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Friction and wear behavior of nickel-alloy-based high temperature self-lubricating composites against Si_3N_4 and Inconel 718

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ABSTRACT

High-temperature self-lubricating nickel-alloy based composites with Ag and three amounts of BaF_2/CaF_2 eutectic were prepared by hot press sintering technique. Both the composites with 5 wt% and 10 wt% BaF_2/CaF_2 eutectic exhibited markedly higher strength than 15 wt% composite. The friction coefficient of the three composites was comparable. All three composites showed the highest wear rate at 600 °C, but very lower at 800 and 900 °C. The friction coefficient of the three composites was slightly lower as sliding against Si_3N_4 than Inconel 718. The friction and wear mechanism was proposed.

1. Introduction

In modern industry, there is a great need for the lubricating materials that possess low friction coefficient, and wear rate at a wide range of working temperature [1,2]. The potential applications include gas turbine seals, cylinder wall/piston ring lubrication for low-heat rejection diesel engines, moving assemblies for hypersonic aircraft and missiles and propulsion bearings, among many others [2,3]. Commonly, most liquid lubricant will lose function owing to volatilizing in vacuum and coking at elevated temperatures. Solid lubricants are therefore employed under these harsh environments. Conventional solid lubricants, such as low shear graphite and molybdenum disulfide, noble metals, inorganic fluorides, and a few metal oxides [4–6], can effectively provide lubricating role in a limit range of ambient conditions. Up to now, there is nearly no single lubricant that can provide low friction and wear in a broad range of temperature, and the only way was reported by combining the function of individual solid lubricant constituents [2,7–13,19].

As been reported, solid lubricant of BaF_2/CaF_2 eutectic has been successfully used for moderate to high temperatures (>500 °C) lubrication as added element in many composites due to its low shear property at temperature range of [14–16]. Soft metal Ag as solid lubricant has self-lubricity at low-to-moderate temperatures [17–21]. The most famous two series of self-lubricating materials, PS coatings with Ag and BaF_2/CaF_2 eutectic lubricants, exhibiting very favorable tribological performance at a broad range of temperature (from 25 °C to 800 °C) in air or vacuum [7–10] and adaptive coatings with Ag and in situ formed double oxides, were first developed by NASA and the Air Force Research Laboratory (AFRL), respectively [22–25]. Kong et al. [26] and Ouyang et al. [27,28] reported that the ZrO_2 based composites with fluoride exhibited low friction and high wear resistance at elevated temperatures. In our group, the Ni_3Al matrix composites with Ag and BaF_2/CaF_2 eutectic lubricants exhibited low friction coefficients (0.29–0.38) and wear rate (4.22×10^{-5} mm^3/N/m) at a wide temperature range (RT to 900 °C) [29]. Moreover, a high strength nickel-alloy-based composite with perfectly self-lubricity ($\mu < 0.25$) from room temperature to 800 °C was also reported [30].

Besides, selecting an appropriate counterface is another important aspect for solid lubrication. Valefi et al. [31] and Kong et al. [32] studied the influence of ceramic counterface on ZrO_2-based composites, and found that friction and wear is lower when sliding against Al_2O_3 than Si_3N_4 balls. Moreover, DellaCorte et al [33] depicted that PS300 has lower friction and wear rate at 25 °C but higher at 650 °C against Inconel X-750 pin than Al_2O_3 ceramic pin. Other similar reports including aluminum alloy 5052 [34], Ti–6Al–4V composites [35] and aluminum matrix composites [36] etc all suggested that selection of the appropriate counterface was very significant. They concluded that a transfer film was formed on the counterface during sliding, which played an important role in the self-lubricating ability of the composites.

In the present work, the authors selected soft metal silver and fluoride eutectic as low-to-moderate and moderate-to-high

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Table 1
Composition and characteristics of the nickel-alloy-based composites.

Materials	Composition (wt%)	Vickers hardness (HV)	Bending strength (MPa)	Compressive strength (MPa)	Density (g/cm^3)
NAF5	Ni-alloy-5BaF_2/CaF_2–12.5Ag	311	934	1339	7.91
NAF10	Ni-alloy-10BaF_2/CaF_2–12.5Ag	322	909	1379	7.78
NAF15	Ni-alloy-15BaF_2/CaF_2–12.5Ag	283	690	1279	7.67

Ni-alloy: Ni15Cr12Mo3Ti1Al.

temperature lubricants of nickel-alloy-based composites, respectively, and studied the effect of the fluoride eutectic's content and counterface materials on the tribological behavior.

2. Experimental details

The three nickel-alloy-based self-lubricating composites were obtained by hot-pressed sintering technique from a mixed powder of nickel-based-alloy (Ni15Cr12Mo3Ti1Al, powder size of 10–20 μm), BaF_2/CaF_2 eutectic and Ag. The powders were enclosed in a graphite mold and set in a hot-press-sintering furnace, and then heated at a rate of 10 °C/min when the furnace was evacuated to a dynamic vacuum of about 10^{-2} Pa. The powders were pressed under 28.3 MPa for 20 min at 950 °C, then heated to 1200 °C and held for 15 min. The composition of the composites was listed in Table 1. Experimental specimens were cut by a wire-electro-discharging machine, and then polished.

The density of the samples was measured by the buoyancy method applying the Archimedes principle. The Vickers microhardness of the composites was measured by an MH-5 tester with a load of 1 kg and an endurance time of 10 s, the average of ten repeat tests was given. The room-temperature bending and compressive tests for the composites were done using a DY35 universal material testing machine. Bending tests of the cuboids bars with dimensions of 3 mm × 3 mm × 30 mm were performed using three-point bend testing set-up with a span of 20 mm at a cross-head speed of 1.7×10^{-3} mm/s. Quasi-static uniaxial compressive tests of the cylindrical samples with dimensions of 3 mm (diameter) × 5 mm were performed with a cross-head speed of 1.7×10^{-3} mm/s.

To exclude the impact of the impurity on the surface, the ball and specimen were ultrasonically cleaned using acetone, then rinsed with distilled water and dried under the hot air before tribological experiment. The tribological behavior was evaluated by a home-built HT-1000 ball-on-disk high-temperature tribometer, as shown in Fig. 1.

Friction tests were carried out by sliding the nickel alloy disks against Si_3N_4 eramic ball with a dimeter of 6.43 mm or a hempispherical tipped pin with a dimeter of 5 mm made from the common heat-treated superalloy Inconel 718 with the Vickers hardness of 4.4 GPa. The testing temperatures range was from RT to 900 °C and each tribological test lasted 30 min with a load of 5 N and sliding speed of 1 m/s. The friction coefficient datum were collected by detector, and recorded on the computer simultaneous; the wear rate of the composites was measured by a contact surface profilometer. All tribological tests and measurements were performed under the same conditions for three times, and the average inaccuracy was less than 10%.

X-ray diffraction (XRD) patterns were obtained using a PAN'Pert Pro diffractometer with a Cu $K\alpha$ radiation in the 2θ range of 20–100°. Microstructures and morphologies of worn surface were examined by a JSM-5600LV scanning electron microscope (SEM). Before observation of microstructures of the composites, the samples were etched by a mixture solution of chlorhydric acid (36–38%) and nitric acid solution (65–68%) with a volume ratio of 1:1. The phase compositions of the wear trace were examined by a Renishaw's inVia Micro-Raman with a leaser wave length of 514 nm.

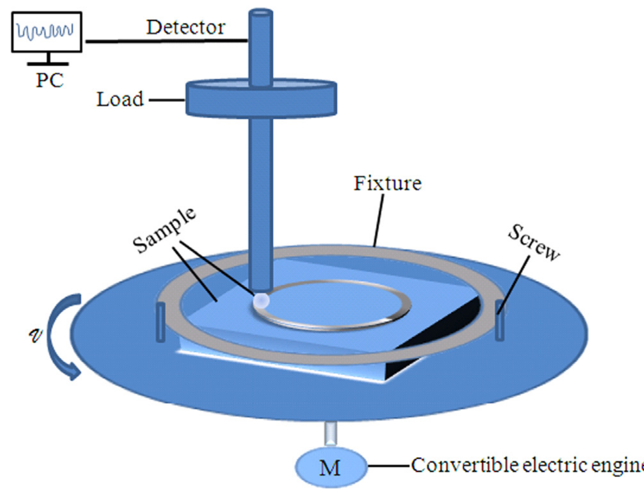

Fig. 1. The mold of HT-1000 ball-on-disk high-temperature tribometer.

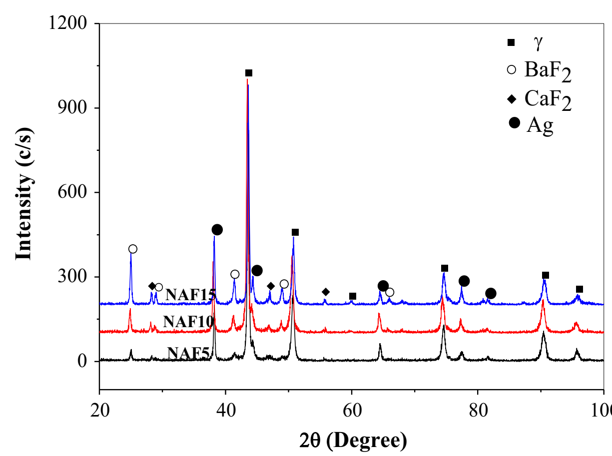

Fig. 2. XRD patterns of the nickel-alloy-based composites.

3. Results and discussion

The phase constituent of the composites indentified by XRD is illuminated in Fig. 2. The three materials are all composed of typical Ni-based alloys γ, Ag and BaF_2/CaF_2 eutectic phases. Due to the lower content of γ' and overlap XRD peaks with γ, γ' is difficult to exam by using XRD technique. Fig. 3 shows the microstructure