

## Effect of compact density on the fabrication of *in situ* Mg–TiC composites

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Metal matrix composite (MMC) technology significantly improves the wear resistance, elastic modulus, and tensile strength of unreinforced metals and alloys. Among numerous MMC systems under development, composites with aluminum and magnesium matrices and ceramic particulate reinforcements are commercial interests to the automotive and aerospace industries [1–3]. In the past decade, much of the research has been focused on cast aluminum-based MMCs [1–4]. However, the research on the same subjects for similar materials using magnesium matrices has received less attention compared to their aluminum counterparts [5–6]. It is well known that magnesium, with its higher stiffness-to-weight ratio, offers better matrix materials for the development of lightweight MMCs. Therefore, magnesium-based MMCs are currently being explored for a number of automotive and aerospace applications, such as automotive pulley [7], cog-tooth sprockets, oil-pump cover [8], cylinder liner, and aircraft engine casting [9].

Self-propagation high-temperature synthesis (SHS) is gaining increasing attention as a technique for synthesis of refractory materials [10]. It has many attractive advantages, such as high purity of products, low processing cost, and energy and time efficiency. A wide variety of materials have been produced by this method. Recently, SHS reaction in the Ti–C–Al system has been widely investigated because of its lower ignited temperature, about 650–800 °C [11], which is approximately the same as the temperature of magnesium alloy molten point. It may be possible that SHS reaction can be conducted in the liquid magnesium alloy. The objective of the letter reported here was to provide an initial assessment of the feasibility of obtaining good dispersions of TiC in magnesium matrices by direct SHS reaction in liquid magnesium alloys.

The characteristics of the powders used in the present study are listed in Table I. Titanium and carbon black powders with an atomic ratio of 1:1 were mixed with 35 wt% aluminum as the starting powders. The reactants were mechanically blended by a ball mill. Then the resulting mixtures were pressed into cylindrical compacts, 20 mm in diameter and 15 mm in length, by using a stainless-steel die with two plungers. The compacts were pressed at pressures of 60–100 MPa to give densities of 65, 70, 75, 80, 85% of the theoretical density.

About 1.2 kg of commercial AZ91D magnesium alloy was selected as the matrices for the composites. The chemical compositions are shown in Table II. When the magnesium alloy had melted, the compact was put into the liquid magnesium alloy. Experiments were conducted under a protective atmosphere of argon. Subsequently, SHS reaction happened and TiC particles were formed in the liquid of magnesium alloy. Processing of the magnesium matrix composites also consisted of melt stirring and composite casting (metal die casting). The as-cast ingots were sectioned, polished, and examined under a scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS). Phase identification of the resultant products was confirmed by X-ray diffraction.

The Mg–TiC composites and base alloy were tested for tensile strength, hardness, and wear resistance properties. A CSS-44100 tensile test machine (made in China) was used to test the tensile strength. The conditions of this experiment were as follows: 3000 N load and 2 mm/min tensile rate. A pin-on-disk apparatus was used for evaluating the wear resistance. The disk was covered with commercial silicon carbide abrasive paper (grit grade 1000 of about 12.4 μm average particle size). The conditions of this experiment were as follows: dry friction, 10 N load and no lubricant.

In order to determine the initiation temperature of SHS reaction of Ti + C + Al system in our experiment, the resulting compact was placed in the reactor, argon glove box, which was filled with argon gas at 0.1 MPa. The combustion reaction was ignited by heating the bottom surface of the compact for several minutes through the tungsten filament. The temperature at which ignition occurs was measured by thermocouples.

TABLE I Characteristics of Al, C, and Ti powders

Reagent	Particle size (μm)	Purity (%)	Source
Aluminum	<29	98.00	Northeast Light Alloy Co., Ltd., China
Graphite	<38	99.99	Jilin Graphite Materials Co., Ltd., China
Titanium	<25	99.50	General Research Institute for Nonferrous Metals, Beijing, China

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TABLE II Chemical compositions of AZ91D magnesium alloy (wt%)

Mg	Al	Zn	Mn	Si	Fe	Ni	Cu	Be	Others
90.344	8.596	0.728	0.270	0.043	0.001	<0.001	0.002	<0.001	0.016

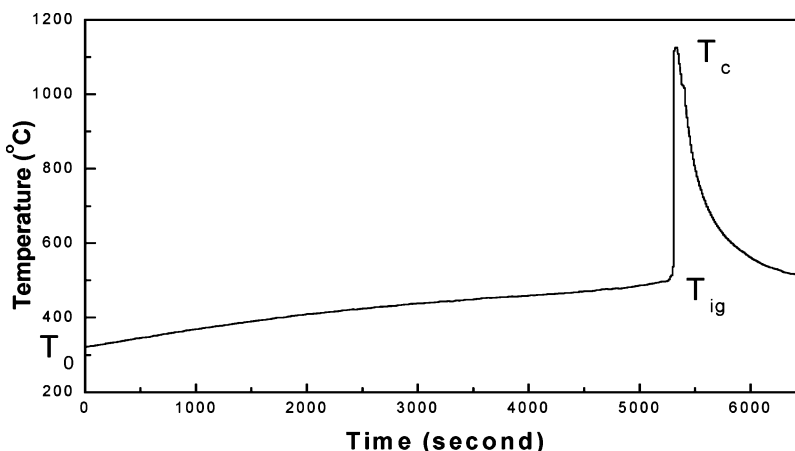


Figure 1 Schematic representation of the typical temperature-time curve during an SHS reaction.

Typical temperature-time histories during heating and ignition for reactant compacts is shown in Fig. 1. The temperature rise before the abrupt increase is caused by heat supplied by the heating coil, whereas the abrupt increase is caused by the combustion reaction between titanium and carbon. Thus, the temperature at the point of the abrupt increase is defined as the ignition temperature ( $T_i$ ). Fig. 2 shows that the ignition temperatures of Ti-C-Al compacts with various compact densities are about 835–965 K. XRD results reveal that there are only two phases, i.e. TiC and Al. The preceding results suggest the possibility that combustion reaction can be ignited as the compacts were placed in the liquid magnesium with temperature over 1023 K, and then *in situ* TiC particles are produced in the liquid magnesium alloy, as a result *in situ* Mg-TiC composites are fabricated.

The as-cast microstructure of the composite fabricated by the compact density of 75% is shown in Fig. 3a. The successful combustion reactions were also produced in the liquid magnesium alloy in compact densities of 70, 80, and 85%, and yielded approximately uniform microstructures in the composites. But the

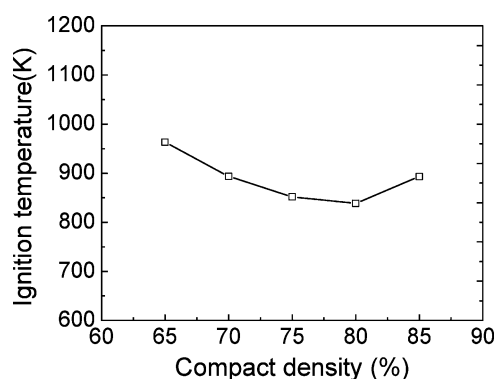
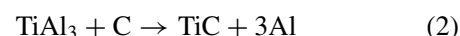
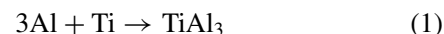


Figure 2 Effect of compact density on the ignition temperature of SHS reaction.

compact density of 65% failed to undergo the SHS reaction. The XRD dot map for titanium is also shown in Fig. 3b. It shows good dispersion of well-rounded reinforcement particles, approximately 2  $\mu\text{m}$  size. Fig. 3c is a magnified SEM micrograph of Fig. 3a. The EDS result illustrated in Fig. 3d reveals that the component of reinforcement particles mainly consists of Ti and C. The magnesium peak was induced by matrix. It suggests that the reinforcement particles must be TiC particles. The fact was further confirmed by X-ray diffraction pattern, as is shown in Fig. 4. The fairly good dispersion of the TiC particles in the magnesium matrix also suggests a good wetting between TiC particles and magnesium. The TiC particles produced are of a rounded form, which is likely to be favorable for impact and wear resistance properties.

It is believed that the mechanism of the thermal explosion synthesis in Ti + C + Al system is as follows [12].



The effect of the magnesium as diluent leads to the compact with a 65% density dispersed into the molten magnesium before the SHS reaction is initiated. As a result, the compact with a 65% density failed to undergo the SHS reaction in the liquid magnesium. Of course, further work is needed to investigate the mechanism of TiC formation in liquid magnesium alloy.

The properties of tensile strength, hardness, and wear loss of the composites are shown in Table III. To evaluate the reinforcement effect of TiC particles, the properties of matrix material were also tested to compare with the composites. It can be seen that Mg-TiC *in situ* fabricated composites exhibited much higher

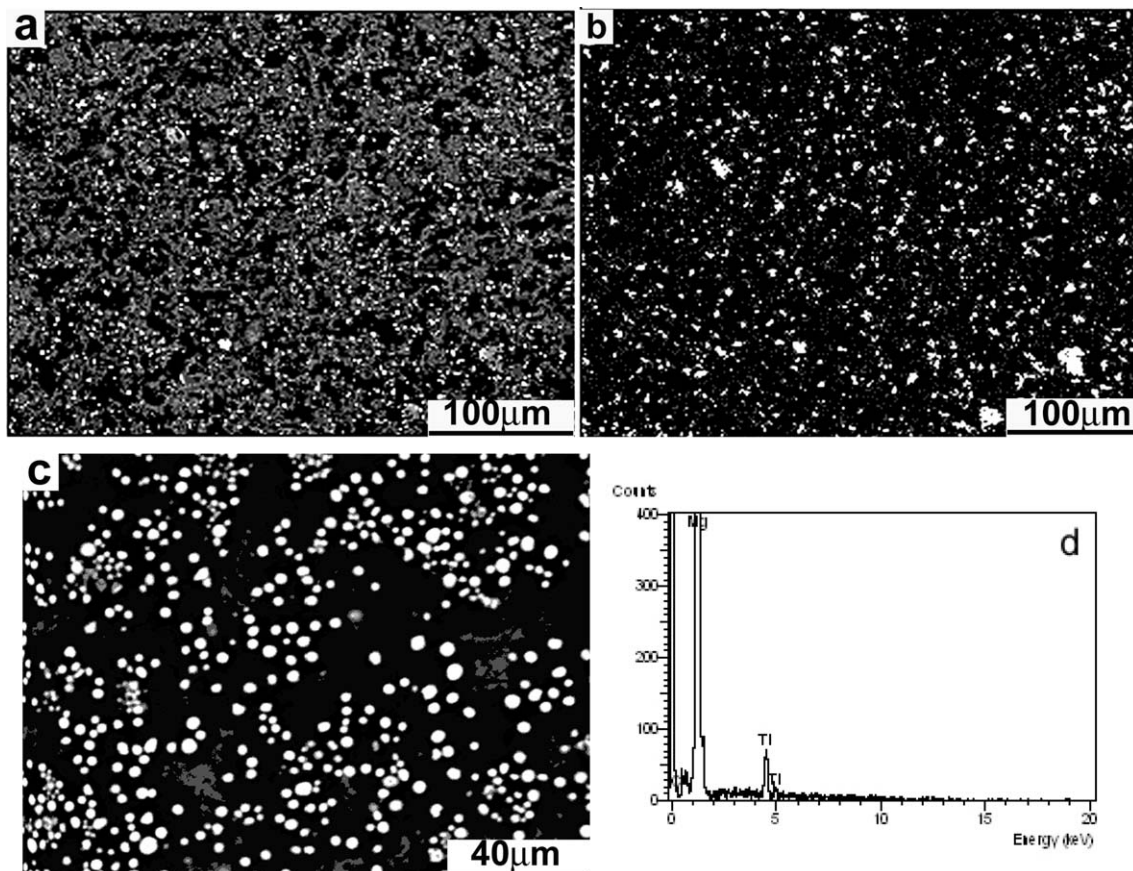


Figure 3 Microstructure of the AZ91D magnesium alloy-TiC composites: (a) Typical SEM microstructure of  $\text{TiC}_p/\text{AZ91D}$  composite, (b) X-ray dot map of Ti, (c) higher magnification of (a) and (d) EDS result of (c).

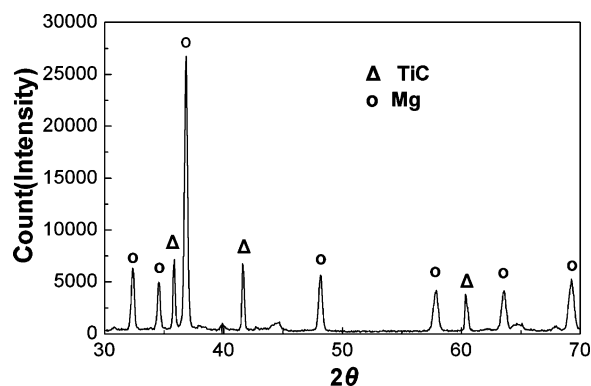


Figure 4 X-ray diffraction pattern of the composite.

tensile strength, hardness, and wear resistance than the unreinforced AZ91 magnesium alloy. This may be attributed to the presence of uniformly dispersed, well-rounded, and fine sized TiC particles in the matrix along with the clean interface between TiC and magnesium. Particularly high volume fractions and good dispersions of TiC can be produced by SHS reaction in local regions of workpiece or tool, which are particularly needed for higher hardness and abrasive wear resistance by use of relatively cheap reagents and simple process.

In conclusion, our results show that the *in situ* Mg-TiC composites with high volume fractions of TiC particles can be successfully fabricated using SHS technique. The SEM analysis and XRD measurement

TABLE III Mechanical properties of AZ91D and  $\text{TiC}_p/\text{AZ91D}$  composites

	$\sigma_b$ (MPa)	HB	$\Delta w$ (g/m)
AZ91	162	61.5	0.030
$\text{TiC}_p/\text{AZ91}$	185	83.5	0.019

indicate that fine size and good dispersions of TiC particles in the Mg-based composite can be achieved. The Mg-TiC composites produced exhibit higher tensile strength, hardness, and abrasive wear resistance than matrix materials.

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