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Microstructure and performance of diamond composites fabricated by self-propagating high-temperature synthesis using high-frequency induction as a heat source

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ABSTRACT

A mixture of Al, Ti, Cu, Ni, and Sn was used as the matrix material to fabricate diamond composites and grinding heads through self-propagating high-temperature synthesis (SHS). High-frequency induction was used as a heat source for preheating to ignite SHS. The SHS was examined, and the microstructure of the reaction products was analyzed by scanning electron microscopy and X-ray diffraction. As a comparison, diamond composites and grinding heads were fabricated by hot pressed sintering (HPS) using Cu-based matrix. The grinding performance of heads was tested in the grinding of Zirconia ceramics. Results showed that ferromagnetic Ni was a key element without which SHS could not start. Increasing frequency prolonged preheating time and decreased combustion temperature. The increasement of Al + Ti content in the matrix aggravated the combustion temperature and thereby aggravated the porosity. The optimal grinding ratios of SHS grinding heads was reached when Al + Ti weight content was 30% and was only 4% lower than that of HPS ones. The grinding forces of SHS grinding heads was lower than that of HPS ones. Carbides Ti_3AlC and Ti_3AlC_2 formed on the diamond surface during SHS.

1. Introduction

Metal sinters with diamond are used for machining concrete, marble, and other building materials. However, the application of metal–diamond sintering is limited by its low energy efficiency. In addition, diamond is one of the most inert substances. Thus, the bonding of diamond to the matrix is a major technological difficulty.

Self-propagating high-temperature synthesis (SHS) has received considerable attention as a novel method for the preparation of various materials including borides, nitrides, aluminides, intermetallics and composites. The prominent advantages of low cost, high energy efficiency, high purity of the reaction products, extremely fast heating and high synthesis temperature have the potential to produce materials with novel structures and properties [1–3].

Some studies reported the fabrication of diamond-containing materials by self-propagating high-temperature synthesis (SHS). Padyukova and Levashov [4,5] fabricated multilayered and functional gradient diamond-containing materials by Ti–B/diamond SHS. Zhang [6] synthesized AlNi nano/micromultilayers and used them to test the bonding of copper and diamond by self-propagation. The quality of diamond–copper joint by nanomultilayer bonding is better than that joint by silver glue bonding. Liang [7,8] fabricated a ceramic titanium aluminum carbide matrix-bonded diamond/c-BN composite by using SHS. The phase composition and microstructure of the reaction products were also analyzed. Michalski [9] synthesized Ni_3Al/diamond composites by pulse plasma sintering with SHS. Zhang [10–12] introduced diamond tool materials with coarse diamond grits fabricated by Ni–Al SHS and Ni–Al/diamond/dilute SHS, and investigated the effect of Ni–Al SHS on diamond grits.

SHS can be initiated by preheating the entire reaction mixture or by ignition of one side of the powder compact by a localized heat source, e.g., filament, spark, or laser [13–16]. In consideration of the weak exothermicity of reactions for some reactants, preheating of the powder compact is required. The heat sources are electric-resistance heating [17–20], electromagnetic field [21–23], and plasma sintering [9]. However, preheating is performed at some time (a few minutes or more than 10 min).

High-frequency induction heating (HFIH) is effective in the sintering of some materials for a short time (within 1 min) [24,25]. Given its advantage of rapid heating, HFIH was used in brazing diamond tool materials with a small diameter (1–30 mm) [26,27]. From this point of view, HFIH is a preferred heat source for SHS. In the present study, a

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Table 1
Compositions of various matrix materials (weight content).

Samples no.	Cu	Ni	Al	Ti	Sn
S-1	47	10	20	20	3
S-2	57	10	15	15	3
S-3	57	20	10	10	3
S-4	57	0	20	20	3

mixture of Al, Ti, Cu, Ni, and Sn was used as a raw material to fabricate diamond composites by SHS. High-frequency induction was first used as a heat source for preheating to ignite SHS. SHS of the reaction sample was examined, and the microstructure of the reaction product was analyzed by scanning electron microscopy (SEM) and X-ray diffraction (XRD).

2. Materials and experimental procedures

The raw materials used in this study included commercial diamonds and metal powders (Al, Ti, Cu, Sn, and Ni). The metal powders were used as the matrix materials of diamond composites. Diamonds (Huanghe Whirlwind Co., Ltd., China) with sizes ranging from 300 μm to 425 μm were used. The size of Cu or Al powder (99.9% pure) was not more than 74 μm. The size of Ti, Sn, or Ni powder (99.9%) was not more than 44 μm.

In this study, the weight contents of Al, Ti, and Ni were adjusted to investigate the influence of Al, Ti, and Ni in SHS. The compositions of the matrix materials of different samples are displayed in Table 1.

Four types of matrix materials with diamond grits (10 vol%) were successively sealed in a stainless steel vial under an atmosphere of argon and mixed on a planetary ball mill for 6 h. The four types of mixtures were then cold-pressed into four types of cylindrical samples (8 mm diameter and 8 mm height) with a green density of 85% at a pressure of 30 MPa.

SHS experiments were conducted in an apparatus as shown in Fig. 1. The cylindrical sample was positioned on top of a 45 steel cylinder under an atmosphere of high-purity argon (99.99%). The sample and the cylinder were preheated at the same time by HFIH. The output powder of the high-frequency induction heater was 15 kW. The output frequency was maintained at 60 kHz. The rapidly rising temperature of the cylinder ignited the SHS of the sample. HFIH was stopped at the start of SHS. The propagating rate was measured by recording the entire SHS with a color Charge Coupled Device video camera at 25 frames/s.

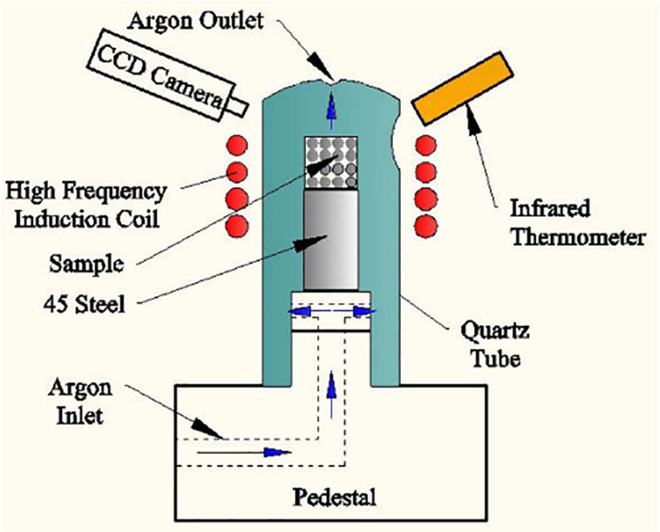

Fig. 1. Schematic illustration of SHS reaction apparatus using high-frequency induction heating method.

The microstructures of the reaction sample fracture surface were characterized using SEM coupled with energy-dispersive X-ray spectroscopy (EDS). The chemical composition of the samples after SHS reaction was detected by XRD (XD-3 A).

The four types of matrix materials with diamond grits (100 vol%) were used to fabricate grinding heads under the same conditions. To evaluate the grinding performance of the grinding heads, the grinding forces F_n and F_t were measured using a piezoelectric transducer-based dynamometer (type Kistler 9257BA) coupled with charge amplifiers and a PC running Dynowear software. For each set of grinding parameters, three grinding passes were undertaken to ensure the reliable results. The grinding forces were measured as previously [28].

As a comparison, diamond composites and grinding heads were fabricated by hot pressed sintering (HPS) using Cu-based matrix (57 wt% Cu–10 wt% Ni–3 wt% Sn–15 wt% Co–Fe). The sintering operation was carried out in the hot-pressing sintering machine at the heating temperature of 850 °C for the dwell durations of 4 min.

3. Experimental results and discussion

3.1. Characteristics of SHS

The differential scanning calorimetry results of the S-1 and S-3 compact samples are shown in Fig. 2. A higher exothermic peak was observed in Fig. 2(a) than in Fig. 2(b) because of SHS. The reaction starting temperature of S-1 (801 °C) was lower than that of S-3 (865 °C). The increasement of Al + Ti content in the matrix caused the increased reaction heat and the decreased starting temperature. SHS can only occur if the temperature of the sample rises to the critical one by preheating.

The SHS of S-1 ignited by HFIH is shown in Fig. 3(a). The propagating time was 0.36 s, which was shorter than that of the SHS system with 60 wt% of dilute reported in other studies [11,29]. The preheating time of the compact sample was 26 s. Thus, the fabrication efficiency greatly improved when high-frequency induction was used as a heat source.

During high-frequency induction preheating, S-1 and the cylinder were preheated at the same time, and the temperature of the cylinder rose rapidly. Then, the critical temperature of the entire S-1 compact sample was reached. At the same time, the thermal transmission from the cylinder to the bottom of the S-1 compact sample further raised its bottom temperature. Therefore, SHS occurred.

Fig. 4 displays the compact samples' preheating time and the combustion temperature of the three reacted samples. The increasement of Al + Ti content caused the increased reaction heat and the short heat transportation distance, which consequently reduced the preheating time and aggravated the combustion temperature of the sample. The SHS reaction of the S-4 compact sample did not occur. In addition, an increase in frequency increased the preheating time and decreased the combustion temperature of the compact samples.

HFIH is accomplished by a source of high-frequency electricity to drive a large alternating current through a work coil. The passage of current through this coil generates a highly intense and rapidly changing magnetic field in the space within the work coil. The induced current flows; therefore, the generated heat is concentrated on the surface of the sample, and its density decreases approximately exponentially with distance from the surface illustrated by the following eq. [30,31]:

$$I_x = I_o \mathrm{e}^{-\frac{x}{\delta}}, \tag{1}$$

where x is the arbitrary depth of the cylindrical sample, and δ is the skin depth or depth of penetration given by the following equation:

$$\delta = \sqrt{\frac{\rho}{\pi\mu_0\mu_r f}}, \tag{2}$$