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Microstructural and tribological characterization of NiAl matrix self-lubricating composite coatings by atmospheric plasma spraying

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A B S T R A C T

The NiAl-Mo-Ag and NiAl-Cr_2O_3-Mo-Ag composite coatings were fabricated by atmospheric plasma spraying with the substrate material of Inconel 718. The effect of heat treatment on the microstructure, adhesive strength, microhardness and tribological properties of NiAl-Cr_2O_3-Mo-Ag composite coating was investigated. The heat treatment temperatures were chosen as 400, 500 and 600 °C. The composition and microstructure of composite coatings were analyzed by X-ray diffraction (XRD), scanning election microscopy (SEM) and transmission electron microscopy (TEM). The results show that the addition of Cr_2O_3 could effectively reduce the wear rate of NiAl-Mo-Ag composite coating. The adhesive strength, microhardness and tribological properties of NiAl-Cr_2O_3-Mo-Ag composite coating were improved by heat treatment. After 500 °C heat treatment, the microstructure of composite coating became more homogeneous and the coating had the highest adhesive strength, microhardness and the best tribological properties. The sliding process could promote the silver, nickel and molybdenum occur tribo-chemical reaction to form silver molybdates and nickel molybdates lubricating films which were responsible for the good tribological properties of composite coatings at elevated temperatures.

1. Introduction

In recent years, high temperature self-lubricating metal matrix composite coatings with good performance are required widely in all types of engines, such as aerospace, auto-motive and nuclear power industries [1–6]. However, it is very difficult for the composite coatings to achieve and maintain low friction coefficient and wear rate at high temperature. So seeking effective lubricants which play lubricating role in wide temperature range is still a challenge task for the self-lubricating composite coatings [1]. Intermetallic compounds are promising materials for several high temperature application because they have the higher melting points than MCrAlY alloys [7]. NiAl intermetallic compound has been extensively studied for structural applications, corrosion resistance and heat resistance because of its high melting point (T_m=1638 °C), high thermal conductivity, as well as excellent oxidation and corrosion resistance at high temperature [7–12]. Nevertheless, the NiAl and MCrAlY coatings suffer the severe high-temperature wear [6]. Therefore, the protective coatings with high hardness, high mechanical strength and good wear resistance hard phases should be added [13]. The WC and Cr_3C_2 usually add into alloy coatings as strengthening hard phases [6]. However, they are liable to oxidize at about 540 °C and 850 °C. NASA reported that NiMoAl coatings containing Cr_2O_3 as a strengthening hard phase showed better resistance to wear at high temperature [14]. Graphite and molybdenum disulfide are widely used as solid lubricants, while they get oxidized or decomposed in air and lose their lubricating effects above 500 °C [15,16]. Silver could decrease the friction coefficient and wear rate of the composites and provide the excellent lubrication below 400 °C due to a large diffusion coefficient and low shear strength on the worn surface in the sliding process [17–21]. In latest years, Ag-Mo dual-lubricant has been reported by several researchers, which has the excellent lubricating performance in wide temperature range [22–26]. J. Chen et al. studied the tribological properties of adaptive NiCrAlY-Ag-Mo coatings prepared by atmospheric plasma spraying, which had excellent lubricating properties in wide temperature range [26], but poor cohesive strength between the coating and substrate. The adhesive strength is an important factor for the plasma-sprayed coatings. For heightening the adhesive strength of the coatings, several researchers made use of a bond coat between the coating and substrate and discussed the effect of bond coat on the adhesion of composite

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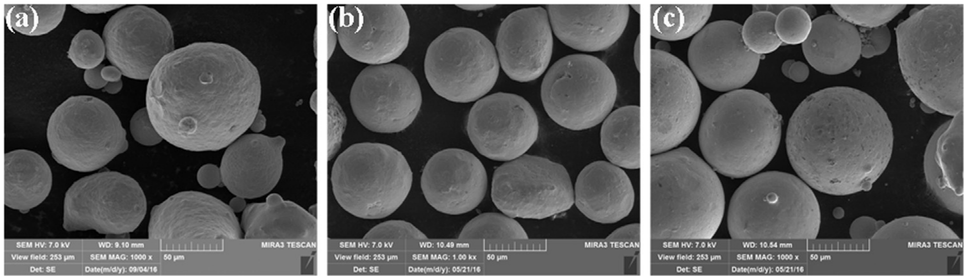

Fig. 1. SEM micrographs of feedstock powders of (a) NiAl, (b) Mo and (c) Ag.

coatings [27–31]. F. Ghadami et al. prepared the APS WC-Co coating with NiCr as the bond coat presenting higher adhesive strength [31]. Because the plasma-sprayed coatings often contain many defects (e.g. cracks and pores), which would deteriorate the performance of the coating greatly [32]. Heat treatment could effectively improve the adhesive strength of composite coatings and make the microstructure of coating more homogenous [33]. In recent years, several researchers investigated the influence of heat treatment on the mechanical properties and microstructures of composite coatings. The results indicate that heat treatment could effectively reduce the defects and improve the adhesive strength and microhardness of composite coatings [11,31,33–36]. Our previous study on the effect of heat treatment on microstructure, mechanical and tribological properties of NiCrAlY-Mo-Ag coatings, indicated that heat treatment resulted in a homogeneous microstructure of composite coating and effectively improved the adhesive strength, microhardness and tribological properties of composite coatings [34].

In this work, the NiAl-Mo-Ag and NiAl-Cr_2O_3-Mo-Ag composite coatings were fabricated with the substrate of Inconel 718 by atmospheric plasma spraying. The NiAl intermetallic compound has the higher melting point (T_m=1638 °C) than Ni-based alloys and has the excellent oxidation and corrosion resistance at high temperatures [7–12]. The Cr_2O_3 acts as a reinforced phase which has the high hardness and excellent wear resistance at high temperature [37–41]. The effect of heat treatment on the microstructure, adhesive strength, microhardness and tribological properties of NiAl-Cr_2O_3-Mo-Ag composite coating were investigated. At the same time, the wear mechanisms of composite coating are also studied at different temperature. The tribological properties of composite coatings are explored against Al_2O_3 ceramic ball in wide temperature range. Meantime, the tribochemical reaction films of silver molybdates and nickel molybdates may form on rubbing surface of coatings and their influences on the tribological properties of composite coatings are analyzed and discussed.

2. Materials and methods

2.1. Material preparation

The composite coatings were fabricated by atmospheric plasma spraying. The feedstock powders of NiAl, Cr_2O_3 and Mo were obtained from Sulzer Metco. The feedstock powder of Ag was purchased from Beijing Research Institute of Mining & Metallurgy. The NiAl, Mo and Ag powders presented spherical shapes and the size was 50–100 µm. The Cr_2O_3 powder was prepared by sintering and crushing and had angular shape with the size of 20–90 µm. Before APS, the substrates (Inconel 718 alloys) were sand blasted with corundum grits and then cleaned by ultrasonic cleaner with acetone. The feedstock powders were mixed mechanically before spraying. The main spraying parameters employed were: Ar flow rate was 40 L/min; H_2 flow rate was 5 L/min; power feed rate was 40 g/min; current was 500 A and voltage was 60 V.

2.2. Heat treatment process

The samples were treated in vacuum furnace and the dynamic vacuum is about 10^{-1} Pa. The heat treatment temperatures were chosen at 400, 500 and 600 °C. The heating rate was 10 °C/min, followed by furnace cooling.

2.3. Characterization

The microhardness was measured by MH-5-VM microhardness tester (made in Shanghai Hengyi Science and Technology Corporation, China) with a normal load of 300 g and a dwell time of 5 s on polished surfaces. Each specimen was measured at least ten times. The adhesive strength were examined by tensile test in accordance with ASTM C633 standard test for all coatings. Each kind of sample was gauged at least five times and the average value were reported. The test sample was 25.4 mm (1 in.) of the diameter. The tensile rate was 0.5 mm/min. The constituent and crystal structure of coatings were characterized using a Philips X′Pert-MRD X-ray diffractometer (XRD) with 40 kV operating voltage and Cu-K_a radiation. The scan speed was 10° min^{-1} and the 2θ range was 10–90°. The morphologies and microstructures of coatings were observed using SEM and HRTEM (Tecnai™ G2 F30, FEI, USA). The compositions of worn surface were studied by Raman spectrometer (Czemy-Tumer Labram HR800) with the wavelength was 532 nm.

The friction tests were performed using a ball-on-disk tribometer (UMT-3). The disk was the coating material with size was φ38 mm×8 mm. Before testing, the samples were cleaned with acetone. The counterpart ball was a 10 mm diameter Al_2O_3 ceramic ball with the hardness of 16.5 GPa and the density of 3.92 g/cm^3. The friction test parameters were as follows: load was 10 N, sliding speed was 0.3 m/s and sliding time was 60 min. Selected test temperatures were 25, 300, 500, 700 and 900 °C. The friction tests were performed three times at every temperature to assure the reproducibility of experimental results. After the friction test, the morphologies of worn surface were observed using SEM.

3. Results and discussion

3.1. Adhesive strength, microhardness and tribological properties of NiAl-Mo-Ag composite coating

Fig. 1 shows the SEM micrographs of NiAl, Mo and Ag powders. The feedstock powders present spherical shapes and the size is 50–100 µm. All of the powders are mixed uniformly and make sure the good flowability, which is important for the stability of feed rate [26].

The NiAl-Mo-Ag coatings with different contents of silver were fabricated by atmospheric plasma spraying. Table 1 gives the composition and Vickers hardness of composite coatings. It can be seen that the hardness of composite coatings decreases from 192.6 HV to 153.4 HV with the rise of silver contents, which is due to the addition of soft phase silver.

In order to improve the adhesive strength of composite coatings, the NiAl is used as the bond coat because NiAl has the well mechanical