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Preparation and characterizations of nickel-based composite coatings with self-lubricating property at elevated temperatures

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ABSTRACT

A series of nickel-based self-lubricating composite coatings containing Ag or Ag-Mo as solid lubricants were prepared by atmospheric plasma spraying (APS). Phase composition, microstructure and mechanical properties of these coatings were characterized. Tribological properties were evaluated using a ball-on-disk high temperature tribometer from room temperature to 800 °C in air. The results showed that the addition of Ag in the composite coating could effectively minimize the mismatch between the coating and substrate, and also increase the mechanical strength of the coating. The addition of Ag or Ag-Mo as solid lubricants effectively reduced the friction coefficient of the coatings especially under a temperature above 400 °C, and elevated the wear resistance property in the whole test temperature ranges. Raman spectra analysis on the wear track has confirmed the formation of silver molybdate and nickel molybdate through tribo-chemistry reaction above 400 °C. Both silver molybdate and nickel molybdate provided synergistic lubrication effect at high temperatures, which decreased friction coefficients and wear rates of the composite coatings.

1. Introduction

Solid lubricating coatings applied on the components working at high temperatures and aggressive environment have been studied for decades [1–4]. These coatings are usually composed of an anti-wear phase, to provide wear resistance under high loads and prolong the coating's service life, a soft lubricating phase to minimize the friction in specific tribological conditions, and a main matrix phase with excellent high temperature mechanical properties, high thermal stability and oxidation resistance [5–7]. Solid lubrication coatings of PS100, PS200, PS300 and PS400 deposited by plasma-spraying have been developed by NASA [8–11]. In the PS series coatings, the Ni-based alloy was used as the main matrix material, such as NiCr for PS100, NiAlCo for PS200, NiMoAl for PS400. Cr_2O_3 or Cr_3C_2 acted as a hard phase, while Ag and $BaF_2 \cdot CaF_2$ were added to provide lubrication over a wide temperature range. Aside from the PS series, many other solid-lubricating coatings were also made by researchers, such as WC-(W, Cr)$_2$C-Ni/Ag/$BaF_2 \cdot CaF_2$ coating and NiCrAlY-Ag-Mo coating prepared by thermal spraying [12,13], Mo_2N/MoS_2/Ag coating and YSZ-Ag-Mo coating prepared by magnetron sputtering [14,15].

The addition of hard phases and solid lubricants could significantly elevate the coating's wear resistance and lubricity, respectively. However, the hard phase such as Cr_2O_3 or Cr_3C_2 in the coating system possesses a lower thermal expansion coefficient in comparison with the metal matrix phase. As the self-lubricating composite coatings deposited on the stainless steel or the Ni-based alloy substrate, the mismatch of thermal expansion coefficient between the cermet coating and the metal substrate can cause great residual thermal stress, and consequently result in the degradation of joint during the thermal cyclic process. This will shorten the service life of the coatings, and leading to disastrous consequences [16–18]. Therefore, a major challenge of fabricating a high-temperature self-lubricating coating which combines excellent tribological performance with high mechanical strength still remains.

In this study, we have prepared a series Ni-based high-temperature self-lubricating composite coatings by atmospheric plasma spraying that possesses both high strength and excellent tribological performance. In this coating, NiCoCrAlY was selected as the main matrix due to its excellent high temperature mechanical properties and oxidation resistance. Cr_2O_3 was used as the hard phase to enhance the coating's wear resistance. Ag was applied as both the low temperature solid lubricant and the soft phase. As a soft phase, Ag could promote the compatibility between coating and substrate due to its high thermal expansion coefficient and low elastic modulus. Besides, it also exhibits good

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Table 1
Composition of the NiCoCrAlY-Cr_2O_3 composite powder.

Composition	Ni	Co	Cr	Al	Y_2O_3	Cr_2O_3
wt%	29.6	1	7	2.2	0.2	60

thermo-chemical stability over a wide range of temperatures. Mo with a synergistic effect of Ag was added to provide high temperature lubrication.

2. Experimental

NiCoCrAlY-Cr_2O_3 composite powder was fabricated by centrifugal spray granulation and solid alloy method. The nominal composition of this powder is shown in Table 1. Ag powders were made by chemical reduction method using $N_2H_4 \cdot H_2O$ as the reducing agent. Ag-Mo composite powders with a weight ratio of 2:1 (Ag/Mo) were made by electroless plating.

Table 2
Detailed compositions of the spray powders.

	Compositions (wt%)		
	NiCoCrAlY-Cr_2O_3	Ag	Mo
NC	100	0	0
NC10A	90	10	0
NC10AM	90	6.66	3.33
NC15AM	85	10	5

NiCoCrAlY-Cr_2O_3 powders and Ag or Ag-Mo powders with different nominal weight percent were blended to fabricate the spray materials. A detailed compositions of all the spray powders (denoted as NC, NC10A, NC10AM, NC15AM) are shown in Table 2. The uniform composite powders were deposited on Ni-based superalloy (74Ni-20Cr-2.6Ti-0.8Al-bal Fe) substrate (25 mm in diameter, 5 mm in thickness) by air plasma spraying technology. The spraying parameters are shown in Table 3. The substrate was blasted with coarse SiC particles before spraying. And then a CoNiCrAlY (37Co-31.5Ni-25.5Cr-5.5Al-0.5Y) bonding layer with a thickness of about 0.1 mm was sprayed.

Table 3
Plasma spraying parameters.

Items	Value
Current (A)	450
Voltage (V)	60
Spray distance (mm)	120
Powder feed rate (g/min)	40
Ar flow rate (L/min)	40

Flowability and apparent density of the spray powders was evaluated by a Hall Flowmeter. A FEI Quanta 200 FEG scanning electron microscope (SEM) accompanied with energy dispersive X-ray analysis system (EDX) was employed to observe the microstructures and morphologies of the feedstock powders and as-sprayed coatings. Phase compositions of the coatings was determined using a Philips X'Pert Pro X-ray diffraction (XRD) meter (PANalytical, Holland, CuKα, $\lambda = 0.154$ nm) over an angular range from 10° to 90° at 40 kV, 40 mA. The variations of the phase compositions on the worn surface were investigate by an inVia-Reflex Raman spectrometer at an excitation wavelength of 532 nm.

An Olympus PMG3 microscope with the Adobe Photoshop utility software was employed to measure the coating's porosity by image analysis method, and an average data was obtained from 10 images. Elastic modulus of the coating was evaluated with Knoop and Vickers indentation technique by a HX-1000TM microhardness device equipped with 1.96 N test load. A Linseis messgeraete thermodilatometer was used to measure the coating's thermal expansion coefficient in air atmosphere with a sample size of 20 mm × 4 mm × 0.5 mm. The coating's bonding strength was evaluated by a universal testing machine (model WDW2100E) at a cross head speed of 1 mm/min (GB/T 8642-2002). The average values of three samples were taken as the coatings' bonding strength.

A ball-on-disk high temperature tribometer (CSM-THT, Switzerland) was employed to measure the tribology properties of the coatings from room temperature to 800 °C. The commercially obtained Si_3N_4 balls (Φ6 mm) were used as the counterpart. The friction tests were carried out at a load of 10 N for a distance of 240 m. Each of these tests was repeated three times. The volumetric wear rate (R_w) of specimens was calculated by $R_w = V/F \cdot S$, where V is the wear volume (mm^3), F is the applied load (N), and S is the sliding distance (m). The wear volume was obtained by a non-contact surface mapping profiler (ADE Corporation, USA). The surface morphologies of the coatings after friction test were observed by the SEM equipped with EDX.

3. Results and discussion

3.1. Characterization of feedstock powders and as-sprayed coatings

Fig. 1 shows the SEM morphologies of NiCoCrAlY-Cr_2O_3, Ag and Ag-Mo composite powders. All powders display a nearly spherical shape with a uniform size distribution of about 50 μm, 60 μm and 70 μm, respectively. As revealed in Fig. 1(c), Mo core is continuously cladded by the Ag coating. This core-shell structure can not only prevent the oxidation of Mo during the spraying process, but also enhance the synergistic lubrication effect of Ag and Mo. The scattered around small particles are the free Ag dropped from the Ag-Mo composite powders.

Fig. 2 lists the flowability and apparent density of the four spray powders. All the powders have suitable flowability of about (48–

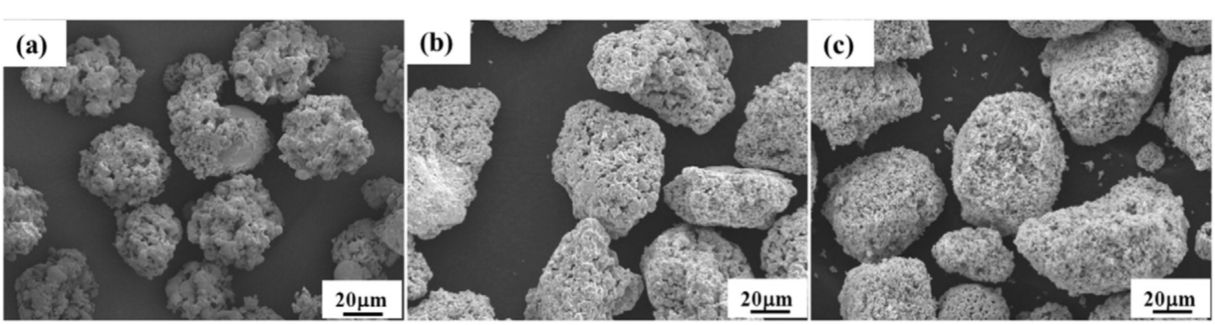

Fig. 1. SEM morphologies of NiCoCrAlY-Cr_2O_3 (a), Ag (b) and Ag-Mo (c) composite powders.