Preparation and high-temperature wear behavior of NiAl-Ti$_3$AlC$_2$ fabricated by thermal explosion

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Abstracts

In this paper, a novel NiAl-based composite reinforced with different content Ti$_3$AlC$_2$ particles was fabricated by thermal explosion using Ni, Al, and Ti$_3$AlC$_2$ powders as starting materials. The microstructure and high-temperature wear behavior of NiAl-Ti$_3$AlC$_2$ composites at 600 °C were investigated. The result showed that increasing Ti$_3$AlC$_2$ content (lower than 15 wt%) could improve the fracture toughness of NiAl-Ti$_3$AlC$_2$, but for the composites with 20 wt% Ti$_3$AlC$_2$ content, the fracture toughness decreased due to low relative density. Wear mechanism of composites was related to the Ti$_3$AlC$_2$ content, the composite with a lower content exhibits oxidation wear, and higher content composite demonstrated both oxidation wear and abrasive wear.

1. Introduction

The NiAl and NiAl-based composites have been recognized as attractive materials for their excellent physical and chemical properties, such as high melting point, low density, good high-oxidation [1–3], and high-temperature corrosion resistance [4]. These excellent properties make NiAl-based composites become potential materials used in turbochargers, hydro turbines, cutting tools and turbines.

In recent years, the wear performance of NiAl-based composites has attracted the interest of many scholars [5, 6]. Several studies reported on NiAl-based materials established that the addition of ceramic in NiAl alloy could improve the high-temperature of the composite due to the higher hardness, higher thermal stability and grain refinement of the ceramics [7, 8]. In this context, some novel NiAl-based composites, such as NiAl-GaB$_2$ [9], NiAl-Al$_2$O$_3$ [10], NiAl–TiC–ZrO$_2$ [11], NiAl–Ti$_3$SiC$_2$ [12], NiAl-WC [13–16] was produced via high-pressure reaction sintering, mechanical alloying, hot isostatic pressing, combustion synthesis, etc. In these NiAl-based composites, the ceramics particles used as lubricant additives can obviously improve the high-temperature wear resistance.

Ti$_3$AlC$_2$ as a member of MAX phase ceramics exhibits the properties of metal and ceramics, such as the thermal conductivity, thermal shock resistance and machinability of similar metals, and wear resistance, self-lubrication, and high-temperature resistance of similar ceramics [17–19]. Some earlier reports indicated that the mechanical properties of metal-based composites and ceramics could be significantly enhanced by adding Ti$_3$AlC$_2$ due to its considerable grain refinement and second-phase reinforcement [20–22]. Maryam Akhlagh [23] et al produced a TiAl-15% Ti$_3$AlC$_2$ via spark plasma sintering and confirmed that the value of fracture toughness can reach 11.9 MPa.m$^{1/2}$ and the flexural strength can reach 336 MPa, which is much higher than that of TiAl alloys.
Among all the preparation technologies of NiAl-based composites and some other composites, thermal explosion is widely used for its simplicity, economy, and high efficiency \[21, 24–28\]. During thermal explosion, the entire green compacts are rapidly heated up till reaction is uniformly initiated throughout the whole sample. The thermal explosion can be adopted to improve the density of the final products. Currently, there are no previous works about the fabrication of NiAl-Ti₃AlC₂ composites via thermal explosion. In this work, NiAl-Ti₃AlC₂ composites are designed on the hypothesis that Ti₃AlC₂ particles offer grain refinement and lubricant additives. It is of great significance to investigate the relationships between Ti₃AlC₂ content and the fracture toughness and high-temperature wear resistance of NiAl-Ti₃AlC₂ composites. The aim of this work is to produce NiAl-Ti₃AlC₂ composites with different Ti₃AlC₂ contents by thermal explosion. The research also focuses on investigating the composition, fracture toughness, and high-temperature wear mechanism of NiAl-Ti₃AlC₂ at a temperature of 600 °C.

2. Experiment procedure

2.1. Preparation of NiAl-Ti₃AlC₂
In this work, Ni₃Al-Ti₃AlC₂ composites were synthesized from raw powders of Ni (about 200 mesh), Al (about 200 mesh), Ti₃AlC₂ (about 200 mesh). Firstly, adding 5 wt%, 10 wt%, 15 wt%, and 20 wt% Ti₃AlC₂ powders into Ni-Al mixed powders with an atomic ratio 1:1, respectively. Secondly, the mixed powders were mixed equality for 2 h. Lastly, the mixed powders were pressed into a cylindrical compact with a size of Φ 45 mm × 5 mm under the pressure. Lastly, the compacts were loaded in a stainless steel mould and then put into a resistance furnace with the preheating temperature of 700 °C until the thermal explosion was ignited. In order to avoid oxidization, all the synthesis process is conducted under Ar environment. After the TE reaction was finished, the reacted compacts were cooled down freely to room temperature in air.

2.2. Tribological testing
The friction and wear test at 600 °C was conducted on a UMT-2 ballon-disk tribometer (made in Center for Tribology Inc., USA). Before the wear test, the surface of Ni₃Al-Ti₃AlC₂ composites was polished by a series of SiC abrasive papers till the roughness parameter Ra = 0.1 μm. Subsequently, Ni₃Al-Ti₃AlC₂ composites were
ultrasonically cleaned in an acetone bath before wear test. In this paper, the counterface of Si3N4 ball with 2 mm in diameter was used for the dry sliding wear test. The contact load in this test is adopted 20 N and testing time was 30 min.

The results of the friction coefficient were recorded by a computer system during the analysis. Also, wear scratches and volume was examined using a confocal scanning microscopy (OLYMPUS LEXT OLS 4000).

Figure 2. Fracture surface of NiAl-Ti3AlC2 composites with different Ti3AlC2 content: (a) 5%wt Ti3AlC2, (b) 10%wt Ti3AlC2, (c) 15%wt Ti3AlC2, and (d) 20%wt Ti3AlC2.

Figure 3. Friction coefficient of NiAl-Ti3AlC2 composites with different Ti3AlC2 content.
2.3. Characterization

The three-point bending technique was used to determine fracture toughness using a CMT5015 universal testing machine (Shenzhen, China) with a single-edge notched beam configuration. The size of the sample was 3 mm × 4 mm × 25 mm. The value of fracture toughness was calculated by the following equation:

\[ K_{IC} = \frac{Y \times 3PLa}{2bh^2} \]

where \( F \), \( L \), \( b \), \( h \) and \( a \) are the applied load, span, width, height and notch depth, respectively.

The density of the composites is measured by the Archimedes method. All the values were measured and averaged five samples.

The fracture surface and worn surface of the NiAl-Ti3AlC2 composites were examined using a FESEM, together with energy-dispersive spectrometry. The phase constituents were analyzed using x-ray diffraction.

3. Result and discussion

3.1. Phase constituent and microstructure

The XRD patterns of synthesized composites are shown in figure 1. According to the result, the product mainly contains NiAl, Ti3AlC2, and TiC phase. The intensity of the Ti3AlC2 peak increase with the Ti3AlC2 content increasing. TiC mainly comes from the decomposition of Ti3AlC2. The previous studies have confirmed that Ti3AlC2 can be decomposed into TiC and Al when the temperature is above 1400 °C [29, 30].

The result of relative density and fracture toughness of NiAl-Ti3AlC2 with different Ti3AlC2 content is shown in table 1. It can be seen that the values of relative density and fracture toughness of NiAl-Ti3AlC2 composites...
have a little rise with the increase of Ti₃AlC₂ content. But for NiAl-20 wt% Ti₃AlC₂, the density and fracture toughness decrease anomaly. The reason is that the high density of composite is a benefit for the fracture toughness.

As some early researches reported, on the one hand, adding some unreacted ceramics particles can decrease the exothermic temperature of the thermal explosion process due to their dilution effect, it does not benefit of density [31, 32]. On the other hand, the unreacted Ti₃AlC₂ particles can moderate the violence of the thermal explosion. The pressure of the samples in the thermal explosion is necessary to the high density.

Figure 2 shows the fracture surface of NiAl-Ti₃AlC₂ with different Ti₃AlC₂ content. As is exhibited in figures 2(a) and (b), the products with low Ti₃AlC₂ content have small grain. Both transgranular fracture and intergranular fracture can be observed in the fracture surface. But in the figures 2(c) and (d), transgranular fracture exhibits the obvious fracture features. Moreover, the fracture surface of NiAl-15%wt Ti₃AlC₂ content and NiAl-20%wt Ti₃AlC₂ content exhibits a lamellar structure.

The curves of friction coefficient versus sliding time of NiAl-Ti₃AlC₂ composites are shown in figure 3. According to the result, NiAl with 10 wt% Ti₃AlC₂ content has the lowest friction coefficient of 0.402 while that with 20 wt% of Ti₃AlC₂ content has the highest friction of about 0.459. The result also reveals the friction coefficient of the composites with higher Ti₃AlC₂ content exhibits significant changes during the wear test.

The worn surface of NiAl-Ti₃AlC₂ composites is shown in figure 4. No furrows and the unobvious worn direction can be observed in the worn surface, and the worn surfaces exhibit dark in color, indicating that oxidation has occurred. The worn surface in figures 4(a) and (b) demonstrates smooth and dense morphology, indicating continuously lubricating films can be produced under high-temperature wear test and oxidation wear is the main wear mechanism in the lower Ti₃AlC₂ content. However, with the increase of Ti₃AlC₂ content,
abrasive wear characteristics can be found in the figures 4(c) and (d). This change is caused by the different thermal expansivity between Ti3AlC2 particles and NiAl base, Ti3AlC2 particles shattered easily from NiAl-Ti3AlC2 composites. After Ti3AlC2 particles were broke off, the worn surface was work under sharp wear. The result coincides well with the friction coefficient of NiAl-Ti3AlC2 composites with high Ti3AlC2 content.

The element distribution of the worn surface of NiAl-15%wt Ti3AlC2 is shown in figure 5. The result shows the worn surface mainly contains Al, Ni, O, Ti, and Si element. The element of Al, Ni, and O in the worn surface presents relative homogeneous distribution, indicating that oxidation wear also occurs on the worn surface. As a lot of literature reported, NiAl-based composites present excellent lubricating performance in the high-temperature wear test [33, 34]. The uniform distribution of Si element in the worn surface is transferred from the counterpart of Si3N4 ceramic ball, indicating that the high-temperature wear resistance of Ti3AlC2 can be improved by adding particles into NiAl.

The 3D-profile of wear traces observed by a confocal scanning laser microscopy is shown in figure 6. The dull-red in the bottom indicates deep wear trace. It can be seen that the bottom of the worn traces presents rougher with the increasing Ti3AlC2 content. Additionally, as is shown in figure 6(d), the maximum width and the maximum depth of the worn traces exist in NiAl-Ti3AlC2 composite with 20 wt% Ti3AlC2 content, indicating that the composite has the highest wear rate in the high temperature. The result reveals that adding

**Figure 6.** 3D-profile micro-graphs of wear tracks for NiAl-Ti3AlC2 composites: (a) 5%wt Ti3AlC2, (b) 10%wt Ti3AlC2, (c) 15%wt Ti3AlC2, and (d) 20%wt Ti3AlC2.

**Figure 7.** Wear rate of NiAl-Ti3AlC2 composites with different Ti3AlC2 content.
higher hardness ceramics into NiAl-based composites can improve their wear resistance, but it is harmful to the wear resistance when the content of the ceramic particles exceeds a certain level.

The wear rate of NiAl-Ti3AlC2 composites is shown in figure 7. The result reveals that the composite with 10 wt% Ti3AlC2 content has the lowest wear rate, but that with 20 wt% Ti3AlC2 content has the highest wear rate. Combining the friction coefficient and analysis on wear mechanism of NiAl-Ti3AlC2, it can be concluded that abrasive wear in the higher Ti3AlC2 content results in the decrease of wear rate.

4. Conclusion

In this paper, a novel NiAl-based composites, NiAl-Ti3AlC2 composites with different Ti3AlC2 content, were successfully produced by thermal explosion. The microstructure and high-temperature wear behavior of the composites were studied. According to the discussion above, the conclusion as follows:

(1) Increasing Ti3AlC2 content (lower than 15 wt%) can improve the fracture toughness of NiAl-Ti3AlC2, while for the composites with 20 wt% Ti3AlC2 content, the value of fracture toughness decrease due to low relative density.

(2) The high-temperature wear mechanism of the NiAl-Ti3AlC2 composites reveals that the low Ti3AlC2 content composites exhibit oxidation wear, while the composites present abrasive wear combine with oxidation wear with the Ti3AlC2 content increase.

(3) NiAl-10wt%Ti3AlC2 composite has the lowest friction coefficient and wear rate, while NiAl-20wt%Ti3AlC2 composite has the highest friction coefficient and wear rate due to severe abrasive wear.

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