Materials Chemistry and Physics 132 (2012) 51–62

Contents lists available at SciVerse ScienceDirect

Materials Chemistry and Physics

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

The mechanism of thermal explosion (TE) synthesis of TiC–TiB_2 particulate locally reinforced steel matrix composites from an Al–Ti–B_4C system via a TE-casting route

Binglin Zou [a,b,**], Ping Shen [a], Xueqiang Cao [b], Qichuan Jiang [a,*]

[a] Key Laboratory of Automobile Materials, Department of Materials Science and Engineering, Jilin University, No. 5988 Renmin Street, Changchun, 130025, Jilin, China
[b] State Key Laboratory of Rare Earth Resource Utilization, Changchun Institute of Applied Chemistry, Chinese Academy of Science, Changchun, 130022, Jilin, China

ARTICLE INFO

Article history:
Received 15 May 2011
Received in revised form
11 September 2011
Accepted 31 October 2011

Keywords:
Steel matrix composites
Borides
Carbides
Thermal explosion (TE)
Mechanism

ABSTRACT

TiC–TiB_2 particulate locally reinforced steel matrix composites were fabricated by a novel TE-casting route from an Al–Ti–B_4C system with various B_4C particle sizes. The formation mechanism of TiC and TiB_2 in the locally reinforced regions was investigated. The results showed that TiC and TiB_2 are formed and precipitated from Al–Ti–B–C melt resulting from the dissociation of B_4C into Al–Ti melt when the concentrations of B and C atoms in the Al–Ti–B–C melt become saturated. However, in the case of coarse B_4C powders ($\geq$40 μm) used, the primary reaction in the Al–Ti–B–C melt is quite limited due to the poor dissociation of B_4C. The poured steel melt infiltrates into the primary reaction product and thus leads to the formation of Al–Fe–Ti–B–C melt, thanks to the favorable reaction of molten Fe with remnant B_4C, and then TiC and TiB_2 are further formed and precipitated from the saturated Al–Fe–Ti–B–C melt. The relationship between the mechanisms of thermal explosion (TE) synthesis of TiC and TiB_2 in the electric resistance furnace and during casting was proposed.

1. Introduction

Steel is the most widely used metallic structural material in industry. However, for various applications, the wear resistant parts require steel to possess superior hardness and wear resistance. The incorporation of ceramic particulates into steel matrix can improve the hardness and the wear resistance in various ways [1,2]. Therefore, steel matrix composites (SMCs) with ceramic particulate reinforcement, which combine the toughness of metal and the hardness of ceramic, have been the subject of intensive investigation.

Combustion synthesis (CS) provides an attractive alternative to produce in situ ceramic particulate reinforced SMCs compared to other methods such as conventional melting and casting [3], powder metallurgy [3] and reactive sintering [4,5], since it offers advantages with respect to simplicity, economy and high efficiency. CS reaction is highly exothermic in nature, and if the reaction is ignited it can become self-sustaining. CS has two modes of self-propagating high-temperature synthesis (SHS) and thermal explosion (TE), which are, respectively, ignited by heating one end of the reactant compact and the whole reactant compact [6]. TiC and TiB_2 are expected to be the best reinforcements for SMCs due to their high hardness, high modulus of elasticity, excellent wear resistance and good wettability and relative stability with steel matrix. During the past, combustion synthesis of TiC and/or TiB_2 particulate reinforced SMCs, which is characterized by low level of interface contamination, fine particle size and uniform distribution of the reinforcements, has been widely studied [7–15]. For example, Capaldi et al. [7] investigated the combustion synthesis of TiC–Fe composites by SHS and TE modes from a Fe–Ti–C system, and they found that the morphology of the products is similar in both reaction modes and the formation of TiC is thought to precipitate from Fe–Ti–C liquid phase that is formed by the diffusion of C into Fe–$FeTi_2$ eutectic. Lepakova et al. [10] reported the mechanism of phase and structure formation of the Fe–Ti–B system in SHS mode. The results showed that the contact eutectics play a significant role in the structure of the products and the composition of eutectic melts is determined by the type of contact between the initial reagents.

However, TiC and/or TiB_2 particulate reinforced SMCs prepared by CS are normally too porous to find applications as advanced structural materials. Therefore, CS must be combined with a densification step, such as hot-pressing, extrusion, quasi-isostatic pressing and shock-wave compaction [16]. Unfortunately, such techniques are too expensive or complex to be accepted by the

* Corresponding author. Tel.: +86 431 8509 4699; fax: +86 431 8509 4699.
** Corresponding author at: State Key Laboratory of Rare Earth Resource Utilization, Changchun Institute of Applied Chemistry, Chinese Academy of Science, Changchun, 130022, Jilin, China. Tel.: +86 431 85262910; fax: +86 431 8526 2285.
E-mail addresses: zoubinglin@ciac.jl.cn (B. Zou), jqc@jlu.edu.cn (Q. Jiang).

0254-0584/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.matchemphys.2011.10.051

engineering community for general application. On the other hand, the particulate reinforced SMCs fabricated by CS are generally monolithic composites, i.e., the ceramic reinforcement is evenly distributed in the entire body of the composites. From the point of view of the application, the service life of component usually relies on the wear resistance of local region, and it is desirable that the local region of component rather than the whole component is reinforced by ceramic particulate to offer high-wear resistance. Therefore, it is a big challenge for CS to prepare in situ particulate locally reinforced SMCs with dense structure. Up to date, several techniques such as cast-sintering [17–19], reactive sintering [20], laser cladding [21,22], plasma spray [23] and gas tungsten arc welding melting process [24] have been developed to produce high hardness and wear resistance film or coating on the steel substrate. However, the thickness of film and coating is thin and the bonding strength with the steel substrate is generally not so high, leading to a short service life for the surface reinforced SMCs under severe wear conditions. In contrast, the locally reinforced SMCs with controllable volume fraction of reinforced region show more potential application for severe wear conditions. Recently, our group suggested a new route, named as TE-casting in the present study, to fabricate ceramic particulate locally reinforced SMCs, in which CS with TE mode combines with traditional casting technique. The general procedure is that the molten steel is poured into a sand mold where the reactant compacts are preplaced and fixed using locating pins. The whole compact is surrounded by the steel melt and rapidly heated by the high-temperature steel melt, followed by the ignition of TE reaction in the reactant compact to form ceramics. Meanwhile, the steel melt infiltrates into the porosity of reacted compact. Using this method, the ceramic particulate locally reinforced SMCs can be prepared, in which local regions of the casting rather than the entire casting are reinforced by the formed particulates to achieve high wear resistance, while high toughness and strength are retained in the bulk casting, which is different from the monolithic composites [25–31].

Our previous studies have demonstrated the feasibility as well as the microstructure, phase composition and wear resistance of TiC and/or TiB_2 ceramic particulate locally reinforced SMCs from Ni/Fe/Al–Ti–B/C/B_4C systems via the TE-casting route [25–31]. However, the mechanism of TE synthesis of TiC and/or TiB_2 in the locally reinforced region of SMCs has been not well explored so far. The understanding of the mechanism provides a concrete basis for producing the TiC and/or TiB_2 ceramic particulate locally reinforced SMCs with tailored microstructures and properties. In this study, we prepared TiC–TiB_2 particulate locally reinforced SMCs using an Al–Ti–B_4C system with various B_4C particle sizes via TE-casting route and tried to explore the mechanism of TE synthesis of TiC and TiB_2 during casting. Also, the TE reaction product and mechanism in the electric resistance furnace (ERF) were investigated and compared with those during casting, from which the relationship between the mechanisms of TE synthesis of TiC and TiB_2 in the ERF and during casting was proposed. Such knowledge is expected to promote the development of the fabrication of ceramic particulate locally reinforced SMCs by the TE-casting route.

2. Experimental procedure

The starting materials were commercial powders of Al (99% purity, ~29 μm, Northeast Light Alloy Ltd. Co., Harbin, China), Ti (99.5% purity, 38–48 μm, Institute of Nonferrous Metals, Beijing, China) and B_4C (~97% purity, Abrasive Ltd. Co., Dunhua, China). The B_4C powders with particle sizes 2.5–3.5 μm (3.5 μm), 20–28 μm (28 μm), 28–40 μm (40 μm), 63–80 μm (80 μm) and 100–125 μm (125 μm) were used (hereafter the size abbreviation in the brackets was used). The 30 wt.%Al–Ti–B_4C system with mole ratio of 3:1 for Ti to B_4C was investigated in this study. The blended powders were dry-mixed in a stainless-steel container using stainless-steel balls at a low speed (~35 rpm) for 8 h. After mixing, the mixtures were uniaxially pressed into cylindrical compacts of 22 mm in diameter and 15 mm in height at a pressure ~60 MPa with green densities of 65 ± 2% of theoretical, as determined from weight and geometric measurements.

In order to investigate the TE reaction outside the steel melt, the compacts were placed in the ERF, and then the ERF was evacuated and filled with industrial argon at 1 atm. During heating process, the power was turned off when the reaction was initiated. The temperature in the centre of the compacts was measured by a pair of W–5%Re/W–26%Re thermocouples and the signals were recorded and processed by a data acquisition system with a speed of 20 points per second. The synthesized products were ground for their phase compositions by X-ray diffraction (XRD, D/Max 2500PC, Japan) using Cu Kα radiation. Microstructures on the fracture surface of the samples were observed by scanning electron microscopy (SEM, JSM-5310, Japan) equipped with an energy-dispersive X-ray spectrometer (EDS, Link-ISIS, England). In order to simulate the TE process during casting, an attempt was made in the ERF. The compact was surrounded by the 24 wt.%Fe–64 wt.%Al–12 wt.%Fe_2O_3

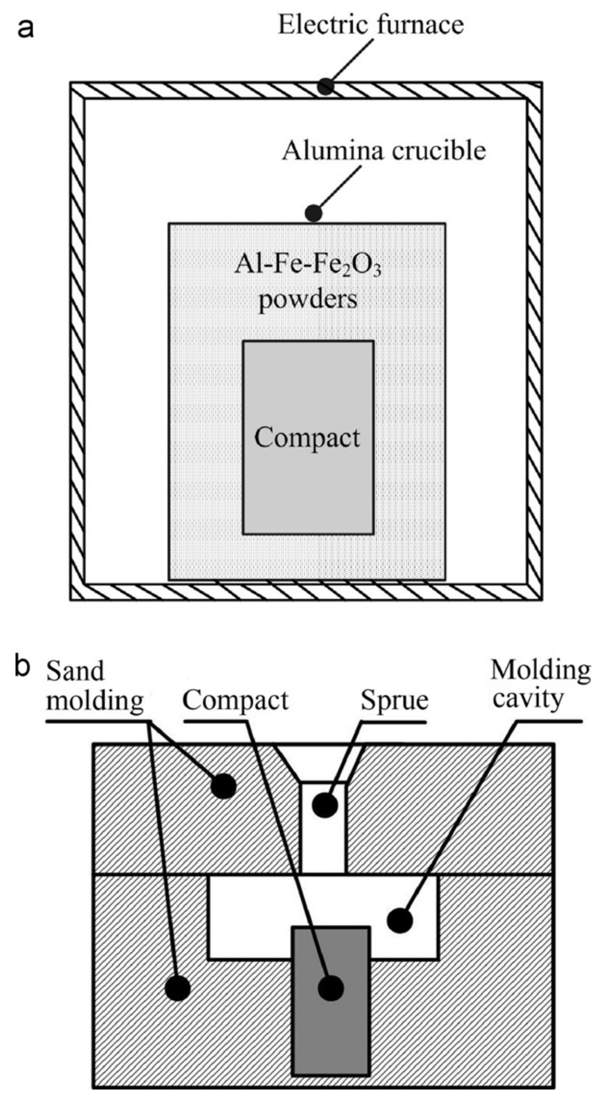

Fig. 1. Schematic settings for (a) simulating the TE reaction during casting via the ERF and (b) quenching TE reaction in the 30 wt.%Al–Ti–B_4C compacts with coarse B_4C powders.