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Fundamental aspects of ultrasonic assisted induction brazing of diamond onto 1045 steel

Guoqin Huang[a,b,*], Jierong Huang[a,b], Meiqin Zhang[c], Dekui Mu[a,d], Guantao Zhou[a,d], Xipeng Xu[a,b]

[a] Institute of Manufacturing Engineering, Huaqiao University, Xiamen, Fujian, 361021, China
[b] Fujian Engineering Research Center of Intelligent Manufacturing for Brittle Materials, Fujian, 361021, China
[c] School of Mechanical and Automotive Engineering, Xiamen University of Technology, Xiamen, 361021, China
[d] MOE Engineering Research Center for Brittle Materials Machining, Xiamen, 361021, China

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ABSTRACT

In this study, ultrasonic-assisted induction brazing (UAIB) of diamond grits onto 1045 steel with Ni–Cr–B–Si–Fe was investigated and compared with those obtained by the conventional induction brazing (CIB). Using UAIB led to the result that the surface of brazed filler alloy was flatter and less slags and the bond zone was of less and smaller cracks. The embedded ratio of brazed diamond was improved 35.4% by UAIB. Furthermore, UAIB-brazed joints contained a more even distribution and smaller grain sizes of interfacial microstructures. In both the methods studied, a layer of Cr_3C_2 was formed on the bonding interface; however, this layer was short and contained more discontinuous laths with random directions when UAIB was used. The maximum compressive residual stress at the bottom of the brazed diamond grits was reduced using UAIB by 21.6%. Using UAIB increased the average shear force of the joints by 28.5% and greatly reduced the percentage of fracture failure joints on the UAIB grinding wheel, suggesting an enhancement in the strength of the joints. These differences were ascribed to the acoustic effects induced by ultrasonic vibration.

1. Introduction

Active brazing of diamond tools has drawn significant attention in the efficient machining of difficult-to-cut materials. Chattopadhyay et al. (1991a) addressed that the use of these tools can produce benefits attributed to the chemical bonding at the interface of the brazed diamond joint, such as high bonding strength between the filler alloy and diamond grits, high grain protrusion from the filler alloy and large chip storage. Using brazed tools in the machining of hard alloys reported by Chattopadhyay et al. (1991b) and brittle materials reported by Sung and Suang (2009) has shown a significant reduction in grinding temperature, a lowering of grinding force and an increase in service life. Similar results obtained by Chen et al. (2010) demonstrated that a brazed diamond wheel was suitable for high speed grinding of engineering ceramics. Wang et al. (2009) summarised that Ni–Cr alloys have been widely used in the fabrication of brazed tools because of their high strength and resistance to heat, wear and corrosion. However, failure behaviour research conducted by Chattopadhyay et al. (1991c) and Buhl et al. (2013) indicated that diamond grits brazed onto tools are vulnerable to fracture failure at the bond junction region. Meanwhile, a recent research by Mukhopadhyay et al. (2017) claimed that this failure still presents an obstacle to the widespread application of active brazed tools.

The study conducted by Chattopadhyay et al. (1991c) indicated this joint fracture failure was mainly induced by the residual stresses in the vicinity of the joining zone. Considerable efforts have been made to understand and relieve these stresses. Finite element simulations conducted by Akbari et al. (2012) and Meng et al. (2015) revealed that residual stresses arise from a mismatch of thermal expansion coefficients of the diamond, the filler alloy and the substrate. Similar results were also reported by Zhu et al. (2017) and Ding et al. (2015) during brazing of CBN. The experimental studies of Buhl et al. (2010) and Sun and Xiao (2018) indicated that the residual stress also depends on the brazing temperature, the dwell time and the thickness of the interfacial layer. One method to minimise residual stress involves employing low melting point filler alloys, such as an Ag–Cu–Ti filler alloy as reported by Klotz et al. (2006) or a Cu–Sn–Ti filler alloy as reported by Buhl et al. (2012). However, Ma and Yu (2012) addressed that these filler alloys were low-strength and less resistant to wear. A second proposed method involves surface modification: Ma and Yu (2012) improved the wear performance of brazed diamond joints by depositing a

* Corresponding author at: Institute of Manufacturing Engineering, Huaqiao University, Xiamen, Fujian, 361021, China.
E-mail address: smarthgq@hqu.edu.cn (G. Huang).

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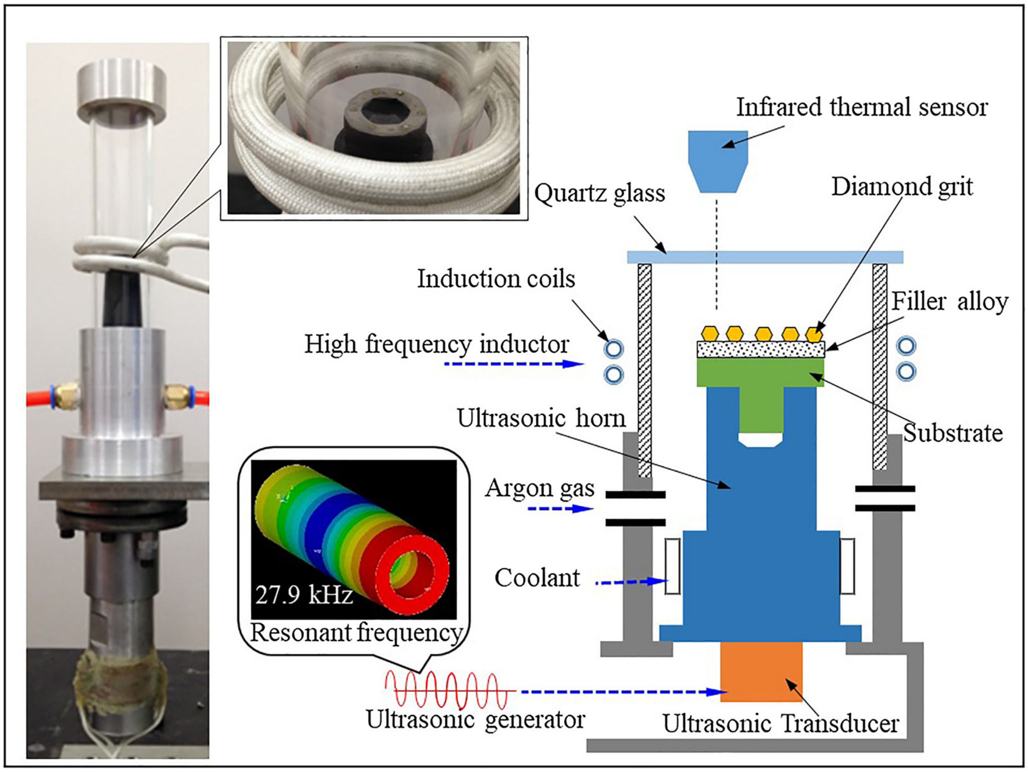

Fig. 1. The UAIB system.

carbon film on the diamond surface that acted as a transition layer to alleviate the thermal coefficient mismatch of the diamond and filler alloy. However, this method produced undesirable side-effects, including cracking and spalling of the coating and blunting of the edges of the diamonds. A third method is to control the cooling stage of brazing; however, Mukhopadhyay et al. (2017) has indicated that the outcomes of control cooling stage were still not satisfactory. Hence, an alternative approach to relieving residual stress on brazed diamonds would be of great significance.

Ishikawa and Kawase (1980) claimed that ultrasonic-assisted brazing (UAB) technology was superior to traditional brazing technology. This technology effectively improves the wettability of liquid filler alloys and is therefore particularly suitable for brazing of materials with poor wettability, such as ceramics (Cui et al., 2015). In the work by Kuckert et al. (2003), ultrasonic vibration was used to control residual stress distribution in glass-metal joints. Similarly, Aoki et al. (2007) found that ultrasonic vibration reduced the residual stress induced in welding. Thus, UAB technology offers the potential to improve the performance of brazed diamond tools.

The goal of this study was to improve the fracture resistance of brazed diamonds by enhancing joint strength using ultrasonic vibration to relieve residual stress on brazed diamond joints. Using commercial Ni–Cr–B–Si–Fe filler alloys, diamond grits were brazed onto a 1045 steel substrate through ultrasonic-assisted induction brazing (UAIB). The interfacial microstructure, residual stress and fracture failure of the brazed diamond grits were compared with those of grits brazed using conventional induction brazing (CIB) which was without ultrasonic assistance. The joint strength and fracture resistance of brazed diamonds was evaluated by single grit shear and grinding testing. The effects of ultrasonic vibration on the brazing process are also discussed.

2. Experimental

2.1. Materials and brazing process

A commercial Ni–Cr–B–Si–Fe powder (85.4Ni7Cr3.1B4.5Si3Fe, in wt. %) with 200 US mesh size particles was used as a filler alloy. Synthetic diamond grits of 30/35 mesh and of ISD–1650 grade were purchased from Element Six. 1045 steel was used as a substrate material.

The customised UAIB platform used consisted of an ultrasonic module, a frequency induction module and an argon protection system; images and a schematic are presented in Fig. 1. The ultrasonic module comprised an ultrasonic generator, an ultrasonic transducer, an ultrasonic horn and a coolant system. The amplitude of the ultrasonic vibration on the substrate was measured using a laser displacement sensor (LK–Navigator 2, Keyence). The frequency induction module comprised induction coils, a high frequency inductor with highly accurate temperature PID control (± 1 °C, WacA–20kW-380AC, Shanghai Ougan Electric Technologies Co., Ltd.) and a high accuracy infrared thermal sensor (CT 2 MH, Optris).

After mixing with a binder, the filler alloy was evenly pasted onto the substrate with a thickness of 180 μm, as schematically shown in Fig. 2. The diamond grits were then placed on the filler alloy in a predetermined pattern. After being dried, the substrate was fastened to the end of the ultrasonic horn, as shown in Fig. 1. The substrate was then induction heated to 1020 °C with a hold time of 10 s, and then cooled to room temperature. Throughout the entire UAIB process, the substrate was exposed to ultrasonic vibration at an amplitude of 3 μm and a frequency of 27.9 kHz, as chosen by an ANASY software simulation with the consideration of resonance