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Fabrication of cast carbon steel with ultrafine TiC particles

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Abstract: The carbon steels dispersed with ultrafine TiC particles were fabricated by conventional casting method. The casting process is more economical than other available routes for metal matrix composite production, and the large sized components to be fabricated in short processing time. However, it is extremely difficult to obtain uniform dispersion of ultrafine ceramic particles in liquid metals due to the poor wettability and the specific gravity difference between the ceramic particle and metal matrix. In order to solve these problems, the mechanical milling (MM) and surface-active processes were introduced. As a result, Cu coated ultrafine TiC powders made by MM process using high energy ball milling machine were mixed with Sn powders as a surfactant to get better wettability by lowering the surface tension of carbon steel melt. The microstructural investigations by OM show that ultrafine TiC particles are distributed uniformly in carbon steel matrix. The grain sizes of the cast matrix with ultrafine TiC particles are much smaller than those without ultrafine TiC particles. This is probably due to the fact that TiC particles act as nucleation sites during solidification. The wear resistance of cast carbon steel composites added with MMed TiC/Cu-Sn powders is improved due to grain size refinement.

Key words: TiC particles; mechanical milling; carbon steel; casting; dispersion; wettability

1 Introduction

The metal matrix composites (MMCs) have been extensively studied in last two decades[1−4] and are significant for numerous applications in the aero space, automobile and military industries[5]. MMC consists of a metallic base with a reinforcing constituent, usually ceramic. The attractive mechanical properties, such as high specific modulus, superior strength, long fatigue life and improved thermal stability are obtained.

Normally, the micro-ceramic particles are used to improve the yield and ultimate strength of the metal. However, the ductility of the MMCs deteriorates at high ceramic particle concentration[6]. The metal matrix, so called metal matrix nano-composite (MMNC) is strengthened by nano-sized ceramic particles[6−7]. The nanoparticle reinforcements can significantly increase the mechanical strength of the metal matrix, as it promotes the particle hardening mechanism more effectively compared to the use of microparticles. Moreover, MMNC offers a significant performance improvement at elevated temperatures because the thermally stable ceramic nanoparticles can maintain their properties at high temperatures. At present, there are several fabrication methods that are used with MMNC materials, including mechanical alloying with high energy milling[4], ball milling[8], nano-sintering[9], vortex process[6], etc.

The casting, as a liquid phase process, is capable to obtain the products with complex shapes[1]. However, this casting technique is applied to manufacturing MMNC materials with nano-sized particles, which is associated with a number of problems. There is very high level of wettability due to the difference in the specific gravity between the molten metal and the ceramic particles. This problem induces the agglomeration and clustering in the matrix[10].

In order to solve this wetting problem during the liquid metal process, the use of a mechanical milling (MM) method and a surfactant powder were introduced in this work. Through the MM process, the micro-sized ceramic particles were converted into nano-sized particles and were simultaneously coated by a metal powder matrix. Accordingly, the as-coated nano-ceramic particles show metallic behavior and reduce the

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disproportionate specific gravity with regard to the liquid metal matrix. Moreover, adding surfactant, such as Sn, has been found to increase the wettability and dispersibility by reducing the surface tension of the melt and decreasing the solid-liquid interfacial energy of the molten metal[6, 11−12]. Therefore, it is expected that the mixing of metal-powder-coated nano-ceramic particles and surfactant powders will enhance the wettability of nano-sized ceramic particles during the casting process.

The aim of this study is to disperse the nano-sized TiC ceramic particles in a carbon steel matrix through the use of a conventional casting method. For this purpose, a MM process for both TiC ceramic and Cu metal powders was utilized to promote the metallic behavior.

Subsequently, Sn powders were used as a surfactant and were mixed with MMed TiC/Cu powders to improve the wettability and dispersibility in the matrix. The changes in the microstructure of the matrix were discussed with respect to the addition of the MMed TiC/Cu-Sn mixed powders.

2 Experimental

In this work, the cast composite consists of medium carbon steel alloy (S25C) with a chemical composition (mass fraction) of 0.44% C, 0.17% Si, 0.67% Mn, 0.17% P, 0.2% S with the balance Fe. The raw materials used to the MM process were TiC (99.98%; Aldrich) with 10 μm in average size and Cu (99.85%; SAMCHUN Chemical) with 20−50 μm in size. The MM process was carried out with a high-energy planetary ball miller. The MM process setup involved a steel ball diameter of 8 mm, a ball-powder mass ratio of 20:1, a rotational speed of 1 100 r/min, a milling time of 6 min and a TiC-to-Cu mass load ratio of 1:1. After the MM process, the surface and a cross-section of the TiC/Cu composite powders were observed on a scanning electron microscope (SEM). Subsequently, Sn (99.9%, high purity chemicals) powders as surfactant were mixed with the MMed TiC/Cu powders. This mixture was then dried at 100 °C for 1 h to remove the humidity from the mixed powders.

The carbon steel alloy was melted in an MgO crucible in an induction heating furnace. After melting, MMed TiC/Cu-Sn (1%, mass fraction) powders were introduced into the molten metal and the mixture was left for 5 min. This molten metal was then poured into a metal mold. The microstructural changes and the dispersion of the ceramic particles in the sample were observed by optical microscopy (OM), SEM and energy dispersive spectroscopy (EDS). The Brinell test assessed the hardness of the cast carbon steel matrix with respect to the added powders. This test utilized a steel ball with a diameter of 10 mm and a dwell time of 15 s. The wear test was carried out for the samples at the sliding speed of 0.1 m/s under a constant load of 5 N. Ball-on-disk type experiments using an Al_2O_3 ball with diameter of 6 mm were performed.

3 Results and discussion

In this work, TiC ceramic and Cu metal powders were selected due to their high chemical stability to Fe and high-specific gravity, respectively. Particularly, it was reported that the wetting angle θ between TiC and molten iron alloy is less than 50° even at high temperatures and in many different types of atmospheres [10].

After the MM processing of the Cu metal and TiC ceramic powders by high-energy ball milling, SEM images of the surface morphology and a cross-section of the MMed powders were obtained, as shown in Fig.1. Fig.1(b) shows that the cross-section of MMed powders consists of dark small spot-like parts as well as bright parts. From the EDS spectra, it was realized that the dark small spot-like image and bright areas represent the TiC ceramic powder and the Cu matrix, respectively. From this figure, the TiC ceramic particles are uniformly distributed in the Cu matrix, although the shape and size of the MMed powders are irregular on the surface of these particles, as shown in Fig.1(a). In the milling of TiC-Cu component systems, it has been observed that the

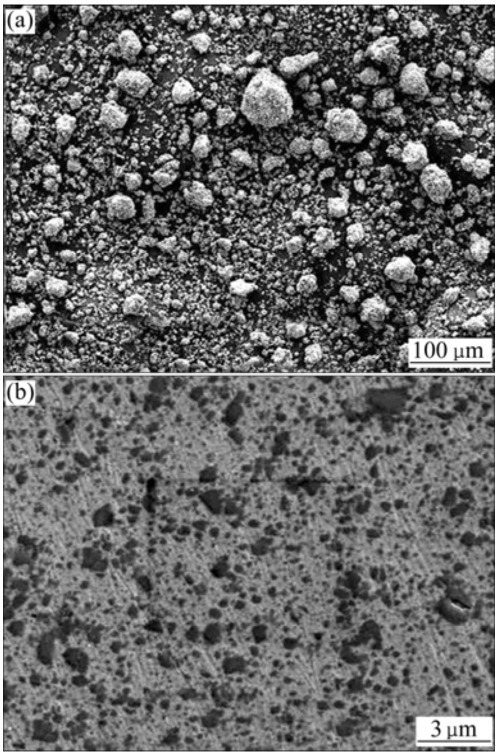

Fig.1 SEM images of raw and MMed powders: (a) Surface morphology of MMed TiC/Cu powders; (b) Cross-section of MMed TiC/Cu powders

harder TiC particles are fragmented, which reduces their particle size continuously. Eventually, they become embedded into the softer Cu powder.

In addition, the cross-sectional images of MM powders show that the size of the TiC ceramic particles in the Cu matrix ranges in the range of 200−300 nm. Hence, it is confirmed that a ball miller operated at a very high energy can effortlessly fabricate MMed TiC/Cu powders with a very small and uniform size in a very short milling time of 6 min. After the MM process of the TiC ceramic and Cu metal powders, these MMed powders were mixed with Sn powders and then poured into molten carbon steel melt by using a conventional casting route. In this study, Sn powders were added to a liquid melt to increase the wettability and dispersibility by reducing the surface tension of the melt.

Fig.2 shows OM images of the microstructure of pure carbon steel and modified steels after the addition of MMed TiC/Cu-Sn powders. The microstructure of the pure carbon steel is generally divided into two phases, as shown in Fig.2(a). The first phase is a dark pearlite phase in which the lamellae of α-ferrite and Fe_3C (cementite) lie side by side, and the second phase is bright α-ferrite. Fig.2(b) shows the microstructure of the carbon steel with the addition of the MMed TiC/Cu-Sn mixed powders. In Fig.2(b), it should be stressed that when MMed TiC/Cu-Sn mixed powders are added, the grain sizes of ferrite and pearlite phase are reduced significantly compared to as-cast carbon steel. In addition, the black spot images are homogeneously over the entire range of the matrix. From the SEM image, these black spot images are characterized as TiC ceramic particles. It is expected that a very small quantity of FeSn intermetallic compounds form in the matrix due to the very small amount of added Sn powders at 0.5% (mass fraction), despite the fact that they cannot be seen in the figure. From Fig.2(b), MMed powders reduce the grain size of the matrix more effectively compared to pure sample. Accordingly, when MMed TiC/Cu and Sn powders are utilized simultaneously, a cast matrix composite with a small grain size of nano-sized ceramic particles can be fabricated easily in a conventional casting route.

Fig.3 shows mass loss and coefficient friction of as-cast and MMed TiC/Cu-Sn carbon steel composite. In Fig.3(a), when it is compared with as-cast and MMed TiC/Cu-Sn, the MAS-loss of as-cast sample (13 mg) is larger than MMed TiC/Cu-Sn (8 mg) till sliding distance of 10 km. Fig.3(b) show the coefficient friction and wear tracks on the disk specimens of each disk specimen slid against an Al_2O_3 ball for the cases of 5 N.

After sliding, many scratches are observed on the wear tracks of the cast samples. In Fig.3(b), the carbon steel with MMed TiC/Cu-Sn shows more superior property than as-cast sample with sliding distance of 10 km. The scratch width values of the as-cast and MMed

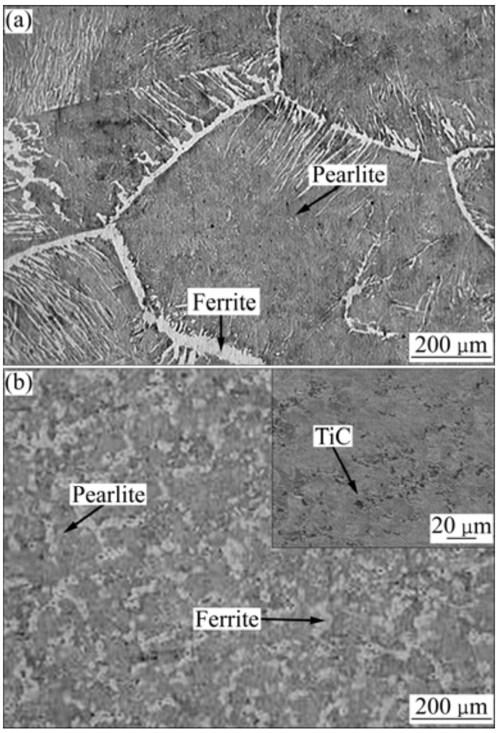

Fig.2 Optical micrographs of as-cast (a) and MMed TiC/Cu-Sn (b) carbon steel composite

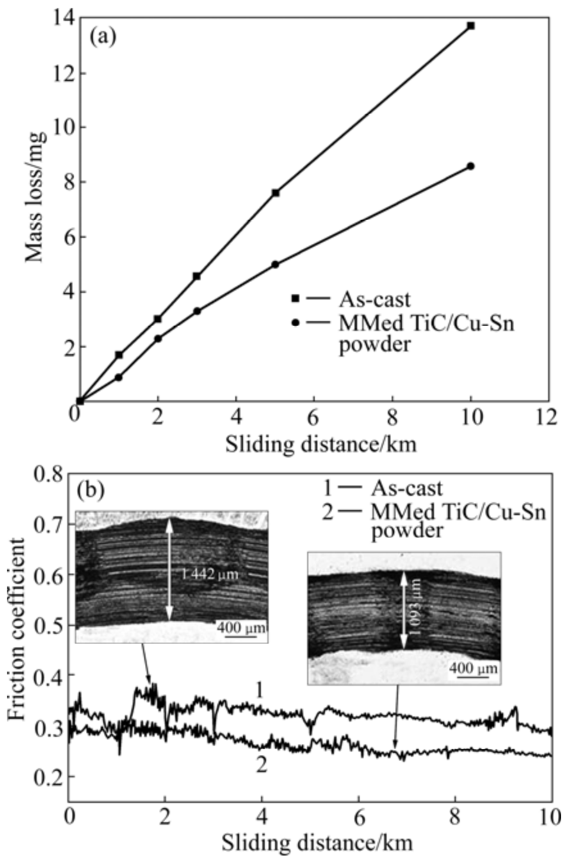

Fig.3 Mass loss and coefficient friction of as-cast (a) and MMed TiC/Cu-Sn (b) carbon steel composite

TiC/Cu-Sn carbon steel are 1 442 μm and 1 093 μm, respectively. Based on this result, the scratch property is significantly improved by uniformly dispersed TiC nanoparticles in the carbon steel matrix, acting as nucleation sites, leading to a decrease in the grain size.

Table 1 shows the values of the Brinell hardness (HB) and strength at fracture (MPa) of the cast carbon steel with regard to the added powders. On the other hand, when MMed TiC/Cu-Sn mixed powders are added, the HB and strength of the cast matrix increase by 27% and 13% compared to the pure sample. This is due to the homogeneous distribution of harder TiC ceramic particles in the matrix.

Table 1 Brinell hardness and strength at fracture of cast carbon steel

Powder	Brinell hardness, HB1)	Strength at fracture/MPa2)
MMed TiC/Cu-Sn (maxied)3)	215	498
Increasing rate/%	27	13

1) HB of S45C carbon steel was measured as 169; 2) Strength of S45C carbon steel was measured as 440; 3) MMed TiC/Cu represents mechanically milled powders of TiC and Cu.

Hence, this study suggests that a combination of a MM process and an addition of surfactant element can efficiently disperse TiC ceramic nanoparticles into a carbon steel melt by greatly enhancing their wettability, leading to the production of as-cast metal matrix nano-ceramic composites. Further, the process is necessary to optimize and the agglomeration phenomena of the nanoparticles is mitigated.

4 Conclusions

1) Carbon steel matrix composite dispersed with TiC nano ceramic particles is fabricated after adding the MMed TiC/Cu-Sn mixed powders by a conventional casting method. From the microscopic observations, MMed TiC/Cu-Sn mixed powders homogeneously disperse the TiC nano particles most effectively and then the grain size decreases. Accordingly, it is possible to achieve TiC nano particles dispersed into carbon steel composites through adding MMed TiC/Cu-Sn mixed powders.

2) Based on the experimental results, the strengthened composites via ceramic dispersion through the homogeneous dispersion of nano-sized ceramic particles in the metal matrix using a liquid metal casting method is possible.

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