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Microstructure and tribological behavior of NiAl/WC composites fabricated by thermal explosion reaction at 800 °C

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ABSTRACT

In order to improve the tribological properties of NiAl intermetallic compound at high temperature, NiAl/WC composites with addition of 5, 10, 20 and 30 wt% WC are successfully fabricated by self-propagation high-temperature synthesis with thermal explosion mode. The composition, microstructure and microhardness of the composites were characterized. It is found that the composites consisted of only NiAl and WC phases. Tribological behavior is studied on the HT-1000 ball-on-disk high temperature tribometer at 800 °C. The results show that both the friction coefficient and wear rate of the composites decrease with the increase of WC content. The NiAl/WC composite with 30 wt% WC content has the lowest friction coefficient and wear rate. The incorporation of WC particles significantly improves tribological properties at elevated temperature.

1. Introduction

The NiAl intermetallic alloys have been recognized as the promising candidate for high temperature structural applications, due to its high melting point, low density and excellent oxidation [1,2] and corrosion resistance [3] at high temperature. Recently, excellent tribological properties of NiAl intermetallic compounds also have been reported [4], exhibiting great potential to be used in severe wear conditions.

Previously, the investigations were focused on the wear properties of NiAl and its alloys, which revealed that NiAl possesses good tribological properties at high temperature and the addition of ceramic strengthening particles can improve their tribological properties further [5–7]. Among the ceramic particles, tungsten carbide (WC) is the most popularly used due to its high hardness and excellent wear resistance [8,9].

Self-propagating high-temperature synthesis (SHS), or combustion synthesis (CS), is considered as an efficient-energy, low-cost method for producing cements and intermetallics [10–13], since it offers advantage with respect to simplicity, economy and high efficiency. Generally, CS has two modes of self-propagating high-temperature synthesis (SHS) and thermal explosion (TE) [14–16], which are, ignited by heating one end of the reactant compact and the whole reactant compact, respectively.

In our previous work [17], NiAl/WC composites with different WC contents were successful fabricated via SHS by its TE mold. However, little information has been devoted to investigate the wear properties of NiAl/WC composites at high temperature. For the potential application of NiAl/WC composites at elevated temperature, the main objective of present study is to investigate the tribological behavior of NiAl/WC composite with different WC contents under dry sliding conditions against Si_3N_4 ceramic ball at 800 °C in air atmosphere.

2. Experimental

The starting materials were made from commercial powders of Ni (99.5% purity, 25–40 μm), Al (99.5% purity, 25–40 μm) and WC (99.5% purity, 25–40 μm). In this paper, Ni and Al were weight at a stoichiometric mole ratio 1:1 and mixed with WC at 5%, 10%,20%,30% and 40% weight percentage (wt.%). The reactant

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powders were mixed in a stainless steel container using stainless-steel balls at a low speed (<35 rpm) for 2 h to ensure homogeneity, and then were pressed into cylindrical compact with the pressure of 300 MPa (about 40 mm in diameter and 10 mm in thickness) using a stainless steel die. After completing the preparations, the compacts were put into an electric resistance heating furnace with temperature of 700 °C under air atmosphere until thermal explosion occurred.

The friction and wear tests were carried out on a HT-1000 ball-on-disk high temperature tribometer (made in ZhongKeKaiHua Corporation, China) according to the ASTM Standard G99-95 [14]. The disc samples of NiAl/WC composites were rotated and slid against a stationary ball slider of 5 mm diameter under a contact load of 10 N. The selected test temperature was 800 °C. The sliding speed was 1.47 m/s. The friction radius was 5 mm. The testing time was 20 min. The counterface ball slider was commercially available balls of Si_3N_4 with surface roughness (Ra) of 0.01 mm. The friction coefficients were automatically measured and recorded in real time by computer system consistently. The cross-section profile of worn surface was measured using a surface profilometer. The wear volume was determined as V = AL, where A is the cross-section area of worn scar, and L is the perimeter of the worn scar. The wear results obtained during this work had been presented in terms of specific wear rate which is calculated as follows:

$$\text{Specific wear rate} = V/PL$$

Where V is the volume worn away in mm^3, P is the normal load in N and L is the sliding distance in mm. All the tribological tests were carried out at least three times to make sure the reproducibility of the experimental results in the same conditions, and the average results were reported.

The relative and bulk densities of the synthesized samples were measured in terms of Archimedes' method in deionized water. The surfaces of the as-prepared specimens were examined by X-ray diffraction (XRD) analysis with Cu Kα radiation at 30 kV and 40 mA at a scanning speed of 0.01 s^{-1} for the identification of the phase constitution. Microhardness tests were carried out using a 0.2 N load for 10 s. Samples were molded within an epoxy resin and polished prior to testing. The morphologies and compositions of worn surfaces of NiAl/WC composites with Si_3N_4 counterface balls were examined using electron probe microanalysis (EPMA, JAX-8230) and energy dispersive spectroscopy (EDS, GENESIS 7000). The microstructure and morphology of the wear scar profile were observed by a scanning electron microscope (SEM, JSM-5610LV).

3. Results and discussion

3.1. Microstructure and mechanical properties of the composite

The XRD patterns of NiAl with different WC content are presented in Fig. 1. Among all the samples, only 40 wt% WC content was not observed thermal explosion reaction. Thermodynamically, the addition of WC acts as a "dilution" agent to the NiAl synthesis. The dilution not only affects the exothermicity but also influences other parameters of SHS. The influence on exothermicity can be divided into two aspects: (a) the reduction of total enthalpy of synthesis for equivalent weight; and (b) the absorption of heat throughout combustion propagation and product synthesis. It can be observed there are two chemical phases, NiAl and WC, in the final product. With the increase of WC content, the diffraction intensity of WC becomes much stronger. No nickel or aluminium can be detected in the X-ray spectrum, which indicates that the combustion reaction is completed for these samples and the NiAl/WC composites are successful fabricated in the reaction.

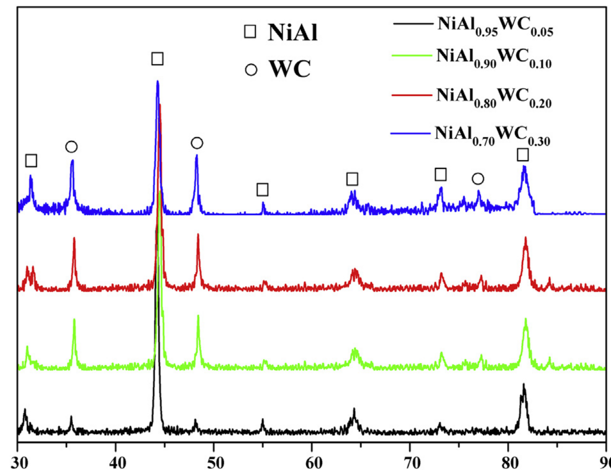

Fig. 1. XRD patterns of NiAl/WC composites.

The typical microstructures of NiAl/WC composites are shown in Fig. 2. It can be seen that the composites have density microstructure, which indicates thermal explosion reaction has advantage in the preparation process. The composites are mainly composed of gray NiAl and bright WC. The results show that WC particles are not only distributed at the NiAl boundary, but also embedded in the NiAl matrix within the NiAl grains with a relatively non-uniform distribution, which indicates that NiAl is in liquid state in the synthesis process.

As is shown in Table 1, the densities of the NiAl/WC composites with different WC content are approximately 4.21 g/cm^3, 4.56 g/cm^3, 4.73 g/cm^3 and 4.90 g/cm^3, respectively. The relative densities of pure NiAl/WC composites measured in terms of Archimedes' principle are 90.01%, 90.04%, 92.30% and 92.60%, respectively. The results show that the density of the NiAl/WC composites has a little rise with the increase of WC content. The reason is that WC particles absorb exothermicity of the synthesis process. When the WC content is lower, the thermal explosion reaction is stronger, which will create more holes in the final products.

3.2. Microhardness

Microhardness test results are shown in Fig. 3. The result shows that the hardness of composites with 5–30 wt% WC increases with increasing WC content. The 5 wt% sample has the lowest hardness of 375HV, while the 30 wt% sample has the highest value of 550 HV. That is because WC particles have high hardness and can improve the composites obviously.

3.3. Tribological performance of NiAl/WC composites

The typical variations of the friction coefficient vs. sliding time under an applied load of 10 N and speed of 1.47 m/min at 800 °C are shown in Fig. 4. It can be seen that the friction coefficient of the NiAl/WC composites have an obvious fluctuation in the running-in period shorted than 2 min, then the composites go into the steady wear period as time increases. Obviously, the friction coefficient of the composite with 5 wt% WC content is much higher than others, but when the WC content ranges from 10 wt% to 30 wt%, the friction coefficient has no obvious change. This is because NiAl-based