HIGH TEMPERATURE WEAR BEHAVIOR OF HOT-DIP ALIMINIZED INCONEL 718

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Abstract

Superalloys are used in a wide range of applications in aviation, aerospace and nuclear energy industries. Inconel 718 is a nickel-based superalloy that provides remarkable mechanical properties and surface stability at elevated temperatures. The surface of Inconel 718 can be modified by several techniques to further improve its surface properties such as oxidation and wear resistance. Among several surface modification techniques, hot-dip aluminizing (HDA) is a highlighted one as an easy and cost-effective high temperature coating (HTC) technique that utilize diffusion mechanisms. In this study, effect of HDA and subsequent diffusion annealing (DA) on high temperature wear behavior of Inconel 718 superalloy was investigated. Inconel 718 samples were first hot-dip aluminized in a molten Al-12wt.%Si bath and subjected to diffusion annealing. Morphological and structural analyses were carried out by using SEM-EDS examinations and XRD analyses. Ball-on-disc wear tests of the bare, HDA and HDA+DA samples were conducted at room temperature, 300 °C and 600 °C. The results revealed that aluminum rich and nickel rich aluminide phases were formed after HDA and HDA+DA processes, respectively. Wear tests results showed that the wear rate of the HDA+DA sample was approximately three times lower than the HDA samples and four times lower than the bare Inconel 718 at room temperature. With increasing temperature, the wear rate of the bare alloy continuously decreased, while higher wear rates were observed for HDA+DA samples at elevated temperatures with respect to that of room temperature. Dominant wear mechanism was discussed based on the wear track morphology examined by SEM.

Keywords: Inconel 718, superalloy, hot-dip aluminizing, diffusion annealing, wear

1. INTRODUCTION

Superalloys are the materials that have capability to sustain its performance with mechanical durability, surface stability against aggressive environment at high temperatures. Especially, nickel-based superalloys have been developed to respond increasing demands for use in the field of aviation and aerospace industries [1]. Inconel 718 is a type of nickel-based superalloy that can be strengthened by the solid solution strengthening and precipitation hardening mechanisms [2]. However, dissolution of coherent γ''-(Ni_3Nb) to detrimental phases decreases mechanical strength above 650 °C [3]. Moreover, protective Cr_2O_3 layer becomes volatile above 1000 °C [4]. Nevertheless, surface coating technologies offer some solutions against these issues [5]. In the open literature, numerous high temperature coatings (HTC) were studied to satisfy the requirements of different environmental circumstances [6-9]. Additionally, many techniques based on diffusion mechanism (e.g. pack cementation process, chemical vapor deposition and slurry application) have been applied to superalloys throughout the last few decades [10-13]. Hot-dip aluminizing (HDA) has stood out concerning applicability and cost. Binary phase diagram of nickel and aluminum was given in (**Figure 1**). In case of hot-dip coating, outward diffusion of nickel and inward diffusion of aluminum lead to the formation of durable nickel-aluminide phases triggered by sufficient time and temperature factors [14].

In particular, dip coating technologies have been studied to investigate formation of nickel-aluminides on nickel-based superalloys and their effects on surface properties [15-17]. Yet, there are still several reasons to investigate high temperature tribological behavior of hot-dip aluminizing coatings on nickel-based superalloys that need to be fully clarified.

The aim of this study is to investigate high temperature wear behavior of hot-dip aluminized nickel-based superalloy and the role of the diffusion annealing as a post-process.

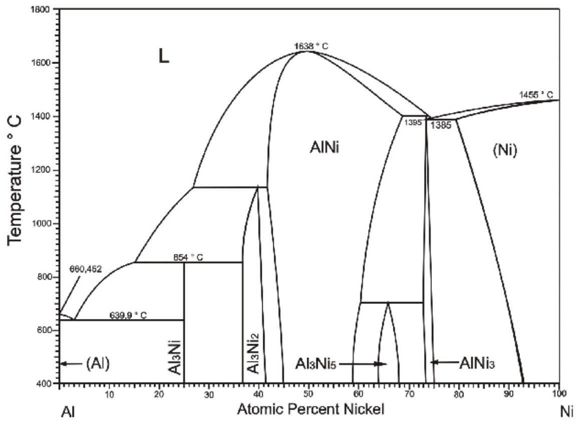

Figure 1 Nickel-Aluminum Binary Phase Diagram

2. EXPERIMENTAL PROCEDURES

Inconel 718 rod was cut to the samples that have 15 mm diameter and 8 mm thickness using a water-cooled abrasive cut-off wheel. Cylindrical samples were abraded to 400 grit SiC papers to obtain adequate surface roughness for a better adhesion. For dipping, 2 mm diameter stainless steel wire was wrapped around the cylindrical samples. Afterwards, the samples were ultrasonically cleaned with the mixture of 5 vol.% HCl and water for 2 minutes, dried with ethanol and washed with water. A MF-1000 electrical furnace was used to melt the aluminum alloy ingots. Molten bath was prepared by using commercial aluminum-silicon eutectic alloy. Prior to melting the ingots, 1 cm^3 mixture of KCl and NaCl of fluxes was added into the crucible to remove the slag. Inconel 718 samples were then subjected to hot-dipping process (HDA) in Al-12Si (wt.%) bath at 700 °C for 2 minutes. Following HDA, the samples were cooled to room temperature in air. Diffusion annealing (DA) process was applied at 700 °C for 10 hours in an atmospheric furnace, and the samples were then furnace cooled to the room temperature. Microstructural images were obtained by Philips XL30 SFEG scanning electron microscope (SEM) equipped with Energy-dispersive X-ray spectrometer (EDS) for mapping, linescan, frame and point analyses for HDA and HDA+DA samples. A Hitachi TM1000 model SEM was used to analyze the wear tracks. X-ray diffraction (XRD) analyses were performed with GBC MMA 027 model device using CuKα radiation. A Ball-on disc tribometer (CSM-High Temperature) was used to conduct the wear tests with the parameters given in **Table 1.** A 2-D stylus type surface profilometer (Veeco Dektak 6M) was used to measure the width, the depth and the area of the wear tracks.

Table 1 Wear Test Parameters

Parameters	Values
Linear velocity, mm/s	50
Total Sliding Distance (m)	100
Load (N)	2
Temperature (°C)	25, 300, 600
Counter-Face	6 mm alumina ball
Radius of Wear Track	3 mm

3. RESULTS AND DISCUSSIONS

3.1. Characterization of Coating

Cross-sectional SEM images and EDS mapping analyses of HDA and HDA+DA samples were shown in **Figure 2**. Thickness of the outer, middle and inter-diffusion zone were approximately measured as 20-25 μm, 20-25 μm and 8-10 μm respectively for HDA samples. No discontinuity such as crack or delamination was observed between the substrate and the coating indicating that the coating was well adhered to the substrate. Various layers from the substrate to the top of the coating in HDA+DA sample was observed. Thickness of the coating was measured approximately 200 µm for HDA+DA sample. Porosities, cavities and voids were not observed in the areas close to inter-diffusion zone after the diffusion annealing process.

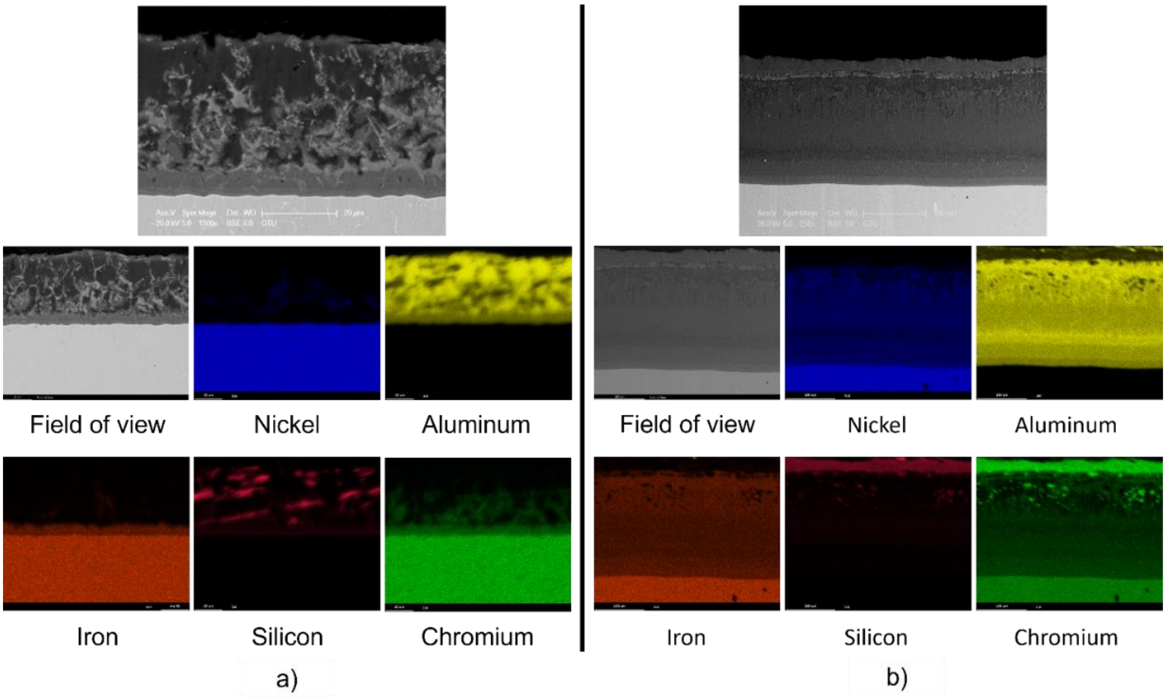

Figure 2 SEM images and EDS mapping analysis of a) HDA and b) HDA+DA samples

For HDA samples, EDS results showed that content of Al is nominally decreasing from the top of the coating to the substrate. Aluminum was mostly detected in the outer layer, with some signals of Si and Cr. Ni and Fe were not appeared in the outer and middle layer, while minor contents of Ni and Fe were detected close to the interdiffusion zone. It can be attributed to intense signals of Ni and Fe coming from the substrate, which were much compared to their contents in the coating. For HDA+DA samples, Al was appeared in all regions of the coating. Signals from Si and Cr were more marked at the outer layer, while Ni and Fe have a homogeneous distribution through the coating layer except in the outer layer. Inward diffusion of Al and outward diffusion of Ni was proven with EDS analysis. XRD patterns of HDA and HDA+DA samples were shown in (**Figure 3**). For HDA samples, excess aluminum layer was detected in addition to Al rich nickel-aluminide phases (e.g. $NiAl_3$, Ni_2Al_3. It has been shown that the diffusion annealing led to the formation of intense nickel rich nickel-aluminide phases such as Ni-rich NiAl and Ni_3Al as compared to HDA sample XRD pattern. Additionally, outward diffusion of Cr and Si elements led to the formation of Cr_3Si phases that is supported by EDS analyses.

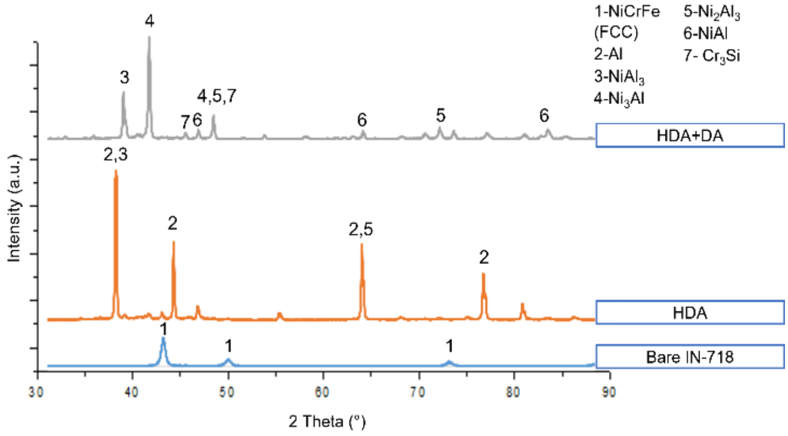

Figure 3 X-ray diffraction patterns of a) HDA and b) HDA+DA samples

3.2. High temperature wear behavior

2-D cross sectional profiles of the wear tracks for the samples tested at 25 °C, 300 °C and 600 °C were given in (**Figure 4**). Similar wear track dimensions were measured for the bare and HDA samples at 25°C, while HDA+DA sample has a significantly smaller wear track at this temperature. The width and the depth of the wear track for HDA sample was significantly increased at 300°C. As the test temperature increased, the wear track dimensions of the bare Inconel 718 alloy contiuously reduced, having the lowest dimensions among all the samples investigated. For HDA+DA sample, on the other hand, the depth of the wear track was approximately the same, while its width was incraesed with increasing temperature.

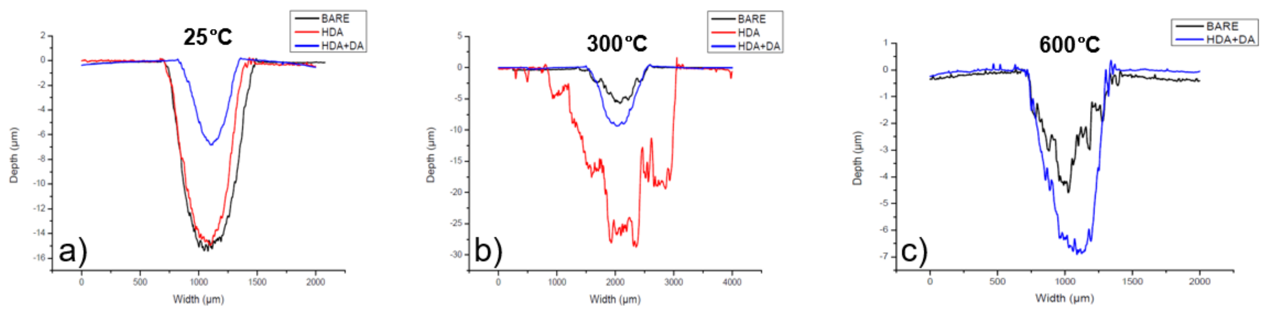

Figure 4 2-D surface profiles showing the dimensions of the war tracks at a) 25 °C, b) 300 °C and c) 600 °C wear tests for bare Inconel 718, HDA and HDA+DA samples.

Wear rates of samples were given in (**Figure 5**). The wear rates of samples were calculated by Eq. (1).

$$Wear\ Rate = \frac{A.2\pi r}{F.x} \quad (1)$$

Where:

A - Wear track area (mm²)

r - Radius of wear track (mm)

F - Applied load (N)

x - Sliding distance (m)

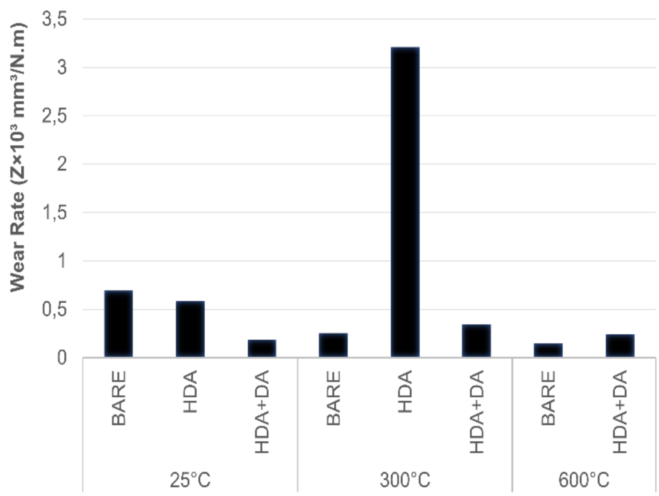

Figure 5 Wear rates of bare, HDA and HDA+DA samples

HDA+DA sample has the lowest wear rate at room temperature, when compared to bare Inconel 718 and HDA samples. The highest wear rate was obtained in HDA sample tested at 300 °C due to excess aluminum layer at the surface. The lowest wear rate was exhibited by bare Inconel 718 tested at 600 °C. It is clear that the bare substrates outperformed HDA+DA samples and their wear rate decrease as the test temperature increases.

The variation of the friction coefficient (CoF) with sliding distance for the samples tested at different temperatures were given in (**Figure 6**). For the wear tests at 25 °C, CoF of the bare Inconel 718 showed a fluctuation during the whole period of the wear tests. It is attributed to successive formation and removal of the oxide layer due to the heat generated by friction [18]. HDA sample exhibited a lower and smoother friction coefficient variation possibly due to the excess aluminum layer at the surface. Friction coefficient of HDA+DA sample was in between those of the bare Inconel 718 and HDA sample. For the wear tests conducted at 300 °C, the bare alloy exhibited a continuously decreasing CoF values from the beginning of the test up to 40 m where it reached a steady state value of approximately 1.2, while HDA sample showed a decreasing terend with significant fluctuations in the friction coefficient. It should be noted that the variation of CoF in HDA+DA sample was stable during the whole test period at both 300 °C and 600 °C. Also average CoF of HDA+DA sample was approximately 1.15 and 0.9 for 300 °C and 600 °C, respectively. It suggests that the Si-and Cr-rich outer layer of this sample in addition to nickel based aluminides might act as a lubricating layer during sliding at higher temperatures. As a result, during the wear tests at 600 °C, the bare Inconel 718 and HDA+DA samples showed almost the same CoF values (0.9) after an initial 20 m of the sliding distance, which are the lowest values for the investigated samples. This is attributed to easy formation of oxides on the surface of the bare Inconel 718 alloy at 600 °C, which then act as a lubricant at the surface to reduce friction coefficient [19]. Strong atomic bonds of Si-and Cr-rich phases provide wear resistance and are used as hardening agents despite high temperature [20]. Similarly, the lowest CoF of HDA+DA can be associated with Cr and Si phases existed in the outer layer.

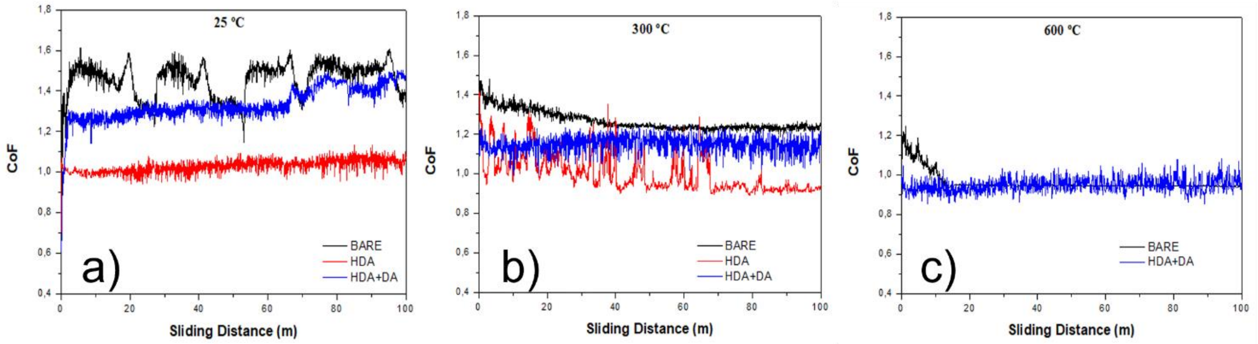

Figure 6 Variation of the coefficient of friction with the sliding distance at various temperature a) 25 °C, b) 300 °C and c) 600 °C.

SEM images of the wear tracks were shown in (**Figure 7**). The wear track of the bare Inconel 718 tested at 25 °C has a uniform appearance with wear scars along the wear path, and intense oxide scale formations in the form of patches (dark areas in **Figure 7a**). Continiuous oxide scales in the form a narrow band in the wear track were also detected at 600 °C (**Figure 7b**).

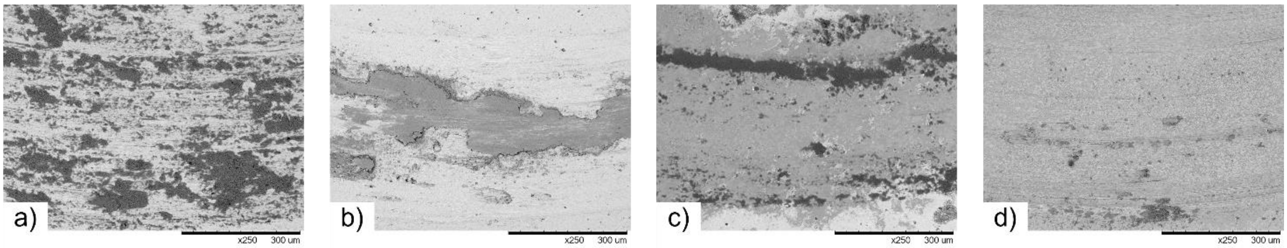

Figure 7 SEM images of the wear tracks a) Inconel 718 at 25 °C, b) Inconel 718 at 600 °C, c) HDA+DA at 25 °C, d) HDA+DA at 600 °C.

In the wear track of HDA+DA sample tested at 25 °C, oxide formation was evident along the edges of the wear track, and hence they were not uniformly distributed in contrast to the bare Inconel 718. Some fine grooves were also evident (**Figure 7c**) along the wear path. Micro-grooves formation appeared in HDA+DA worn surface (**Figure 7d**) due to brittle and hard Cr_3Si phases. The wear track of HDA+DA sample tested at 600 °C has a more uniform appearance than 25 °C with less oxide scales in the wear track. These observations suggest that abrasive wear and oxidative wear are the dominant wear mechanisms for the bare Inconel 718 at 25 °C and 600 °C, respectively, and abrasive wear is the dominant mechanism for HDA+DA sample at both temperatures.

4. CONCLUSIONS

Conclusions of the present study could be outlined as in the followings.

- Strongly adherent and fully dense nickel-aluminide coating layer was obtained on the surface of Inconel 718 superalloy by hot-dip aluminizing.
- Diffusion annealing increased the intensity of Ni-rich phases in the coating layer.
- Diffusion annealing following HDA significantly reduced the wear rate of both HDA sample and the bare Inconel 718 alloy at room temperature.
- Bare Inconel 718 was more resistant to wear than HDA+DA sample at 600 °C.
- HDA+DA process slightly reduced friction coefficient of the bare Inconel 718 up to 300 °C. However, this is not observed at 600 °C because both samples have the same CoF values at this temperature, which are the lowest for the present investigation.

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