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Effects of in situ formed TiCx on the microstructure, mechanical properties and abrasive wear behavior of a high chromium white iron

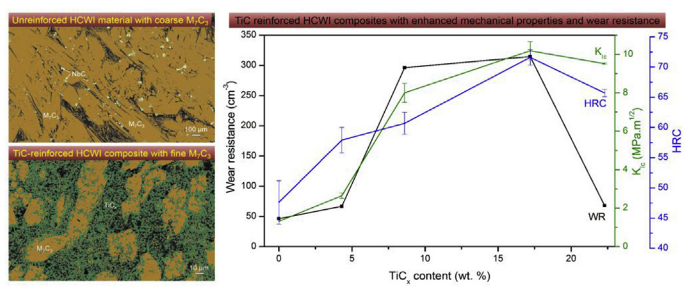
Jipeng Jiang, Shibo Li*, Shujun Hu, Yang Zhou

Center of Materials Science and Engineering, School of Mechanical and Electronic Control Engineering, Beijing Jiaotong University, Beijing 100044, China

HIGHLIGHTS

- Dense TiC_x reinforced high chromium white iron (HCWI) composites have been achieved.
- The TiC_x/HCWI composites exhibited enhanced mechanical properties and wear resistance.
- The toughness and strength of composites were nearly eight times those of the unreinforced HCWI.
- The wear resistance of composites was seven times higher than that of the unreinforced HCWI.

GRAPHICAL ABSTRACT



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ABSTRACT

High chromium white iron (HCWI) composites reinforced with in situ formed TiC_x have been prepared by powder metallurgy. Processing conditions for the preparation of dense composites have been investigated. The influence of TiC_x content on the mechanical properties and wear resistance of composites has been studied. Compared to the unreinforced HCWI material, the TiC_x/HCWI composites demonstrated a remarkable improvement in mechanical properties and abrasive wear resistance. A strength of 310 MPa and a fracture toughness of 10.19 MPa $m^{1/2}$, nearly eight times those of unreinforced HCWI, and a wear resistance of 315.1 cm^{-3}, seven times that of unreinforced HCWI, were achieved in the 17.2 wt%TiC_x/HCWI composite. Strengthening and wear mechanisms have been discussed.

1. Introduction

High chromium white irons (HCWIs) are ferrous based alloys, and consist of hard eutectic M_7C_3 (M: Fe, Cr and other strong carbide formers) carbides in a ferrous matrix. HCWIs have excellent abrasion resistance due to the presence of hard M_7C_3 carbides, thus they have been widely used in mining and mineral industries. However, the volume fraction, carbide size and morphology of the M_7C_3 carbides have an important effect on the mechanical properties and wear behavior of HCWIs [1,2]. For example, the appearance of large and coarse M_7C_3 carbides is detrimental to wear and mechanical properties of HCWIs. Hence, controlling the microstructure allows for an improvement in the performance of HCWIs.

Many methods, such as rapid cooling [3,4], heat treatment [5–8], semi-solid processing [9], alloying additions [10–17], and second carbide precipitation [18,19], have been adopted to get finer carbides in ferrous based alloys. Among them, alloying additions (such as Si, B, Ti, Mo, W, and rare-earth elements) have been extensively used to modify microstructure and improve properties of HCWIs [10–17]. It was found that wear resistance may be

* Corresponding author.
E-mail address: shbli1@bjtu.edu.cn (S. Li).

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increased by increasing precipitated secondary carbide contents in the alloys, however, with some sacrifice of toughness. Incorporation of ceramic reinforcements including oxides (Al_2O_3, ZrO_2), nitrides (TiN, Si_3N_4), and carbides (TiC, ZrC) in ferrous alloys has been proved to be an effective way to offer hardness and toughness.

Among the ceramic reinforcements, TiC is one of the most effective reinforcements for improving properties due to its high hardness and thermodynamic stability in ferrous alloys. The mechanical properties and wear resistance of TiC-reinforced ferrous composites have been improved [20–23]. Powder metallurgy (PM) has been always adopted to produce the TiC-reinforced ferrous composites. The PM prepares the composites with a wide range of TiC reinforcement content and size, and also ensures a homogeneous distribution of TiC in the matrix. However, the direct incorporation of TiC in the ferrous matrix may introduce weak interfaces between TiC and the matrix because gas adsorption or oxidation on the surface of TiC particles affects the wettability of TiC with the ferrous matrix. In addition, there is little information on whether the incorporated TiC can refine the M_7C_3 carbide structure in the powder metallurgically processed HCWIs [20–23].

In contrast to the direct incorporation of TiC, in situ formation of TiC in the ferrous based composites exhibits the following advantages: the in situ formed TiC is finer, more uniform in size distribution in the metal matrix, able to refine the microstructure of matrix, and has a good wettability with the ferrous matrix thus leading to stronger bonding interfaces. The in situ formed TiC is generally from the reaction of Ti and C [20,24–30] and the decomposition of ternary carbides, such as Ti_3AlC_2, Ti_3SiC_2 and Ti_2AlC [31–35]. Our previous work shows that the in situ formed nonstoichiometric TiC_x from the decomposition of Ti_3AlC_2, Ti_3SiC_2 and Ti_2AlC has effectively reinforced metal matrices [33–35]. The in-situ formed TiC_x grains with submicron sizes not only have a good wettability with metal matrices, but also lead to a finer microstructure in metal based composites.

Recently, we have modified the coarse microstructure of a high chromium white iron by in situ formed TiC_x from the decomposition of Ti_3AlC_2 [36]. The in situ formed TiC_x grains are round with a size of about 1–2 μm. The small round TiC_x grains effectively inhibited the growth of M_7C_3, leading to a fine M_7C_3 carbide structure. In addition, the TiC_x grains were well dispersed in the HCWI during sintering at 1500 °C for only 5 min. It has been reported that the TiC particle size has an influence on the abrasive wear rate of Fe-based composites produced through the PM technique. Fine TiC particles (5.6–22.5 μm) have better wear resistance than the coarse particles (50–100 μm) [21]. Therefore, the TiC_x-reinforced HCWI composites with a finer microstructure (fine M_7C_3 and TiC_x) are expected to demonstrate superior properties than the already existing HCWI materials.

In the present study, reinforced and modified HCWI composites by in situ formed TiC_x have been prepared by powder metallurgy. To achieve dense composites with a fine M_7C_3 structure and a uniform dispersion of TiC_x, a two-step sintering method was adopted. The mechanical properties and wear resistance of composites were investigated.

2. Experimental procedures

2.1. Preparation of materials

A gas-atomized high Cr white iron (HCWI) powder (−325 mesh, General Research Institute for Nonferrous Metals, China) and a Ti_3AlC_2 powder were used as starting materials. The gas-atomized HCWI powder contains 26 wt % Cr, 3.0 wt % C, 2.2 wt % Mo, 2.2 wt % V, 1.5 wt % Si and 1.4 wt % Nb and Fe being balance, determined by EDS. The Ti_3AlC_2 powder was prepared in our laboratory. Briefly, Ti, Al and C powders with a molar ratio of Ti:Al:C = 3:1.1:2 were mixed for 10 h and then cold-pressed in a stainless steel mold to form $\Phi 50 \times 5\ mm^2$ compacts. The compacts were pressurelessly sintered at 1450 °C for 1 h in Ar. The sintered samples were pulverized to a powder and sifted with a 200-mesh sieve. The gas-atomized HCWI particles are spherical and less than 45 μm in size, and the Ti_3AlC_2 particles with irregular shapes are less than 45 μm in size [36]. The Ti_3AlC_2 powder with weight fractions of 5%, 10%, 15%, 20% and 25% were respectively mixed with the HCWI powder in polypropylene jars for 10 h by a rotary drum type ball-miller with a speed of 150 rpm.

To obtain dense composites, we used a two-step sintering method. Our previous work demonstrated that the in situ formed TiC_x grains from Ti_3AlC_2 decomposition could be dispersed after sintering at 1500 °C for only 5 min [36]. In addition, a liquid appears at about 1206 °C in the Ti_3AlC_2-HCWI system [36]. Hence the above mixtures were first pressurelessly sintered at 1500 °C for 5 min to disperse TiC_x in the matrix, and then hot-pressed at 1200 °C under 20 MPa for 1 h in Ar to avoid the loss of liquid and further densify the composite. If Ti_3AlC_2 completely decomposed into TiC_x (x = 0.67), the weight fractions of TiC_x in the HCWI composites were 4.3 wt %, 8.6 wt %, 17.2 wt %, and 22.3 wt %, respectively. Herein the composites are denoted as 4.3 wt % TiC_x/HCWI, 8.6 wt % TiC_x/HCWI, 17.2 wt % TiC_x/HCWI, and 22.3 wt % TiC_x/HCWI, respectively. For comparison, the unreinforced HCWI material was also prepared under the same conditions as for the composites. To investigate the effect of sintering conditions on the microstructure of the composites, the 17.2 wt % TiC_x/HCWI samples were prepared by pressurelessly sintering at 1500 °C for 5 min and then at 1200 °C for 1 h, and directly hot-pressed at 1200 °C under 20 MPa for 1 h in Ar, respectively.

2.2. Mechanical property and wear resistance tests

The flexural strength of 3 mm × 4 mm × 36 mm bars was measured by the three-point bending test using a WDW-100E compression tester. The span size and crosshead speed were 30 mm and 0.5 mm/min, respectively. The fracture toughness of 2 mm × 4 mm × 24 mm bars was measured by the single edge notched beam test in the same tester. The notch width was 0.1 mm. The span size and the crosshead speed were 20 mm and 0.05 mm/min, respectively. Rockwell C hardness (HRC) test was performed in a HR-150DT hardness tester with a load of 150 kg and a diamond cone indenter. Six measurements in different areas were taken for each sample. Each reported hardness is an average of six measurements.

Wear tests were performed on a pin-on-disc wear testing apparatus (Fig. 1). Specimens as the pin with a size of $6 \times 6 \times 8\ mm^3$ were ground against a YG8 alloy disk 48 mm in diameter. The YG8 alloy is mainly composed of 92 wt %WC and has a measured hardness of HRC75. A specimen with a known weight was pressed with a load of 123 N against the YG8 disk, which was rotating at a speed of 300 rpm. The test was run for 30 min and the wear distance was about 1 km. Each wear test was repeated at least 3 times. After testing, the specimens were weighed using a digital scale with an accuracy of 0.1 mg to determine the weight loss. Equation (1) was used to calculate wear resistance (WR) of the specimens.

$$\mathrm{WR}\left(\mathrm{cm}^{-3}\right) = \Delta \mathrm{V}^{-1} = \rho/\Delta \mathrm{m} \quad (1)$$

where ΔV is the volume loss (cm^3), ρ (g/cm^3) is the density, and Δm (g) is the weight loss of the material.