Materials and Design 54 (2014) 564–569

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Microstructure and abrasive wear characteristics of in situ vanadium carbide particulate-reinforced iron matrix composites

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ARTICLE INFO

Article history:
Received 4 May 2013
Accepted 28 August 2013
Available online 3 September 2013

Keywords:
Composites
Casting
Wear

ABSTRACT

In this work, in situ synthesis with infiltration casting and subsequent heat treatment was applied to fabricate vanadium carbide (V_8C_7) particulate-reinforced iron matrix composites. The microstructure and wear-resistance of V_8C_7 particulate-reinforced iron matrix composites with different volume fraction were studied using scanning electron microscopy, X-ray diffraction, and wear testing. The V_8C_7 particles were uniformly distributed in the matrix, and the size of the V_8C_7 reinforcement was 2–12 μm. The relative wear resistance of the composites initially increases decreases with higher V_8C_7 volume fractions. The best wear resistance of the composites was 21.2 times higher than that of gray cast iron under a 20 N load. This was achieved at 24% V_8C_7 volume fraction. Wear of the composites manifests as grooves, broken carbide particles, and re-embedment of wear debris.

1. Introduction

Particulate-reinforced iron matrix composites are widely used in fields where high hardness, good strength, high wear resistance and temperature resistance are required [1,2]. These composites are increasingly being studied. Their superior performance and low cost are responsible for their extensive industrial applications. Vanadium is an element that has strong affinity for carbon. Vanadium carbide, which has a high melting temperature (2830 °C) is easily produced in the matrix through several methods. Vanadium carbide also has high microstructure hardness (2460–3150 $HV_{0.05}$), making it suitable for the reinforced phase of wear-resistant materials [3]. It significantly improves abrasion performance [4]. Most importantly, this material has a low standard free energy of formation and better wettability. It forms a small contact angle ($\theta = 28°$) with the iron matrix [5]. Therefore, V_8C_7 is a suitable reinforcement for iron matrix composites.

Many methods for preparing V_8C_7 particle-reinforced iron matrix composites, such as powder metallurgy [6,7], laser cladding [8], spark-plasma sintering [9], and cast sintering [10–12] have been reported. Vanadium carbide dispersions are generated in situ in liquid steel alloys. Carbide volume fractions of up to 14%, with carbide particle sizes of 3–10 μm produced in situ through powder metallurgy were reported [13]. Nurminen et al. [14] prepared V_8C_7 coatings for metal matrix composites by laser coating methods using different matrices such as metallic tool steel M2, Stellite 21, and NiCrBSi-alloy. The vanadium carbide particles were 5–20 μm in size and many secondary carbides of smaller particle size formed between the primary injected carbides. An iron-based surface composite reinforced with V_8C_7 particles was produced by a metal-coated casting technique, and the volume fraction of V_8C_7 particles reached 39, % and particle sizes were 1–3 μm [15]. These results show that an in situ synthesis route is favorable for preparing iron-based composites reinforced by vanadium carbide particles. However, these results were obtained using combined methods, i.e. in situ with powder metallurgy, in situ with laser cladding, and in situ with cast sintering, which had the advantages of perfect surface quality and high precision in the final products. The in situ powder metallurgy method is based on the addition of V_8C_7 reinforcements to the matrix prepared separately prior to the composite fabrication. Due to the density difference between the matrix and the vanadium carbide reinforcement, particle segregation of reinforcement from the matrix is likely to be uneven if casting technologies are used. In addition, the volume fraction of reinforcement is limited because the fluidity of the matrix is reduced at high reinforcement levels.

The present work explains a method of producing V_8C_7 reinforcement in an iron matrix by an in situ technique with an infiltration casting process and subsequent heat treatment, which has been used elsewhere by authors [16]. The route involves a chemical reaction that results in the formation of V_8C_7 within a gray cast iron matrix. The reinforcement formed in situ is thermodynamically stable and the reinforcement-matrix interfaces are

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http://dx.doi.org/10.1016/j.matdes.2013.08.097

clean, resulting in strong interfacial bonding. The reinforcing particles are also finer compared with those produced by previous methods. The synthesis and microstructural characterization of a vanadium carbide-reinforced iron composite, and the influence of V_8C_7 volume fraction on the abrasive wear characteristics and wear mechanism of the composite were studied.

2. Materials and methodology

2.1. Materials

The starting materials were gray cast iron and vanadium wire (⌀1 mm) with 99.99% purity. These were used as the carbon and vanadium sources, respectively, for the in situ synthesis of V_8C_7 within the iron matrix. The chemical composition (wt.%) of other elements in the gray cast iron is 4.20% C, 1.26% Si, 1.28% Mn, 0.104% P, and 0.102% S.

3. Experimental procedure

The gray cast iron mold was fabricated into a rectangular shape, as shown in Fig. 1a. A number of holes were inversely drilled (⌀1 mm) on both sides. Various distances were specified between holes. The vanadium wires were passed through the holes on both sides and then firmly fixed to the mold (Fig. 1b). The iron mold was then inserted into the graphite mold (Fig. 1c). All dimensions of the mold are indicated in Fig. 1. Molten gray cast iron was produced in a medium-frequency induction furnace and poured into the mold at 1430 °C. The specimen was immediately covered with quartz sand to avoid crack generation, and was cooled down to room temperature. It was then cut to a size of 10 mm × 10 mm × 25 mm using a numerically controlled wire-cut EDM machine (Suzhou Nutac Electro Mechanic Co. Ltd., China).

The prepared samples were subjected to heat treatment at 1164 °C for 3 h in a horizontal tube furnace (GSL 1400, Hefei Kejing Materials Technology Co. Ltd., China). The processing was done under argon supplied at medium flow. After treatment, the samples were air cooled to room temperature. Samples of various carbide volume fractions were prepared by changing the spacing between the holes. Four spacing lengths between holes (D, in Fig. 1b) were used, namely, 4.5, 3.5, 2.5, and 1.5 mm, marked C1, C2, C3, and C4, respectively.

After polishing with diamond paste and etching with 4% Nital, the microstructure of the specimens was examined using a JSM-5800 scanning electron microscope (JEOL, Japan) equipped with an energy dispersive X-ray spectrometer (EDS). The X-ray diffraction (XRD) data were recorded in the 2θ range of 10–90° on a PW 1730 X-ray diffractometer (Philips, The Netherlands) with monochromatic CuKα radiation at 40 kV and 40 mA. The microhardness of the specimens are measured according to ASTM: E384-11e1, which is the standard test method for Knoop and Vickers Hardness of materials. Using an HDX-1000 digital microhardness tester (Shanghai Shuangxu Electronic Co. Ltd., China), which consisted of a square-based pyramidal diamond indenter with a 136° angle between the two opposite faces. The static load was 50 g and the dwell time of loading was 15 s. The macrohardness of the specimens were measured according to ASTM: E18-12, which is standard test methods for Rockwell Hardness of metallic materials. The macrohardness of samples were measured using an HRS-150 digital Rockwell hardness tester (Shanghai Shuangxu Electronic Co. Ltd., China). An average value of hardness was taken from at least five different measurements.

3.1. Abrasive wear test

The abrasive wear resistance were tested according to JB/T7506-1994 [17], which is the Mechanical Industry Standard of China. The specimen was cut to the size of ⌀6 × 25 mm for the abrasive wear test. The test was carried out on an ML-100 wear test machine (Zhangjiakou Xuan Ke Testing Machine Manufacturing Co. Ltd., China). Abrasion tests were carried out using a pin-on-disc

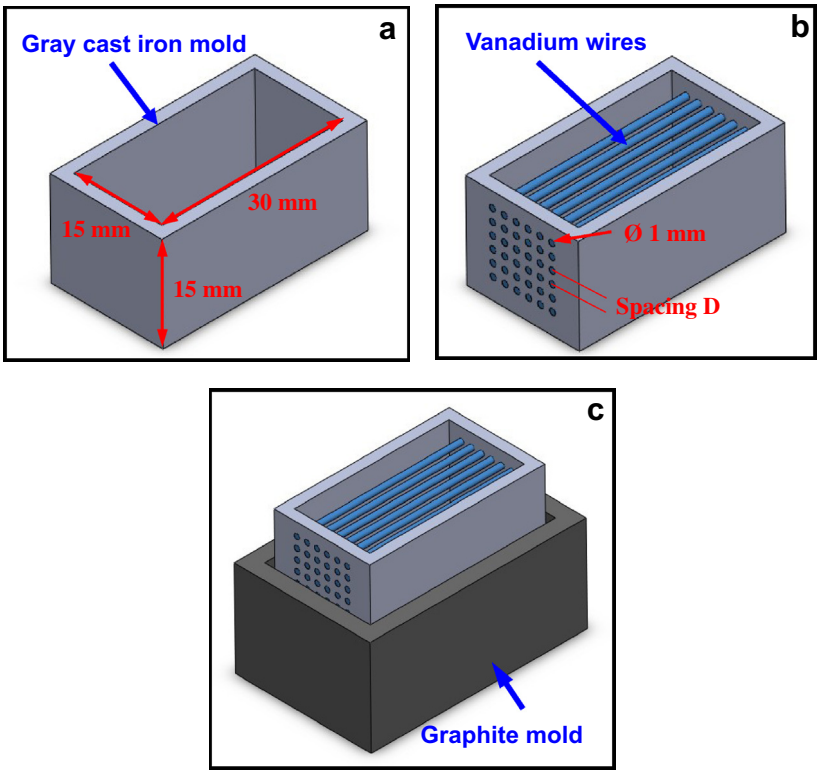

Fig. 1. 3D image of (a) the gray cast iron mold, (b) the preform, and (c) the graphite mold used in the experiment.