Materials Science Forum *Online: 2014-04-22*
ISSN: 1662-9752, Vol. 789, pp 489-494
doi:10.4028/www.scientific.net/MSF.789.489

Diffusion Behavior of Interface between 6061 Aluminum Substrate and Ni–5wt.%Al Coating

Ribao Feng[1, a*], Ningning Qiao[1, b] and Shaojia Gong[1, c]

[1]College of Science, Civil Aviation University of China, Tianjin 300300, China

[a]rbfeng@cauc.edu.cn, [b]qiao198814@163.com , [c]shaojiagong852@126.com

Keywords: Diffusion, Ni–5wt.%Al, Coating, 6061-T6.

Abstract. In this article, the diffusion behavior between 6061 aluminum alloy substrate and Ni–5wt.%Al coating was studied by changing the heat treatment temperature and processing time. The experiment results of EDS and XRD showed that a diffusion zone generated between coating and substrate even if there was no change in phase compositions of the coating. The thickness of diffusion zone increased with the process temperature accompanied with the scale-up of Al concentration. In the decrease direction of aluminum concentration, the results of computation indicated that the phase composition transformed into $NiAl_3$, Ni_2Al_3 and Ni solid solution in the diffusion zone. It was concluded that microstructure and phase composition in diffusion zone between 6061 aluminum substrate and Ni–5wt.%Al coating was mainly controlled by aluminum diffusion during different heating conditions.

Introduction

Nickel aluminides are important intermetallic material utilized by aerospace and other advanced industries[1]. Nickel and aluminum formed intermetallic compounds can be prepared by several techniques such as casting and physical vapor deposition, and thermal spraying etc. Thermally sprayed nickel aluminum materials have complex microstructure including various phases and microstructural features giving them distinct tribo-mechanical properties. Except for the good cohesion and adhesion properties as bond coats, Arc sprayed nickel aluminum coatings also shows good adhesion to the substrate and have been successfully used in wear resistant condition[2].

Ni–5wt.%Al alloy are offen used to form nickel aluminides coating by thermal spraying technology and has been investigated for decades because of their superior properties[3,4]. Ni–5wt.%Al coating deposited on steel substrate has been studied by Sampath[5]. It is shown in their study that due to the formation of denser coating with less porosity and less oxide content, the HVOF((High Velocity Oxygen Fuel) sprayed Ni–5wt.%Al coating exhibits the superior elastic and plastic properties. Deshpande have studied the mechanisms of oxidation and its influence on microstructural evolution of Ni–5wt.%Al coating deposited using HVOF, APS, and Wire Arc spraying[6]. It is reported in their study that the high quality of the HVOF sprayed Ni–5wt.%Al coating is also due to its less porosity and oxide contents.

Under the service conditions, such as high temperature,oxidation and fatigue cycles etc., the bond strength between Ni–5wt.%Al coating and its substrate are effected obviously by evolution of phases structure and components diffusion process. Several possible nickel aluminides, such as Al_3Ni, NiAl and Ni_3Al etc., may generated at the interface between Ni–5wt.%Al coating and its substrate according to the diffusion interface componets. These nickel aluminides have different properties and effects on the bond strength. NiAl is more promising than Ni_3Al due to some of its physical and chemical properties, like high melting point, low density and better corrosion and oxidation resistance at high temperatures. Ni_3Al, with boron additions, is used in structural applications where corrosion protection is needed, while NiAl, because of its poor ductility at ambient temperatures and low strength and creep resistance at elevated temperatures, is used for coating materials for hot components that work in corrosive environments [7,8].

Plenty of research work have been carried out on Ni/Al and Ni/Ni_3Al diffusion couples, but the study of Ni–5wt.%Al/Al(6061-T6) is seldom to be reported. For example, G.A. López et. al studied the kinetic behaviour of Ni/Al/Ni diffusion couple and explained that the growth of nickel aluminides is controlled by the diffusion velocity of Ni and Al[9]. Kozo Fujiwara et.al measured the diffusion coefficients of Al and Ni in Ni_3Al using Ni/NiAl diffusion couples under the temperature range (1423–1523 K)[10]. D.F Susan studied the interdiffusion of Ni matrix/Al particle composite coatings and nickel substrates and explained the lifetime estimation of coating based on the Al diffusion behaviour at 800℃ to 1100℃ aged condition [11].

In general, the bond strength of thermally sprayed coatings is effected not only by the diffusion process between the coating and substrate, but also by the inner diffusion of complex splat based layered structure. It is necessary to understand the mechanism of diffusion in thermal spray coating in order to predict their response under service conditions,such as high temperature work condition and thermal shock mode.

In this paper, two-wire arc sprayed Ni–5wt.%Al coatings was fabricated and tested to evaluate the difussion process in the coating under different work conditions. The integrated set of results from SEM, XRD, EDS etc., are presented to explain the microstructural evolution process.

Experimental procedure

Coating preparation. Ni–5wt.%Al alloy coating was deposited by the TWA methods on 6061-T6 aluminum alloy. The spraying parameters are listed in Table 1, together with spraying system. The substrate surface was preheated to around 120℃ for all the cases before the coating was deposited. The coating thickness was 0.5 mm.

Table 1 Thermal spraying conditions for Ni–5wt.%Al coating.

Technique	Two wire arc method
Material	TAFA Ni–5wt.%Al wire
Gun	TAFA 9935
Voltage	30 [V]
Current	220 [A]
Air pressure	60 [psi]
Stand-off distance	130 [mm]
Substrate Material	6061-T6 aluminum alloy

Experimental methods. The as-sprayed coating samples were heated at 400, 480 and 550℃for 4, 24 and 96h in air. For comparing the diffusion process at different temperature, the coated samples prepared by standard metallographic techniques were used to evaluate microstructure. The profile of coating was measured by LEO 1530VP field emission scanning electron microscopy (SEM) equipped with OXFORD INCA energy dispersive spectrum (EDS). X-ray diffraction (XRD) measurements were performed using D/max-2500.

Results and discussion

XRD pattern on Fig. 1 (see a and d) reveals the phases of the coating surfaces after different heat treatments. It can be seen that all of coating surfaces have the same phase compositions,such as Ni solid solution,Al_2O_3 and NiO oxide, comparing with as-sprayed coating surface. It is also found that NiO increases with heat temperature from 400℃ to 550℃. There is a little change in Al_2O_3 phase volume because of the generation of NiO due to the higher Ni concentration.

In order to study the impact of heat treatment time on the coating microstructure and interface morphology , coating samples was heated up to 400℃ for 4, 24 and 96h respectively. From SEM

images in Figs. 2 a-c, it can be seen that obvious diffusion process generated between the coating and substrate with the increased heating time. The diffusion layer gradually grew up from interface to coating side with increased keeping time. Combined with results of G.A. López , M. Lieblich et.al[9,12] and EDS (see Fig. 2 d,e, f and Fig. 3) results, it could be explained that there were three compounds,i.e. Ni solid solution, Ni_2Al_3 and $NiAl_3$ intermetallic compound, existed in diffusion layer. These three compounds were lined along the increasing direction of Al concentration from coating to the substrate.

To observe the diffusion behaviour of Ni,Al and O elements, three kinds of interface between coating and substrate were tested by EDS after heat treatment, and the heating conditions were set up at 400, 480 and 550℃ for 96h. From Figs. 2 d-f, it can be seen that there were different diffusion phenomenon from line scan results of Al, O and Ni element.

It could be judged that there was no obvious oxidation existed in diffusion layer because of unchanging volume of O element. And also, except for the sharp decline of volume at interface between coating and substrate, Ni element volume remain the same level through the diffusion layer. However, line scan curve of Al element revealed the mode of step change in diffusion layer obviously. That is to say, although Ni And Al element have the higher concentration gradient at each side of interface between the coating and substrate , transfering of Al element dominated the main diffusion process only.

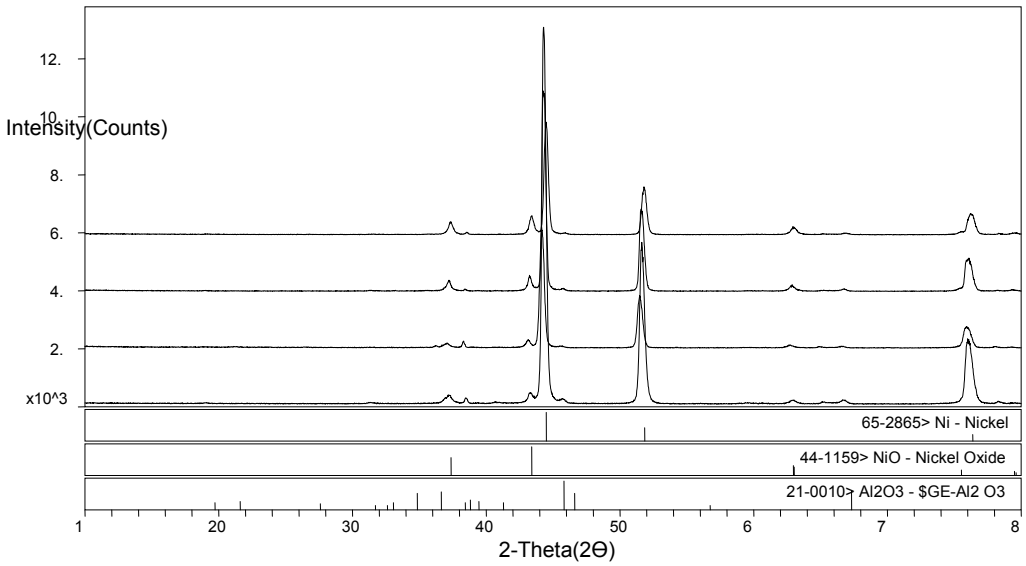

Fig. 1 XRD patterns of coatings with heat treatment at different temperature and 96h heat time. (a) as-sprayed ;(b)400℃;(c) 480℃; (d) 550℃.

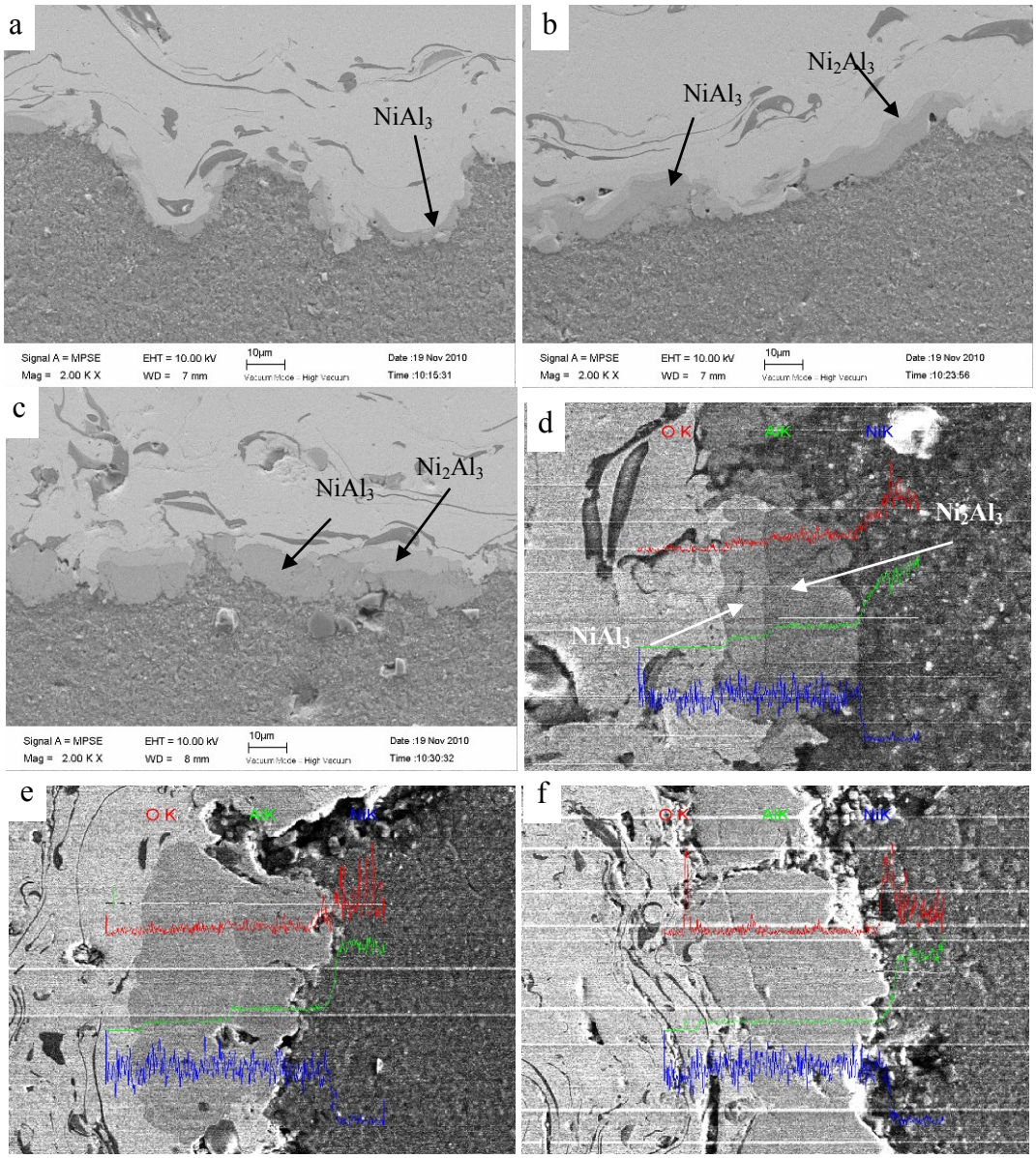

Fig. 2 SEM and EDS results of Ni–5wt.%Al coating at different heat conditions:
(a) SEM image,400℃&4h; (b) SEM image,400℃&24h;(c) SEM image,400℃&96h;
(d) EDS pattern,400℃&96h; (e) EDS pattern,480℃&96h; (f) EDS pattern,550℃&96h.

To explain the diffusion process, the line scan results of Al, O and Ni element in Fig. 2 d,e,f. were integrated to bring out the Al concentration analysis in Fig. 3. According to the Al concentration distribution, combined with the atomic content of Ni-Al system intermediate phases listed in Table 2 [12,13], the generated Ni-Al intermediate phases corresponding with the step change of Al element listed in the Fig. 3.

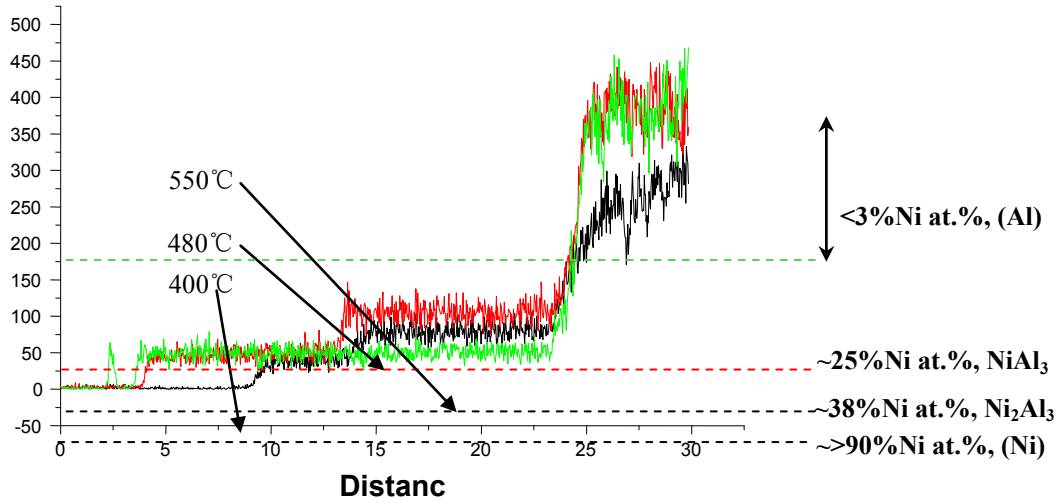

Fig. 3 Relative concentration analysis of Ni element in Ni–5wt.%Al coating (dimensionless).

Table 2 Ni atomic content of Ni - Al system intermediate phase

Phase	Composition range as per phase diagram(at.%)
Ni Al_3	20.5-32.9
Ni_2Al_3	36.8-40.8
Stoichiometric NiAl	47.7-53.1
Ni-rich NiAl	57.7-60.7
$AlNi_3$	72.2-77.5
(Ni)	87.5-100

Based on the results of Fig. 3, it can be seen that the diffusion process was mainly controlled by transferring of Al element and thereafter generated the phase change of Ni-Al compound. For all that heat conditions of 96h, the diffusion process are stable in spite of different temperatures. In condition of 400℃ and 96h in Fig. 2d, stabilized Al transfering generated the $NiAl_3$, Ni_2Al_3 intermetallic compound. Increasing temperture up to 480℃, it is shown that Ni_2Al_3 diffusion layer continuously grew up and was thicker than $NiAl_3$ layer because of the long distance diffusion and relative lower concentration of Al element. At last, with the highest temperature of 550℃ for 96h, Al element diffusion tended to uniform stabilization and developed into single Ni_2Al_3 compound layer because of the Al deletion caused by crack generated between coating and substrate.

Conclusions

1) The phase composition of the Ni–5wt.%Al coating surface was no obvious change after heating 400, 480 and 550℃ for 96h except for little increasing of NiO oxide amount.

2) The growth of diffusion layer of the Ni–5wt.%Al coating during heat treatment was controlled by Al element transfering and spread out layer by layer with step change of Al element volume. The phases composition of diffusion layer were determined as Ni_2Al_3 and $NiAl_3$, and sorted by Al element volume at direction from coating to substrate.

3) Increasing the temperature, the thickness of Ni_2Al_3 and $NiAl_3$ diffusion layer gradually increased and grew up to coating direction, but growth velocity of Ni_2Al_3 layer was faster than that of $NiAl_3$. At 550℃ for 96h, diffusion zone became uniform Ni_2Al_3 layer because of the Al deletion caused by crack at interface between coating and substrate.

Acknowledgements

This work was supported by the Fundamental Research Funds for the Central Universities under award No. ZXH 2009-C003 and Starting Research Project of Civil Aviation University of China.

References

[1] V. Vega，U. Nguyen Huynh，J. Holmes，J. DeChellis, P. Stoyanov, D. Piatknowski, E.W. Lee, J. Ogren, N. Drusina, O.S. Es-Said, Analysis of heat effects on marine corps AM2 mat mechanical properties, J. Mater. Eng. Perform. 20(2011)257-264．

[2] Y.Q. Ding, Y. Zhang, D.O. Northwood, A.T. Alpas, PVD NiAl intermetallic coatings: microstructure and mechanical properties, Surf. Coat. Technol. 94-95 (1997)483–489.

[3] S.Sampath, B. Katz, H. Herman, Vacuum plasma sprayed hard coatings, Mém. Etudes Sci. Rev.Métall., 88(1991)289.

[4] S.Sampath,R.Tiwari, B.Gudmundsson, H.Herman, Microstructure and properties of plasma-spray consolidated two-phase nickel aluminides, Scripta Metall. Mater. 25(1991)1425-1430.

[5] S.Sampath, X.Y. Jiang, J. Matejicek, L. Prchlik, A. Kulkarni, A. Vaidya, Role of thermal spray processing method on the microstructure, residual stress and properties of coatings: an integrated study for Ni-5wt.%Al bond coats, Mater. Sci. Eng. A. 364 (2004) 216–231.

[6] S.Deshpande, S. Sampath, H. Zhang, Mechanisms of oxidation and its role in microstructural evolution of metallic thermal spray coatings—case study for Ni–Al, Surf. Coat. Technol. 200(2006)5395–5406.

[7] L. Prchlik, S. Sampath, Effect of the microstructure of thermally sprayed coatings on friction and wear response under lubricated and dry sliding conditions, Wear, 262(2007)11-23.

[8] S. Sampath, G.A. Bancke, H. Herman, S. Rangaswamy, Plasma sprayed Ni-Al coatings, Surf. Eng. 5 (1989)293–298.

[9] G.A.López,S.Sommadossi,P.Zieba,W gust,E.J Mittemeijer, Kinetic behavior of diffusion-soldered Ni/Al/Ni interconnections, Chem. Phys. 78(2002)459-463.

[10] F. Kozo, H. Zenji, Measurement of intrinsic diffusion coefficients of Al and Ni in Ni3Al using Ni/NiAl diffusion couples, Acta Mater. 50(2002)1571-1579.

[11] D.F Susan, A.R Marder, Ni–Al composite coatings: diffusion analysis and coating lifetime estimation, Acta Mater. 49(2001)1153-1163.

[12] M. Lieblich，J. L. Gonzalez-Carrasco, F. Garcia-Cano, Asymmetrical phase growth in a PM Al/Ni_3Al composite, J. Mater. Sci. Lett. 18(1999)905-908.

[13] H.A. Pour, M. Lieblich, S.G. Shabestari, M.T. Salehi, Influence of pre-oxidation of NiAl intermetallic particles on thermal stability of Al/NiAlp composites at 500℃, Scripta Mater. 53(2005) 977-982.