Note

In Situ Production of Locally Reinforced Steel-based Composites with TiC Particulates Using High-frequency Induction Process

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1. Introduction

The incorporation of ceramic reinforcements into metal matrices to produce composite materials with improved properties has been the subject of intensive investigation during the past three decades.¹⁾ Historically, most of the works have been dealing with aluminum and magnesium matrices for applications requiring light weight in combination with high strength and/or stiffness,^{2–4)} but more recently studies using iron- and steel-based matrices have been performed. It is great significance for MMCs to use iron or steel alloys as the matrix materials, since they are the most widely used metallic material with a variety of commercially available steel grades. Additionally, steels have higher stiffness, strength, toughness, low cost compared with light metals, and show good mechanical properties (in the annealed condition), weldability, and some grades offer improved corrosion resistance.^{1,5)} Work by Ramquist has shown that TiC particulates are easily wet by iron at high temperatures, and as time progresses, wetting further improves because of chemical wetting⁶⁾; further more TiC particulate is a very good reinforcement for iron- or steel-based composites with high hardness and thermal stability.⁷⁾ Generally, production routes used to fabricate TiC particulates reinforced iron- or steel-based composites involves powder metallurgy,^{1,8)} aluminothermic reduction,⁹⁾ traditional casting⁷⁾ and self-propagating high-temperature synthesis (SHS),^{8,10,11)} etc.

For the sake of the different needs of engineering structural accessories, the authors classified the iron- or steel-based composites as two groups according to the distribution of the reinforcements: particulates whole^{10,11)} and locally reinforced composites.^{12,13)} The latter is of great promise in the applications of wear resistance conditions. As matrix materials, iron or steel is more suitable for par-

ticulates locally reinforced wear resistance composites, due to their low cost, versatility, adequate mechanical properties,⁵⁾ etc. In the present study, the feasibility of synthesis *in situ* TiC/steel composites utilizing the self-propagating high-temperature synthesis (SHS) route, and the green preforms consisting of Al, ferrotitanium (Ti–Fe) and C powders, ignited by high-frequency induction process was investigated. The purpose is to provide a simpler, faster and more economic way to fabricate particulates locally reinforced composites. This process can be applied to fabricate small-size cutting or wearable tools.

2. Experimental Details

The preforms in this study were made from commercial powders of aluminum (98.0% purity), graphite (99.9% purity) and ferrotitanium (a much cheaper material compares with titanium, and the composition is shown in **Table 1**), and the typical average particulate size less than 75 μm . The Ti and C were at a ratio corresponding to that of stoichiometric TiC. The powders were mixed using a ball-grinding mill for 12 h, and then were uniaxially pressed into cylindrical preforms (12 mm diameter and 5–8 mm length) under pressures from 32–40 MPa to obtain densities $65 \pm 5\%$ theoretical density. The green preforms were dried in a vacuum oven at about 300°C for 1 h to remove the moisture. A medium steel (12 mm diameter and 15 mm length) was selected for the matrix material of the composite, and its composition is shown in Table 1. The scheme of the high-frequency induction process is shown in **Fig. 1**. The process has four major steps associated with it. First, the medium steel was placed into the bottom of the graphite crucible. Second, the preform was inserted into the graphite crucible. Third, the graphite crucible was put into the induction coil of the high-frequency induction stove. Fourth, when the preform was ignited by the induction coil (the particular parameters of the electric current are shown in **Table 2**), the preform was pressed into the steel melt using an Al_2O_3 ceramic stick. The final result is that the TiC particulates locally reinforced steel matrix composites were fabricated.

Fig. 1. Scheme of the high-frequency induction process.

Table 1. Chemical composition (wt%) of ferrotitanium and medium steel used for composite production.

Material	C	Ti	S	P	Si	Al	Mn	Cu	Fe
Ferrotitanium	0.3	65	0.7	0.05	0.7	5	1	0.3	balance
Medium steel	0.476	—	—	—	0.451	—	0.279	—	balance

Table 2. Parameters of the electric current.

$I_{\text{heat up}} = 650\text{A}$	$T_{\text{heat up}} = 40\text{S}$
$I_{\text{heat preservation}} = 500\text{A}$	$T_{\text{heat preservation}} = 20\text{S}$

Fig. 2. Optical micrograph of TiC/Fe composites fabricated using high-frequency induction process.

After solidification and cooling, the metallographic sample was cut, polished and etched with 3 vol% HNO_3 ethanol alcohol solution for 15S. Microstructure and phase analyses of the composite were investigated by using scanning electron microscopy (SEM) (Model SHIMADZA SSX-500, Japan) and X-ray diffraction (XRD) (Model D/Max 2500PC, Rigaku, Japan). Microcosmic hardness was examined using microcosmic hardness apparatus (Model HXD-1000, China), and experimental load was 50 g, as well as holding pressure time was 20 s.

3. Results and Discussion

Figure 2 shows the microstructure of the material by optical microscope. The left dark area is the composite region, and the right area is the medium steel matrix. There is a clear bond-interface between the two parts, as well as the interface shows the good metallurgy-bond between the composite and the medium steel matrix. No obvious macro-pores were generated in the bond-interface region. However, the micro-pores with a size of $\sim 180\ \mu\text{m}$ were detected. Such phenomenon may be explained from the bad air permeability of the graphite crucible and the short SHS reaction time. Because the gases absorbed and resided in the original green preform were not able to vent in such a short time, but gathered near the bond-interface region and reunited into big air bladders. In addition, due to the bad fluid of the master alloy, the steel melt could not infiltrate into it spontaneously, so we must use an Al_2O_3 ceramic stick to push the master alloy into the steel melt. The steel melt was infiltrated in the master alloy by the capillary force and the negative air pressure produced by the solidification after the SHS reaction. The SEM micrographs of the composite region are shown in **Fig. 3**. Nearly spherical TiC particulates with the size of $\sim 5\ \mu\text{m}$ are uniformly dispersed in the matrix, and **Fig. 4** shows the XRD pattern of this region. XRD pattern reveals the composite consists of TiC, AlFe and Fe phases. Lee *et al.*¹⁴⁾ and Saidi *et al.*¹⁵⁾ studied the combustion reaction of Ti–C–Al and Ti–C–Fe system, and reported that TiAl_x ($x=1, 3$) and Ti_2Fe compounds were

Fig. 3. SEM micrograph of composite region. **Fig. 4.** X-ray diffraction pattern of TiC/Fe composites fabricated using high-frequency induction process.

generated firstly before the TiC, and the exothermic reaction may take place as follows:

But in the present system, no any trace of TiAl_x ($x=1, 3$) or Ti_2Fe phase is found in the XRD result, the reaction of (Ti–Fe)–Al–C system may take place as follow two steps: first, Al melt reacts with Fe to form AlFe phase, as well as the reaction emits the exothermic quantity of heat. Second, the quantity of heat produces generating from the reaction and the induction coil directly ignites the reaction between Ti and C to form TiC.

The medium steel matrix composite locally reinforced with in situ TiC particulates synthesized by SHS reaction of (Ti–Fe)–Al–C system are successfully fabricated utilizing high-frequency induction process. The microcosmic hardness value of the composite is significantly higher than that of medium steel matrix (as shown in **Table 3**).

Table 3. Microcosmic hardness of the medium steel matrix and composite locally reinforced with *in situ* TiC particulates.

Materials	Medium steel matrix	Composite
Microcosmic hardness (HV)	477.8	873.7

4. Conclusions

From the present study, the following conclusions can be drawn:

(1) The self-propagating high-temperature synthesis of (Ti–Fe)–Al–C system of *in situ* TiC particulates locally reinforced steel matrix composites are successfully fabricated utilizing high-frequency induction process.

(2) X-ray diffraction result reveals that the reaction productions of (Ti–Fe)–Al–C system are Fe, TiC and AlFe phases.

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