl and S particles, which led to an active corrosion phenomenon at the Al2O3/aluminide coating interface.

The weight gain of AS containing NaCl deposits decreased slowly at oxidation times ranging from 9 to 49 h. This slow decrease may have been due to disruption of Al2O3 scale growth by Cl via cyclic oxychloridation, which forms volatile metal chlorides [7,9,19]. 3.3 Hot-corrosion mechanisms i n AS To elucidate the hot-corrosion behaviour and phase transfor- mation in the aluminide layer, saturated NaCl and Na2SO4 solutions were deposited on AS specimen surfaces, which were then isothermally oxidized at 700?C for 1–49 h.

In the present study, we speculated that during the initial stages of oxidation, the kinetics was controlled by oxidation of the aluminide coating with oxygen to form Al2O3. In further stages of oxidation, hot corrosion occurs in which Al2O3 later reacts with the salt deposits and forms a mixture of salts having a lower-melting point than the original salts. The melt- ing points of NaCl and Na2SO4 salts were 801 and 884?C [20], respectively.

The NaCl hot-corrosion mechanisms at a 700?C appeared to be similar to those reported by Ciszak et al[18] and Godlewska et al[21]. Furthermore, the Na2SO4 hot-corrosion mechanisms at 700?C appear to be similar to those reported by Shi [17] and Yan et al[19]. Thermodynamic data for the reaction kinetics of Fe and Al in the formation of metal chlorides and sulphates were determined based on Gibbs free energy change (_ G) calculations [22]._ G values at 700?C are tabulated in table 1.

Table 1 shows a detailed summary of the possible chemical reactions for accelerating hot-corrosion processes of aluminide layers with NaCl and Na2SO4 deposits. The cross-sectional morphologies of AS specimens with NaCl deposits hot corroded at 700?C for 1, 9 and 25 h are presented in ?gure3. After 1 h of oxidation, an Fe2Al5/FeAl2 layer and a thin FeAl layer formed on the steel substrate (?gure 3a).

The thickness of the aluminide layer depended on the diffusional processing at high temperatures between Al atoms from the aluminide coating and Fe atoms from the steel substrate [13], in which the diffusion coef?cient of Fe into Al was 53× 10-4 m2 s-1 (520-650?C) [23], which was larger than that of Al into Fe, 1.8×10-4 m2 s-1 (730-1400?C) [24]. 11 Page 4 of 8 Bull. Mater. Sci. (2020) 43:11 Ta b l e 1 . Gibbs free energy change (_ G) of reaction [22].

_ G700 (kJ) NaCl hot corrosion 2Al(s) +2NaCl(s) +2O2(g) ? Al2O3(s) +Na2O(s) +Cl2(g) -1010.4 2Al+3Cl2(g) ? 2AlCl3(s) -471.6 4AlCl3(s) +3O2(g) ? 2Al2O3(s) +6Cl2(g) -592.4 2Fe+3Cl2(g) ? 2FeCl3(s) -157.6 4FeCl3(s) +3O2(g) ? 2Fe2O3 +6Cl2(g) -109.3 2Al(s) +3/2O2(g) ? Al2O3(s) -1383.1 Na2SO4 hot corrosion 2Al(s) +3SO3(s) +3O2(g) ? Al2(SO4(s))3 -807.0 2Al(s) +3/2S(s) ? Al2S3 -676.5 Fe(s) +SO2(g) +O2(g) ? FeSO4(s)

-275.6

FeSO4 ? 1/2Fe2O3(s) +SO2(g) +1/4O2(g) -7.2 SO2(g) +1/2O2(g) ? SO3(g) -7.6 Figure 3. OM cross-sectional micrographs of AS with NaCl deposits oxidized at 700?C for(a) 1 h, (b)9hand(c) 25 h. Therefore, the thickness of an aluminide layer was 162µm and consisted of Fe2Al5, FeAl2 and FeAl layers and a thin Al2O3 scale (?gure 3a).

In addition, some voids could be observed in the outer part of the aluminide layer (?gure3a) as a result of outward diffusion of Al atoms to form the Al2O3 scale, which presented thin and dense characteristics and con- sisted of an adherent Al2O3 layer on the aluminide layer. As the oxidation time increased to 9 and 25 h, the thickness of the Fe2Al5/FeAl2 intermetallic layer decreased due to hot-corrosion attack in the aluminide coating (?gure3b and c). Some coarse voids and cavities formed in the outer part were ?lled with a mixture of oxides beneath the Al2O3 scale as shown in ?gure 3b and c.

XRD examination indi- cated that identical intermetallic phases (Fe2Al5, FeAl2 and Bull. Mater. Sci. (2020) 43:11 Page 5 of 8 11 Figure 4. XRD patterns of AS specimens oxidized at 700?C for 9 h in three different environments. FeAl) formed in the aluminide layer after oxidation of the AS specimens containing NaCl and Na2SO4 at 700?C during oxidation progress in an air atmosphere (?gure4).

As oxida- tion time increased, void formation due to outward/inward Al transport predominantly formed pores in the outer part and in the aluminide layer, which is known as the Kirkendall effect [25]. Later, an interconnection of coalescing pores generated crack paths and allowed oxygen (O), Cl2g and Sg penetration into the aluminide layer, forming the internal oxides (?gure3b and c). The protective Al2O3 layer formed during the early stages could protect the aluminide layer that was directly in contact with NaCl.

However, after 25 h of corrosion, the Fe2Al5/FeAl2 layer was severely degraded (?gure 3c). This result implies that the NaCl deposit plays an important role in the hot-corrosion behaviour of the aluminide layer over long periods. Figure 4 displays the XRD results for the AS with and without NaCl and Na2SO4 salt deposits, which con?rmed the presence of the oxidation product, Al2O3 scale, together with some iron oxide (Fe2O3) scales.

The low-intensity diffraction peaks of Al2O3 seen in the XRD spectrum in ?gure4were due to the thin Al2O3 scale on the AS specimens oxidized in air. The intensities of Al2O3 and Fe2O3 peaks for AS specimens with NaCl and Na2SO4 deposits increased, indicating that the corrosion layer thickened. It may be argued that Fe2Al5, FeAl2 and FeAl can behave as Al reservoirs that maintain the growth of the Al2O3 scale during

long-term oxidation.

As mentioned above, some pores became interconnected and resulted in crack features in which oxidant and corro- sive gases consisting of O2g,Cl 2g and sulphur trioxide (SO3g) penetrated into the aluminide layer through the pores and crack paths [25]. The relative decrease in weight gains of the NaCl-deposited AS specimens during a longer oxidation time (9 h) of exposure is believed to be caused by reactions involv- ing metal, NaCl and O, which prevented the formation of a protective oxide scale.

As reported by Ciszak et al[18], Cl2g is the ?rst major gaseous species that forms during the reaction of Na–titanium (Ti) oxides at 560?C. In the present study, the Al2O3 formed during the early stage could further react with NaCl and O in the gas atmosphere according to the following reaction [21]: 2NaCl+Al2O3 +1/2O2 ? 2NaAlO2 +Cl2 (1) Cl2g was generated by the reaction among Al2O3, NaCl (s) and O2g in which Na–Al oxides that readily penetrated the Fe2Al5/FeAl2 layer through crack paths generated during oxi- dation were also formed.

The Cl2g caused corrosion of the aluminide layer, thereby forming the metal chlorides, ferric chloride (FeCl3) and AlCl3. Both Fe and Al were the driving forces behind metal-chloride formation in the aluminide layer during the initial stages of the reaction [7]. Furthermore, Fe and Al could have dissolved in the molten salt and volatilized or reacted with O.

The melting points of AlCl3 and FeCl3 were 182 and 304?C, respectively [20], and their thermodynamic equilibrium Gibbs free energies at 700?C(_ G700)were about -471.6 and -157.6 kJ (table 1), respectively. The negative values of_ G700 for the metal chlorides suggest that degrada- tion of the aluminide layer was caused by the formation of Fe and Al chlorides, which are similar ?ndings to those reported by Liu et al[7] and Tsaur et al[25].

In addition, FeCl3 forma- tion was dependent on the activity of Al atoms in the aluminide layer, in which they reach lower concentrations because of their inward diffusion into the steel substrate. Metal chlorides resulted from the reaction of both Al and Fe atoms with Cl2g at 700?C in the aluminide layer, thereby increasing the par- tial pressure of metal chlorides and forcing AlCl3 and FeCl3 to move towards O at high-partial pressures [7].

At the same time, Fe atoms in Fe2Al5 and FeAl2 diffused outwards and reacted with Cl to form FeCl3. Subsequently, FeCl3 moved towards O at high-partial pressure, reacting again with O to form Fe2O3. These results are observed in the XRD scan and the

SEM/EDS elemental maps (?gures4and5a, respectively).

SEM observation and EDS elemental mapping of the aluminide layer (?gure 5a) clearly show that Cl2g resulted from oxychloridation, which destroyed the protective Al2O3 scale on the aluminide layer [15]. Almost all of the Fe2O3 scales formed on the FeAl layer, and only a small portion of FeAl2 remained in the aluminide layer. Fe2O3 and Al2O3 formed together above the FeAl layer as shown in ?gure 5a. The Al2O3 scale that grew was loose. During oxidation for 11 Page 6 of 8 Bull. Mater.

Sci. (2020) 43:11 Figure 5. SEM and EDS elemental maps of AS specimens with (a) NaCl deposits and (b)Na 2SO4 deposits, oxidized at 700?C for 49 h. 49 h, the FeAl layer replaced the Fe2Al5 and FeAl2 layers, supplying Al atoms that formed the protective Al2O3 scale. Furthermore, the presence of Na2SO4 deposits on the AS specimens oxidized at 700?C for 49 h had a considerable effect on the corrosion kinetics when compared with AS specimens oxidized in dry air (?gure1a).

In the present study, the experimental temperature was lower than the melting point of Na2SO4 (884?C)[20], and the increase in weight gain was about 3.5 times that of AS oxidized in dry air (?gure 1a). XRD measurements (?gure 4) showed that the intermetallic phases that formed Fe2Al5, FeAl2 and FeAl were the same in various environments.

In addition, Al2O3 formed during the early stages of oxidation acted as a barrier to Sg, which could penetrate the aluminide layer in the reaction over short periods. Na2SO4 remained on the specimen surface after cor- rosion testing (?gure4). As reported by Shi [17], accelerated oxidation of Fe with Na2SO4 deposits at 750?C may be attributed to a Na2O/Na2SO4 eutectic-melt formation on the surface of the specimen. The salt decomposes when the local partial pres- sure of O in the environment is lower than that at equilibrium with the Na2O/Na2SO4 eutectic mixture [26].

The partial pressure of O decreased because of O consumption during Al2O3 formation in the early stages. When the Na2SO4 salt that is deposited on the surface of the specimens does not melt, the following reaction tends to occur on the alumina scale [19]: Na2SO4 ? Na2O+SO2 +1/2O2 (2) Subsequently, the formed Na2O(s) dissolved in Na2SO4, reaching equilibrium with the Na2O/Na2SO4 eutectic mixture [17].

The lower temperature of the eutectic mixture (550?C) [17] is strongly believed to support the formation of alu- minium sulphide (Al2S3) in the aluminide layer by allowing the release of SO3g into the atmosphere. Because Na2SO4 was still found on the aluminide layer surface after it was oxidized for 9 h (?gure 4), the decomposition is believed to supply S that forms Al2S3 on the Fe2Al5/FeAl2 layer.

Examination of the SEM cross-sectional micrographs and EDS elemental maps of O, Fe, Al, Cl and S clearly shows a difference between the effects of NaCl [15] and Na2SO4 deposits on AS with respect to acceleration of oxidation and corrosion (?gure 5a and b). The micrograph of the corroded sample clearly shows that the aluminide Fe2Al5/FeAl2 layer formed on the FeAl layer (?gure 5b).

Elemental mapping of this scale (?gure 5b) suggests that the corrosion products consisted mainly of Al2O3 and some Fe2O3 scales. In the early stage of corrosion, an Al2O3 scale was quickly formed by unmelted Na2SO4 on the surface of the specimens. Bull. Mater. Sci. (2020) 43:11 Page 7 of 8 11 Figure 6.

SEM images of the surface morphologies of AS oxidized at 700?C for 49 h (a)indryair,(b)in an NaCl environment and (c)inanNa 2SO4 environment. SEM observation of the AS surface after oxidation in dry air at 700?C for 49 h (?gure6a) indicates that the Al2O3 scale on the aluminide coating is compact. In contrast, Fe2O3 and Al2O3 grew together on AS with NaCl deposits (?gure 6b).

Furthermore, EDS analysis of the oxide scale (?gure6c) indi- cated that a sulphur concentration of 10.02 wt% was suf?cient to increase the high ratio of the partial pressure of Sg to the partial pressure of O2g [27]. SO3 thus released into the atmosphere diffuse and dissolve in the Al2O3 scale, form- ing Al2(SO4)3 as con?rmed by XRD (?gure4).

The sulphate particles in this scale combine with the oxide matrix in the reaction over long periods. According to the Gibbs free energy (_ G700 =- 807 kJ) given in table 1, the chemical reaction is spontaneous when sulphur ions dissolved in the aluminium oxide matrix Al2(SO4)3 diffuse into Al2O3 viaAl3+ vacancy defects, eventually coming into contact with Al ions diffus- ing from the aluminide layer.

When the activities of both ions were high enough [5], Al2S3 forms as shown in the XRD results in ?gure 4. This result supports the hypothesis that Na2SO4 decomposition supplies S for the direct formation of trace amounts of Al2S3 in the oxide scale at low temperatures (such as during Na2SO4 melting). EDS examination of the surface of the corroded sam- ple (?gure 6c) showed the composition in wt% in which Fe (28.17 wt%) was higher than that of Al (13.65 wt%).

The composition of Al decreased because Al atoms diffused outwards to react ?rst with oxygen, forming the Al2O3 scale and then diffused inwards into the steel substrate. Conse- quently, Al activity was decreased to a lower concentration, and the rest of the

Fe reacted with the rest of the Sg remaining in the atmosphere. This result explains why SO3g and O2g in the atmosphere also diffused into the aluminide layer to form FeSO4 in which the Fe atom activity was high.

The low-formation energy of FeSO4 (_ G700 =- 7.2kJ) facil- itated FeSO4 dissociation to Fe2O3 and subsequent release of SO2 into the atmosphere. The reaction of sulphur gas (as SO2) with O2g in the atmosphere also produced SO3 gas. These reactions continued cyclically, forming an Fe-rich oxide (?gure 6c) and Al2S3 as con?rmed by XRD measure- ments (?gure 4).

Consequently, Al2O3 failed to protect the aluminide layer and the steel substrate at 700?C during cor- rosion over long periods. 4. Conclusions The presence of NaCl and Na2SO4 deposits on the surface of AISI 1020 steel can accelerate oxidation and corrosion. However, the aluminizing coating on the steel could cause a one to three orders of magnitude reduction in kp for oxidation at 700?C for 49 h in an environment containing Cl2g and Sg, relative to that of steel without the coating. During the early stages of hot corrosion, a thin and dense Al2O3 scale was created.

During the subsequent corrosion, this Al2O3 layer 11 Page 8 of 8 Bull. Mater. Sci. (2020) 43:11 facilitated the formation of a porous Fe2O3 scale on itself, which allowed Cl and S penetration into the aluminide layer and enhanced the corrosion kinetics.

Vaporization of Al2Cl3 and Fe2Cl3 is believed to strongly affect the corrosion kinetics of AS with NaCl deposits, contributing to the decrease in weight gain after oxidation for 9 h. In contrast, S from Na2SO4 decomposition degraded the protective Al2Cl3 scale, allowing S to easily penetrate the oxide scale and form Al2S3. The consequent and appreciable increase in the penetration depth of S appears to have resulted in the precipitation of sulphide particles and growth of Fe2O3.

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19 105 [3] Mishra N K and Mishra S B 2015 Bull. Mater. Sci. 38 1679 [4] Lindberg D, Niemi J, Engblom M, Yrjas P, Lauren T and Hupa M 2016 Fuel Process. Technol. 141285 [5] Badaruddin M, Risano A Y E, Wardono H and Asmi D 2017 AIP C onf. P roc. 1788 030066 [6] Sen M, Balasubramaniam R and Kumar A V R 2000 Bull. Mater. Sci. 23399 [7]

Liu H H, Cheng W J and Wang C J 2011 Appl. Surf. Sci. 257 10645 [8] Badaruddin M, Wang C J, Wardono H, Tarkono and Asmi D 2016 AIP C onf. P roc.

1711 040002 [9] Wang C J and Li C C 2004 Surf. Coat. Technol. 177–178 37 [10] Wang C J, Lee J W and Twu T H 2003 Surf. Coat. Technol. 163–164 37 [11] Bose S 2018 High-temperature corrosion in High temperature coating, chapter 5, 2nd edn (Butterworth-Heinemann: Else- vier) 74. https://doi.org/10.1016/C2015-0-01316-8 [12] Yajiang L, Juan W, Yonglan Z and Holly X 2002 Bull. Mater. Sci. 25635 [13] Bouche K, Barbier F and Coulet A 1998 Mater. Sci. Eng.

A 249 167 [14] Pieraggi B 1987 Oxid. Met. 27 177 [15] Badaruddin M and Sugiyanto 2013 Adv. Mater. Res. 789 463 [16] Koech P K and Wang C J 2018 Oxid. Met. 90 713 [17] Shi L 1993 Oxid. M et. 40 197 [18] Ciszak C, Popa I, Brossard J M, Monceau D and Chevalier S 2016 C o r ro s . Sc i. 110 91 [19] Yan Y F, Xu X Q, Zhou D Q, Wang H, Wu Y, Liu X J et al 2013 C o r ro s . Sc i.

77 202 [20] Speight J G 2002 Lange's handbook of chemistry 16th edn (New York: McGraw-Hill) [21] Godlewska E, Mitoraj M and Leszczynska K 2014 C o r ro s . Sc i. 78 63 [22] Knacke O, Kubaschewski O and Hesselmann K 1977 Thermo- chemical properties of i norganic s ubstance (Berlin: Springer) 91. https://doi.org/10.1007/978-3-662-02293-1 [23] Neumann G 1990 in Diff usion i n s olid metals and alloys, numerical data and functional relationships in science and technology H Mehrer (ed) (Springer-Verlag, Berlin) vol.

26, p 152 [24] Le Claire A D 1990 in Diff usion i n s olid metals and alloys, numerical data and functional relationship i n s cience and tech- nology H Mehrer (ed) (Springer-Verlag, Berlin) vol. 26, p 129 [25] Tsaur C C, Rock J C, Wang C J and Su Y H 2005 Mater. Chem. Phys. 89 445 [26] Buscaglia V, Nanni P and Bottino C 1990 C o r ro s . Sc i. 30 327 [27] Lee W H and Lin R Y 1999 Mater. Chem. P hys.

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