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Fabrication, microstructure and abrasive wear characteristics of an in situ tantalum carbide ceramic gradient composite

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Abstract

A tantalum carbide (TaC) ceramic gradient composite was produced on the surface of an iron matrix by an in situ technique comprising a casting process and a subsequent heat treatment. In this study, the phase constituents, microstructure, microhardness, and wear resistance of the gradient composite were analysed by X-ray diffraction (XRD), scanning electron microscopy (SEM) and transmission electron microscopy (TEM), a Vickers hardness tester, and a wear resistance tester, respectively. The results showed that the gradient composite can be divided into three zones according to the variation in the volume fraction of TaC ceramic particulates, which can be labelled as follows: micro-nanostructure TaC ceramic dense layer, micro-structure TaC ceramic layer and TaC ceramic particulate composite layer, where the combination between the gradient composite and matrix present a perfect metallurgical bond. The mean micro-hardness of the TaC ceramic gradient composite gradually decreased from the upper surface to the matrix due to the TaC ceramic particulates growing larger and their volume fraction gradually decreasing in different reaction zones.

The microhardness of the micro-nanostructure TaC ceramic dense layer was the highest (2028 $HV_{0.1}$), and the average size of the TaC particulates in this layer was less than 200 nm, with a volume fraction of more than 95%. In addition, the relative wear resistance gradually increased from the matrix to the surface. The wear mechanism of zone [A] was mainly characterised by plastic deformation and a few microcracks, while zones [B] and [C] experienced a combination of micro-ploughing with some TaC particulates broken. zone [C] was also characterised by squeeze traces because of the increased matrix. On the whole, the surface TaC ceramic gradient composite effectively protected the iron matrix from serious abrasion.

Keywords: B. Composites; C. Wear resistance; D. Carbides; E. Structural applications

1. Introduction

Gradient composites are materials with a variation of microstructure and composition along their thickness. A spatial variation in the composition is introduced during the fabrication to achieve the desired gradient in the material properties [1]. In comparison with conventional homogeneous composite materials, gradient composites can provide a number of distinct advantages [2–3], such as a smoother stress distribution, reduced stress concentrations, elimination of stress singularities and greatly improved bond strength and fracture toughness. It is well known that damage and failure occur mainly on the surface of materials, and body enhancement is wasteful, expensive, and complicated. Surface enhancement could achieve excellent surface performance and good toughness of the matrix at the same time. Surface gradient composites present continuous or step-by-step changes in the

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microstructure and characteristics from the surface to the matrix, so they can generally avoid undesirable effects due to sudden changes in properties [4].

Gradient composites have successfully been utilised to produce thermal barrier coatings, gas turbine blades and chemical reaction vessels [5–7]. In all of these applications, the satisfactory performance of the gradient composites depends on the processing strategies adopted and the resulting microstructure. In recent years, gradient composites have been produced by various processing techniques such as laser cladding [8–9], plasma spraying [10–11], magnetron sputtering [12–13], powder metallurgy [14], and centrifugal casting [15]. However, most of them are secondary processes on the moulding surface, so various shortcomings limit their application, such as excessive energy consumption, severe deformation, and inferior metallurgical combination. These limit the improvement in performance of the work piece. In situ synthesis technology is considered the most promising method for the preparation of surface gradient composite materials. Its prominent advantages include that (1) the type, size, distribution and quantity of the reinforcement phase are controllable; (2) the interface bonding between the reinforcement phase and matrix forms a perfect metallurgical combination; and (3) the preparation process is low-cost and simple.

TaC is an important carbide ceramic material used widely in cutting tools. It is an abrasive substance that possesses a high melting point (3980 °C), high hardness, low thermal expansion, moderately low thermal conductivity (22 W/(m K)), good oxidation resistance [16], and outstanding wettability with molten iron. On the basis of the above-mentioned advantages, tantalum carbide is regarded as an excellent candidate for reinforcing wear-resistant composite materials and providing improved abrasion performance [17–19]. To study the microstructures and mechanical properties of the TaC coating, Xiong et al. [20] fabricated a new set of C/C composites in which the carbon fibre is reinforced by the tantalum carbide coating via a combination of chemical vapour infiltration with impregnation/carbonization of a thermosetting phenolic resin. Because the thickness of the TaC coating is only ~0.7 μm and thermal stress is induced by the mismatch coefficient of the cubical thermal expansion between the C and the TaC ceramic, internal flaws are generated that weaken the mechanical properties. Chao et al. [21]developed a TaC/Ni60 composite coating prepared by laser cladding on a steel A3 substrate and investigated the microstructure, metallography, microhardness and wear resistance of the coatings, indicating that the coating possesses a good wear resistance (high average hardness of $HV_{0.3}$ 1100) that is four times that of a pure Ni60 coating.

However, to our knowledge, there has been no report of a TaC ceramic gradient composite. Therefore, in the present study, the feasibility of the in situ reactive synthesis of a TaC ceramic reinforced iron matrix composite with a gradient distribution was investigated. This method of an in situ casting process and subsequent heat treatment will provide a new and promising process for the production of a gradient composite on the surface of an iron matrix because of its inherent simplicity and potential cost-effectiveness in scaling up for manufacture. The microstructures and mechanical properties of the TaC ceramic gradient composite fabricated by this method will be characterised, and the formation mechanism of the TaC ceramic gradient composite will be discussed.

2. Experimental

2.1. Preparation

For the fabrication of the TaC ceramic gradient composite, grey cast iron and a tantalum plate (with thicknesses of approximately 1 mm and purities of 99.9%) were employed as the carbon and tantalum sources, respectively. The chemical composition (wt%) of grey cast iron is Fe–2.57C–1.04Mn–1.03Si–0.046P–0.018S.

The TaC ceramic gradient composite was prepared by an infiltration casting in situ process. The experimental process is shown in Fig. 1 and described as follows. First, a tantalum plate was placed at the bottom of a graphite crucible. The grey cast iron was then melted in a medium-frequency induction furnace at 1430 °C and cast into the crucible. The sample was immediately covered with quartz sand to avoid crack generation and cooled down to room temperature. Finally, the prepared sample was taken out of the graphite mould and cut to a size of 10 mm × 10 mm × 15 mm using a numerically controlled wire-cut electron discharge machining apparatus (Suzhou Nutac Electro Mechanic Co. Ltd., China). Previous research reported [22] that TaC ceramic gradient composites had been successfully prepared by in situ synthesis with subsequent heat treatment at 1172 °C for 40 min.

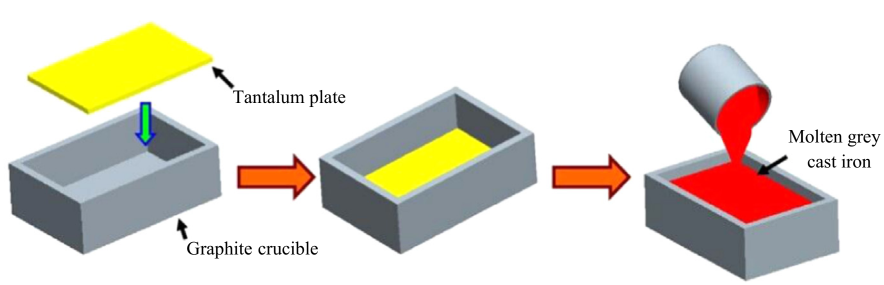

Fig. 1. Schematic illustration of the casting process.