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The hot corrosion resistance of hot-dip aluminized low carbon steel with nickel interlayer under static load

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ABSTRACT

The failure mechanism of hot-dip aluminized (HDA) low carbon steel with nickel interlayer under static loading was studied. The nickel interlayer was plated using electric method with a current density of 1.8 A/cm^2 for 10 min in Watts bath, followed by hot-dipped in molten pure aluminum (> 99.5%) for 10 s at 700 °C. The specimens were smoothly deposited with 2 mg/cm^2 of $NaCl/Na_2SO_4$ salt mixture, with a portion of 50/50 wt% ratio. The tensile test in hot corrosion, induced by salt mixture, was carried out by applying a static load at 750 °C. The results show that the intermetallic layer of Ni/Al exhibits high adhesion and formability while the elongation of gauge length rising to 7%. Owing to the inter-diffusion between Ni/Al, the intermetallic layer gradually changes to laminar structure with higher nickel content which also contributes to enhance the performance. However, hot corrosion induced by salt mixture reduces the amount of aluminum on the outer layer lowering the thickness of Ni/Al intermetallic layer. As the perpendicular cracks formed, the salt mixture penetrates to the interface between substrate and coating layer causing the oxidation of the carbide and accelerating the phenomenon of break away. Overall, the HDA with nickel interlayer on low carbon steel improved the lifetime to about 5 times compared to bare material.

1. Introduction

Commercial alloys applied in high temperature environment should have high oxidation resistance in order to lower the thickness reduction rate. Under hot-corrosion condition, the lifetime for alloys may be much lower due to the effective cross-section area continuously decreasing [1–3]. Therefore, the good mechanical properties and corrosion resistance are required for alloys used in high-temperature application. For instance, stainless steels and nickel super alloys are usually represented as the candidate materials which contain protective or austenite-stabilizer elements. However, the cost of these alloys is the critical consideration in construction designed. In contrast, carbon steels are cheaper with poor corrosion resistance and mechanical properties at high-temperature. Therefore, carbon steels are commonly applied as structural materials in atmosphere environment.

Hot-dip aluminized technique has the high net shape rate and cost in moderation. At the same time, the aluminide coating presents good adhesion and high productivity [4]. Owing to a continuous and compact alumina layer forming at high temperature, the oxidation and corrosion resistance of alloys and carbon steels are rapidly enhanced [5–7]. According to the diffusion rate between Fe/Al diffusion couple, the aluminide layer can be divided into topmost aluminum layer with $FeAl_3$ scattered, and inner Fe/Al intermetallic layer [8,9]. Additionally, the tongue-like Fe_2Al_5 is the major phase in intermetallic layer because of vacancies on the c-axis of the crystal structure [10]. The rough surface between Fe_2Al_5 and substrate leads to stress concentration when external force applied. This phenomenon causes the crack to form along the interface [11,12]. Furthermore, the voids induced by kirkendall effect also act as accelerant for crack propagation [13–15]. In summary, the brittle Fe/Al intermetallic phase, with 4% in elongation at 750 °C [16,17], lacks the ability to make deformation with substrate. Owing to the applied force beyond capacity, the vertical cracks form inside the aluminide layer. The cracks act as the easy-path for oxygen and corrosive substances which arise the potential to oxidize carbon steels. The weight gained will dramatically increase once the carbon steels be oxidized [18].

Considering the risks mentioned above, the nickel interlayer operated before hot-dip aluminized to form a multiple microstructure presents another result. Since the interface of Ni/Fe becomes flat [19,20], the phenomenon of stress concentration has been eliminated. Meanwhile, the mismatch of coefficient of thermal expansion (CTE) between Ni/Al intermetallic phase and carbon steel is lower compared to that of

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Fe/Al intermetallic layers [21]. This is inferred to contribute greatly in eliminating the phenomenon of crack formation inside the aluminide layer. The topmost aluminide layer gradually transforms to Ni_3Al and NiAl respectively as the duration increased under oxidation test [22,23] which still exhibit high oxidation resistance.

Though a few research reported the corrosion resistance and cyclic oxidation behavior on hot-dip aluminized with nickel interlayer, the tests were only carried out in static atmosphere. The practical application for aluminized steel is usually under various load which leads to complicated failure prediction and lifetime evaluation. Thus, the aim of this work is to investigate the effect of nickel interlayer on the hot corrosion resistance performance of the hot-dip aluminized low carbon steel under static load. The correlation of creep, hot corrosion was performed in this study in order to estimate the strength of nickel interlayer process.

2. Experimental process

2.1. Prior treatment and nickel plating

The commercial low carbon steel (LCS) sheet (Fe-0.055C-0.219Mn-0.015P-0.005S wt%) and pure aluminum (99.5 wt%) were used in this study. LCS-specimens, with 2 mm in thickness, were machined into the dimension according to Fig. 1 by wire electric discharge machining (WEDM), and grounded by precise grinding machine to the surface-roughness lower than 5 μm. The nickel interlayer was performed by electro-deposition method. Prior to nickel plating process, the specimens were ultrasonically cleaned in alkaline, acetone, phosphorous acid, and methylene for 5 min respectively. Watt bath was used as nickel reservoir containing 500 g/l $NiSO_4 \cdot 6H_2O$, 45 g/l $NiCl_2$, and 35 g/l H_3BO_3. The working parameters of nickel plating were a current density of 1.8 A/cm^2, in a bath temperature of 60 °C, and rotor speed of 60 rpm. Carbon bars were applied as the anode electrode. The nickel interlayer was controlled to achieve a thickness of about 30 to 35 μm.

2.2. Hot-dipped aluminum

Tensile specimens with nickel plating were aluminized by immersion into molten aluminum bath at 700 °C for 10 s. The paste-like flux consisting of KCl-LiCl-Na_2SiF_6 was used to cover the surface of specimens to improve the adhesion between nickel layer and liquid aluminum. The hot-dipping system was controlled by step-motor and reducer in order to precisely maintain the speed in a range of 2.5 to 2.6 cm/s. Fig. 2 reveal the microstructure of as-aluminized LCS with nickel interlayer (Ni-HDA). The components of multilayer structure were introduced by our previous study [22]. The purpose of this condition was to produce a portion of 50/50 in thickness of nickel layer and Ni/Al inter-diffusion layer. In addition, the interface between nickel layer and LCS still kept smooth.

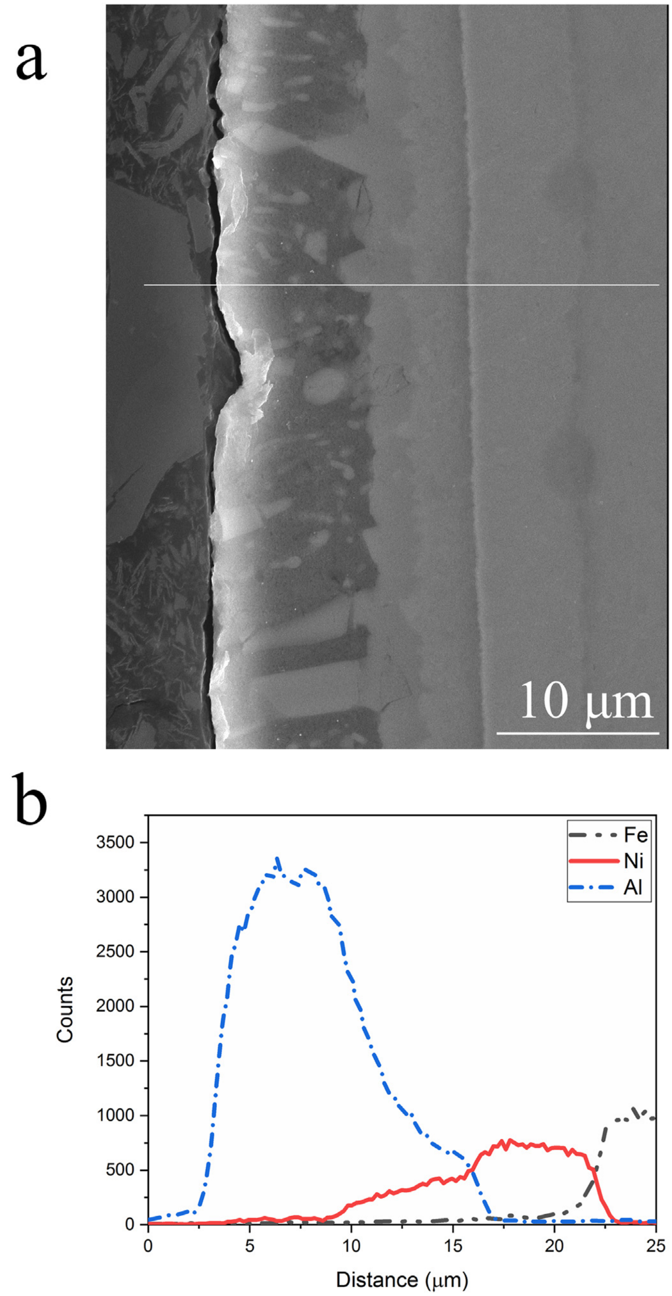

Fig. 2. Cross-sectional SE micrograph of Ni-HDA with line scan result.

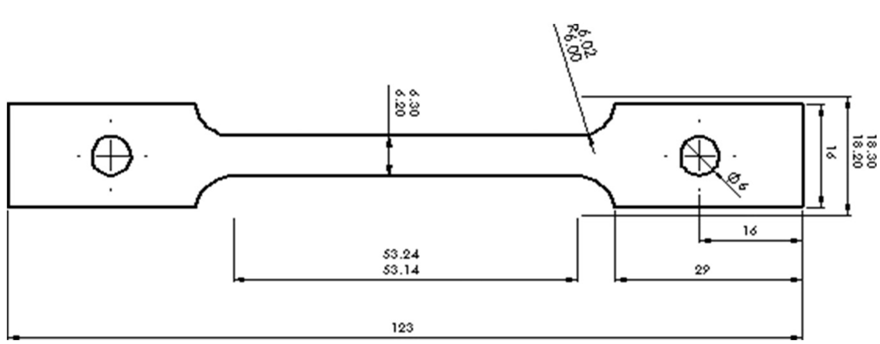

Fig. 1. Dimension of the tensile specimen for the static load test.