Journal of Asian Ceramic Societies 1 (2013) 339–345

Contents lists available at ScienceDirect

Journal of Asian Ceramic Societies

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

# Fabrication of bionic composite material using self-propagating high-temperature synthesis in the Cu–Ti–$B_4C$ system during steel casting

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ARTICLE INFO

*Article history:*
Received 22 August 2013
Received in revised form 18 October 2013
Accepted 21 October 2013
Available online 13 November 2013

*Keywords:*
Bionic composite material
Ceramic
Self-propagating high-temperature synthesis
TiC–$TiB_2$
Wear

ABSTRACT

Enlightened by the nacreous layer of shell, this study successfully fabricated the bionic composite material using self-propagating high-temperature synthesis (SHS) reaction in the 40 wt.% Cu–Ti–$B_4C$ system during manganese steel casting. The phase constituents, microstructures and wear resistance of the bionic composite material were investigated. The results show that bionic composite material was alternant combination of manganese steel matrix and unit region in a relatively large dimension. Excellent metallurgy bonding between the unit region and steel matrix in the bionic composite material was presented. The results analyzed with X-ray diffraction (XRD) reveal the existence of TiC, $TiB_2$, Cu and austenite without any intermediate phases in the unit region. Due to sufficient infiltration of the melted steel, the unit region had the fewest macro-pores and blowholes. This indicates that the near fully dense bionic composite material can be fabricated. The wear tests show that the wear resistance of the bionic composite material fabricated was better than that of the pure manganese steel.



## 1. Introduction

During the construction of national economy and military defense, equipment efficiency can be decreased caused by the consumption of energy and wear of materials. For example, the medium austenite manganese steel that is usually used in the engineering equipments possesses better wear resistance under the low stress abrasive wear condition [1]. However, the wear resistance of medium austenite manganese steel under high stress abrasive condition needs to be improved. In many research fields, more and more attentions have been paid to and focused on the abrasion, which is one of the most significant technology problems that might be solved in a long time. Many technical problems in engineering can be resolved using the concepts of bionics [2–7]. Through learning and imitating the wear phenomenon of the animals and plants, human can explore methods to solve many wear problems that human are facing for the technology development currently [8–10].

Lots of biological organisms are living in wear environment in the natural world. They gradually acquire exceptional wear resistance through the synergic actions of morphology, structure and material in the surfaces of organism. These organisms, such as dung beetle, desert lizard, pangolins and intertidal shellfish, have excellent wear-resistant function [11–14] which can help them to survive against the wear environments. For the nacreous layer of shell, for instance, 95 percent of its compositions are brittle calcium carbonate, and the rest are organic matter mainly including protein [15]. Neither of these two kinds of compositions has high strength and good wear resistance. However, they couple with each other in the "brick-mud" form of alternate arrangement of overlapping as a composite. In this form, the rupture toughness is 3000 times higher than that of the single calcium carbonate resulting excellent wear resistance of nacreous layer [15]. With perfect and special structures naturally selected through zillion years of evolution in shell, the materials of nacreous layer possess unsurpassable advanced performance in comparison to man-made materials.

Self-propagating high-temperature synthesis (SHS) has been widely utilized to produce a variety of materials including ceramics, ceramic–metal composites, intermetallics [16–18]. The SHS process is related to the capability of highly exothermic chemical reactions to self-sustain after ignition, which is carried out by a local energy input at one of the ends of the sample [19,20]. Thereafter, the exothermic character of the reaction provides the energy required for its completion in the whole sample. The prominent

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Peer review under responsibility of The Ceramic Society of Japan and the Korean Ceramic Society.

Production and hosting by Elsevier

2187-0764 
http://dx.doi.org/10.1016/j.jascer.2013.10.004

**Table 1**
The main composition of manganese steel (wt.%).

| Mn | C | Si | S | Ni | P | Fe |
|---|---|---|---|---|---|---|
| 8.30 | 0.45 | 0.42 | <0.01 | <0.02 | <0.06 | Bal. |

advantages of this technique are its low cost, high energy efficiency, easy operation, and high purity of the reaction products. Therefore, SHS and traditional casting routes provide an easy process to produce ceramic–metal composites [21]. It combines the advantages of the SHS reaction in the casting process.

Enlightened by the fine wear-resistant characteristic of nacreous layer, the idea of forming a similar structure on the steel surface to improve the wear property was suggested. According to the principles of bionics, the nacreous layer of shell was abstracted to apply on the composite structure with characteristic of alternately soft and hard. Then, the composite was successfully fabricated using SHS reaction in the 40 wt.% Cu–Ti–$B_4C$ system during the casting of austenite manganese steel. Austenite manganese steel has excellent strength and toughness, while its wear resistance is poor [22]. $TiB_2$ and TiC ceramic particles reinforced metal matrix composites have higher strength and wear resistance due to the high resistance of ceramic phases to abrasive wear [23,24,17]. In this study, the bionic composite material was a combination of manganese steel region (matrix, soft) and $TiB_2$/TiC ceramic particles reinforced manganese steel matrix region (unit, hard). The phase constituents, microstructures and wear resistance of the bionic composite material were investigated. It is expected that the preliminary results could promote the development and practical application of the bionic composite material, and further offer a new technique and method to increase the wear resistance of the austenite manganese steel. The method of combining SHS reaction and casting routes provides a new and promising process for the production of bionic composite material, since it is significant in inherent simplicity and potential cost-effectiveness for scale-up manufacturing.

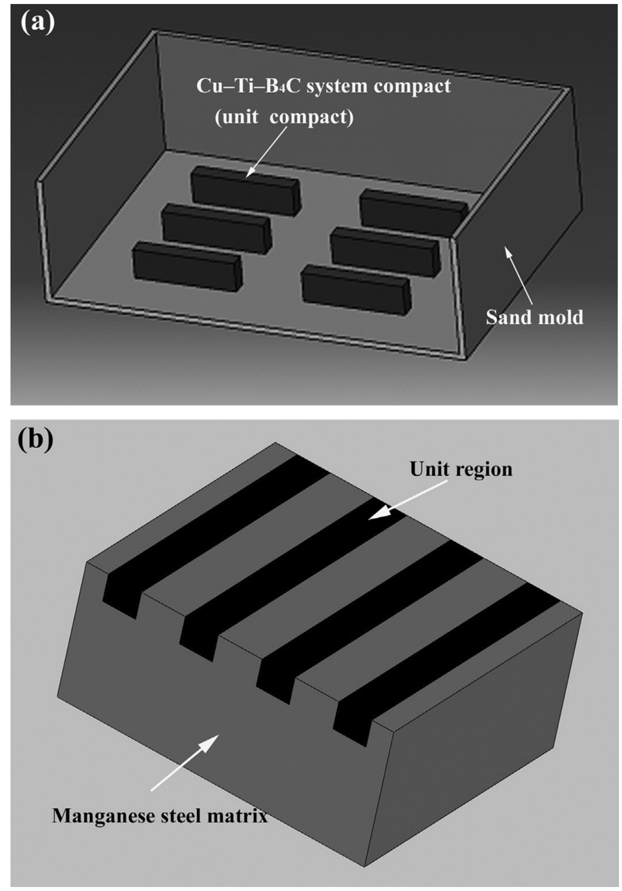


**Fig. 1.** (a) Schematic diagram of the unit compacts located in the sand mold; and (b) schematic diagram of the bionic composite material casting.

## 2. Experimental design

The Cu–Ti–$B_4C$ system was made from commercial powders of Cu (99.5%, ~45 μm), Ti (99.5%, ~38 μm) and $B_4C$ (99.9%, ~3.5 μm). The Ti and $B_4C$ powders with a ratio corresponding to that of stoichiometric $2TiB_2$–TiC were mixed with 40 wt.% Cu and used for the powder blends. The powder blends were mixed sufficiently by ball milling for 8 h and then filled into a rectangular bar (30 mm × 12 mm × 20 mm) where the theoretical density of 65 ± 2% was obtained for the powder blends. The austenite manganese steel was selected as the matrix materials, of which the composition was listed in Table 1. The manganese steel was melted in an induction furnace with 5 kg medium-frequency in air environment. After being dried in a vacuum oven at about 300 °C for 3 h to completely remove moisture, the Cu–Ti–$B_4C$ system compacts were placed on the bottom of the sand mold as illustrated in Fig. 1a. The space between two adjacent compacts was about 15 mm. Subsequently, the melted steel with temperature of about 1500 °C was poured into the sand mold to ignite the SHS reactions of these compacts. After solidification and cooling, the bionic composite material casting was formed and removed from the sand mold as shown in Fig. 1b.

Due to the high combustion temperature and extremely fast SHS reaction of the Cu–Ti–$B_4C$ system in the liquid steel, the knowledge of microscopic reaction behavior involved in these processes is still quite limited. Thus, the SHS experiments were firstly conducted in a self-made vacuum vessel filled with Ar at 1 atm. In order to obtain some guidance to understand the fabrication, the unit region in the bionic composite material was investigated. The Cu–Ti–$B_4C$ system compacts were ignited on the graphite flat which was placed at the top of tungsten electrode and heated by the heat of arc. A small hole (2 mm in diameter and 2 mm in depth) was drilled at the top of the compact. A thermocouple pair of W/Re5-W/Re26 (0.5 mm in diameter) was inserted into the hole and connected with a temperature acquisition system which can record the temperature over time. The current in this experiment was selected as 90 A. More details about the experimental apparatus and procedure for the SHS reaction were given in the previous paper [25]. In addition, the ignition process of the reactions in the Cu–Ti–$B_4C$ system was also studied using the differential thermal analysis (DTA, Rigaku-8150, Japan) experiments. The experiments were conducted in the argon gas with flow rate of 60 ml/min heated by 40 °C/min.

The wear experiments were conducted using a pin-on-disk machine with an applied load of 35 N. The commercial SiC abrasive papers with abrasive particle size of ~20 μm (600 grit) were used as the counterface. The wear weight loss was measured by an analytical balance with a sensitivity of 0.0001 g. In addition, the microstructures of the bionic composite material were examined using scanning electron microscopy (SEM) (Model JSM-5310, Japan) together with energy-dispersive spectrometry (EDS) (Model Link-Isis, Britain). The phases were identified using X-ray diffraction (XRD) (Model D/Max 2500PC Rigaku, Japan).