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# Pressureless sintering of metal-bonded diamond particle composite blocks

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Metal-bonded diamond particle composite blocks were fabricated by pressureless sintering, using multi-phase copper based alloys as the bonding materials. The processing sequences included ball-milling the diamond particles and metallic powders, uniaxially pressing the milled powder mixtures into green compacts, and sintering the green compacts in vacuum. The bonding materials, constituted of Cu, Sn, Ti, Mo and TiC, were prepared by blending various elemental and prealloyed powders. Addition of Ti as an active element effectively enhanced the interfacial cohesion strength, by developing an intermediate layer between the diamond particles and the matrix phase. This resulted in the observation that the failure mode of the composite blocks in a bending test was predominantly cleavage of diamond particles instead of pull-out of diamond particles. 

## 1. Introduction

Different materials, including materials based on polymers, ceramics, and metals, are currently used as the bonding agents of diamond particle composite blocks. Among these three categories of bonding agents, metallic bonding materials exhibit the optimal combination of mechanical and thermal properties, and are the primary bonding materials in the fabrication of composite blocks containing diamond particles [1]. Metal-bonded diamond tools are used extensively for cutting, drilling, and surface grinding of stones, concrete, advanced ceramics, and cemented carbides [2–6].

The primary consolidation route to fabricating metal-bonded diamond particle composite blocks is hot pressing, primarily using alloys based on cobalt or bronze. In a recent report [7], alloys based on iron successfully substituted for cobalt in hot-pressed diamond particle composite blocks and improved service performance was documented. Nevertheless, hot-pressing is a tedious operation with several constraints in regard to mass-production. Pressureless sintering of diamond particle composite blocks using cast iron as the bonding material has been proposed [1]. In this approach, relatively high concentrations of carbon have to be added to the bonding material and consolidation of the composite has to be carried out at low temperatures to avoid conversion of diamond into graphite. Still, the properties of this category of composite blocks are inherently mediocre. In addition, the metal matrix is relatively difficult to grind off during service, such that an electrical current had to be supplied to the composite blocks to corrode the metal matrix in order to expose new diamond particle cutting edges.

Though with different approaches, all the above mentioned systems involve weak interfacial bonding strength between diamond particles and metal matrix such that pull-out of diamond particles during service predominates as the mode of tool failure. During service, the interface between the metal matrix and the diamond particles must withstand the moment to which the diamond particles are subjected. A weak bonding strength between the diamond particles and the metal matrix, arising from weak physical type bonding, is often insufficient to endure the stress. A weak interfacial bonding strength usually results in excessive pull-out of diamond particles from the matrix phase during service and, consequently, degraded tool life. This phenomenon frequently occurs in hot-pressed diamond tools using cobalt as the primary constituent [8]. Thus, an interfacial reaction that promotes bonding between diamond particles and metal matrix is the fundamental requirement for enhancing tool life [9]. Chemical bonding between the metal matrix and the diamond particles can develop when an active metal is added to

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the bonding materials [10–12]. Among the common active metals, titanium has been most used and standard grades of diamond particles coated with titanium or titanium carbide are commercially available. Enhanced performance has been documented. For example, the fracture toughness of composite blocks based on diamond particle and Cu-10%Ni was substantially enhanced when the diamond particles was coated with titanium [13]. In addition to coating the surface of diamond particles with active metals, active metals can also be added in the form of an alloying constituent in the bonding materials. For example, it has been shown that a thin interfacial layer, predominantly composed of chromium, preferentially developed around the surface of diamond particles when chromium is presented in a prealloyed form in the matrix phase [8].

It is the purpose of this study to apply pressureless sintering to the fabrication of composite blocks of diamond particle and metal matrix, with an interfacial bonding strength enhanced by a chemical reaction. As diamond particles easily convert to graphite at high temperatures, densification of the composite blocks has to be carried out at low temperatures and in the absence of carburization catalyst. Thus, densification of the composite blocks should be assisted by the formation of a liquid phase during sintering. The composition of the metal matrix is designed to be composed of a backbone constituent that dictates the mechanical properties of the matrix phase, a liquid phase formation constituent, and an active metal. A processing route of press-and-sinter is employed for the consolidation of the composite blocks and the performances of the sintered specimens are compared with commercial products fabricated via hot-pressing.

## 2. Experimental procedures

Natural diamond particles having sizes smaller than 30 mesh but larger than 40 mesh were used. The volume percentage of diamond particles in the composite blocks was maintained at 10%. The binding materials were composed of mixed powders of prealloyed Cu-10Sn-15Ti (wt%), Mo, and TiC powders. The mean particle sizes of the prealloyed Cu-10Sn-15Ti, Mo, and Tic powders were 15.6 $\mu$m, 8.0 $\mu$m, and 2.3 $\mu$m, respectively. The volume percentage of Cu-10Sn-15Ti in the composite blocks was maintained at 40%, while Mo and TiC split the remaining volume percentage of 50%. The relative volume percentage of Mo to TiC was the only variable investigated in this study. Paraffin wax was used to enhance the handling strength of green compacts. Initially, 80 vol% of diamond particles and bonding agents was milled with 20 vol% of paraffin wax in the medium of heptane and 304 stainless steel balls. The slurry was then dried, granulated, and sieved with a screen of 10 mesh. The granules were subsequently pressed at a pressure of 100 MPa into rectangular specimens having the dimensions of 1.5 mm $\times$ 5 mm $\times$ 50 mm, and cylindrical specimens having the dimensions of 15 mm ($L$) $\times$ 6 mm ($D$).

The specimens were sintered at 1000°C in vacuum. The sintering profile is shown in Fig. 1. Hardness of the matrix phase was determined using a Vickers hardness tester under a load of 500 g. Transverse rupture strength of the sintered specimen was determined by a four-point bending test with a gauge length of 40 mm. Relative wear resistance test of the sintered specimens against granite was carried out in a dry condition, using a modified turning machine. The machine operated at 800 rpm and the specimen ground against the granite plate along a circle having a diameter of 5 cm, which resulted in a peripheral speed of 2.1 m/s. The feed rate of the specimen to the granite plate was 0.4 mm/min. The morphologies of the diamond particles exposed to various tests were examined using a scanning electron microscope (SEM).

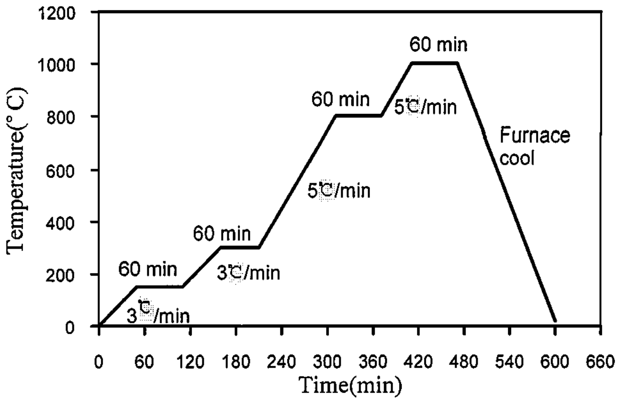


*Figure 1* Thermal profile used in the sintering of metal-bonded diamond particle composite blocks.

## 3. Results and discussion

Fig. 2 shows the effect of adjusting the volume percentage of Mo and, consequently, TiC in the composite blocks on the hardness of the matrix phase. As expected, the hardness of the matrix phase decreased with the increase in Mo concentration. The hardness of the matrix phase ranged from about 270 kgf/mm$^2$ to about 570 kgf/mm$^2$, which was much lower than that of granite, 920 kgf/mm$^2$. Accordingly, the matrix phase can be easily ground off by granite to allow the passage of debris and to expose new cutting edges of diamond particles during machining. On the other hand, the matrix phases of commercial diamond tools do not possess such a wide range of hardness. For example,

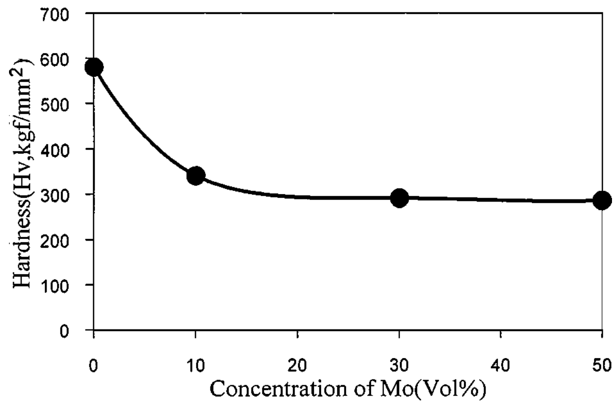


*Figure 2* Variation of hardness of matrix phase with the increase of volumetric percentage of Mo in the composite blocks.

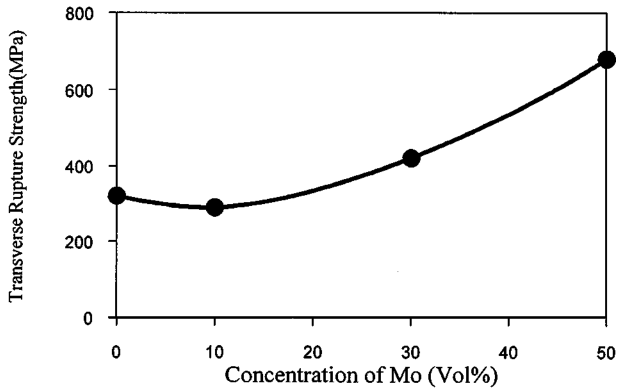


*Figure 3* Variation of transverse rupture strength of the composite blocks with the increase of volumetric percentage of Mo in the composite blocks.

the hardness of hot-pressed cobalt ranges from 310 to 433 kgf/mm$^2$ [14], while that of cast iron ranges from 150 to 350 kgf/mm$^2$. Obviously, a matrix with a wider range of hardness could be fabricated via the processing route carried out in this study. The capability of fabricating tools having a wide range of hardness values of the matrix phase is important in the fabrication of diamond tools, as the materials to be machined have a wide range of hardness.

Fig. 3 shows the effect of adjusting the volume percentage of Mo and, consequently, TiC in the composite blocks on the transverse rupture strength of the sintered specimens. Increase in the concentration of Mo resulted in substantial increase in the transverse rupture strength of the composite blocks. The strength levels achieved in this study were much higher than those of hot-pressed composite blocks of diamond particles using cobalt as the primary bonding material, which usually have transverse rupture strengths lower than 200 MPa [9]. The low strength of the cobalt-bonded diamond tools is associated with the fact that hot-pressing of the composite blocks is usually carried out at such low temperatures as to avoid excessive degradation of diamond particles. In addition, the lack of an interfacial bonding promoter in the cobalt-based matrix also causes low bending strength in the composite blocks. Fig. 4 shows the fracture surface of a specimen sintered using 40 vol% Cu-Sn-Ti and 50 vol% Mo (10 vol% diamond) as the bonding material. There existed a fine-grained thin layer located between the diamond particles and the matrix phase. As the grains were very fine (less than 0.2 $\mu$m), they were not densified grains of the original powders but instead grains formed subsequent to liquid phase sintering. It is thus expected that these fine grains are not simply the crystallized liquid phase, as the cooling rate subsequent to isothermal hold was not rapid enough to yield these fine grains. The fine grains are possibly the products of reaction between the active elements and the diamond particles. Energy dispersive X-ray analysis (EDXA) indicated that this thin layer was primarily composed of Ti, though Mo also had a strong affinity to form carbides with carbon. It is thus very clear that the incorporation of Ti as an active element in the bonding material substantially enhanced the transverse rupture strength of the composite blocks, by forming an intermediate layer between the diamond particles and the matrix phase. Similar observations were also documented with the addition of small concentrations of active elements to systems comprised of copper and diamond [10–12], where the interfacial bonding strength between copper and diamond increased due to the formation of an intermediate carbide layer.

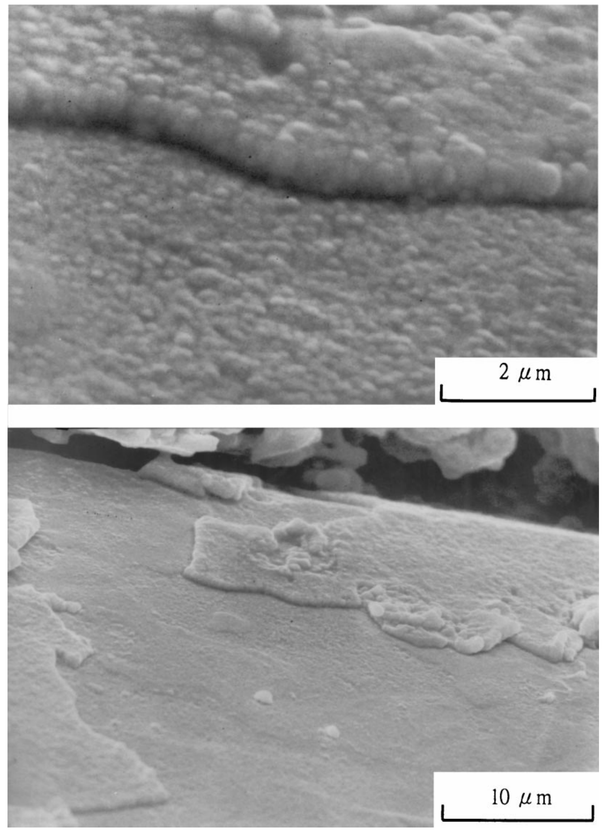


*Figure 4* Fracture surface of a composite block having 50 vol% Mo (0% TiC).

Fig. 5 shows the fracture surface of a composite block whose matrix phase was composed of 40 vol% Cu-Sn-Ti and 50 vol% of TiC (10% diamond). Two distinct features can be observed in these micrographs that can explain the relatively high transverse rupture strength of this composite block compared to hot-pressed composite blocks using cobalt as the primary bonding constituent. First, cleavage of diamond particles was the predominant mode of fracture around the diamond particles. This observation is clearly different from the excessive pull-out of diamond particles from the matrix phase for hot-pressed composite blocks using cobalt as the primary bonding constituent [9]. Second, the interfacial cohesion between the diamond particles and the matrix phase was very strong, as indicated previously, even with abundant brittle TiC grains in the matrix.

Fig. 6 shows the relative wear resistance of the composite blocks against granite with the variation of matrix composition. The wear resistance is expressed in terms of ratio of volumetric loss of granite to volumetric loss of tool (Grinding ratio, *G* ratio). It is noted that the test conditions were so severe that a large amount of heat was generated during testing, which caused surface oxidation of the tools. This might have resulted in

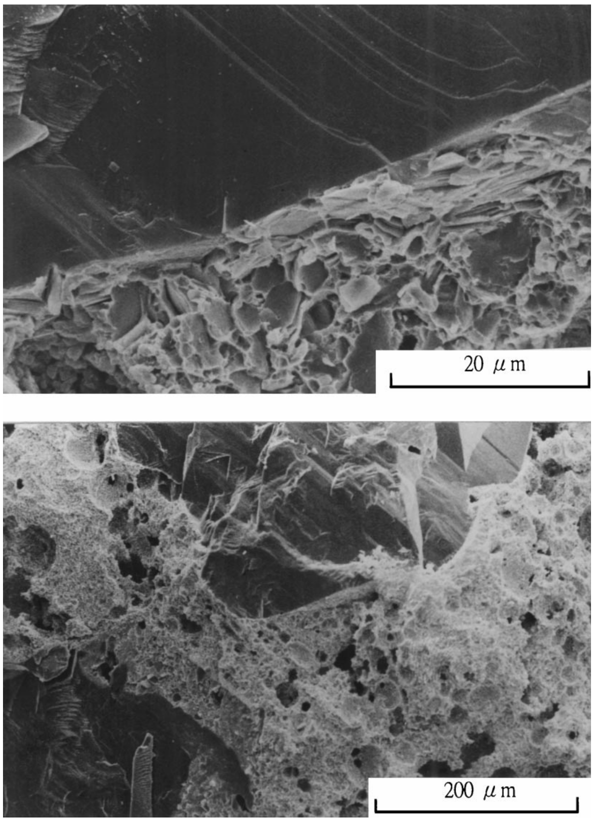


*Figure 5* Fracture surface of a composite block having 50 vol% TiC (0% Mo).

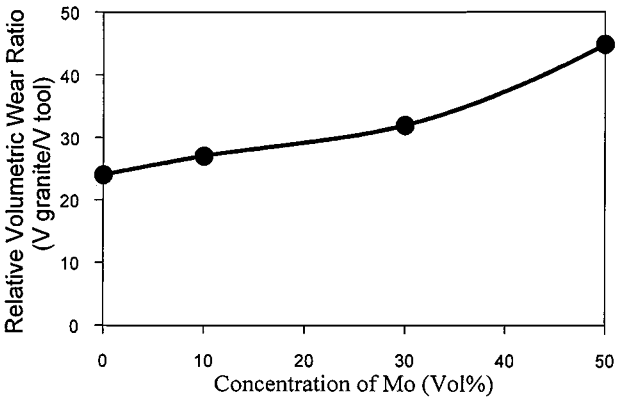


*Figure 6* Variation of relative wear ratio of worked piece to tool with the increase of volumetric percentage of Mo in the composite blocks.

the relatively low $G$ ratios compared with those ranging in the several thousands in a water-cooled test [15]. In this study, there was almost a two-fold increase in the relative wear resistance of the tool when the refractory phase was altered from TiC to Mo. Thus, bonding strength instead of hardness of matrix phase was the primary factor determining the tool life. The relatively high feeding rate during the wear test did not cause fracture of the tool, even when the hardness of the matrix phase was as high as 570 kgf/mm$^2$ and the residual pores in the tools were very abundant. Accordingly, the ductile copper-based alloy did compensate for the low toughness of the components in the composite blocks.

Fig .7 shows the micrographs of an as-ground surface for the composite blocks whose bonding material was composed of 40 vol% Cu-Sn-Ti and 50 vol% of TiC

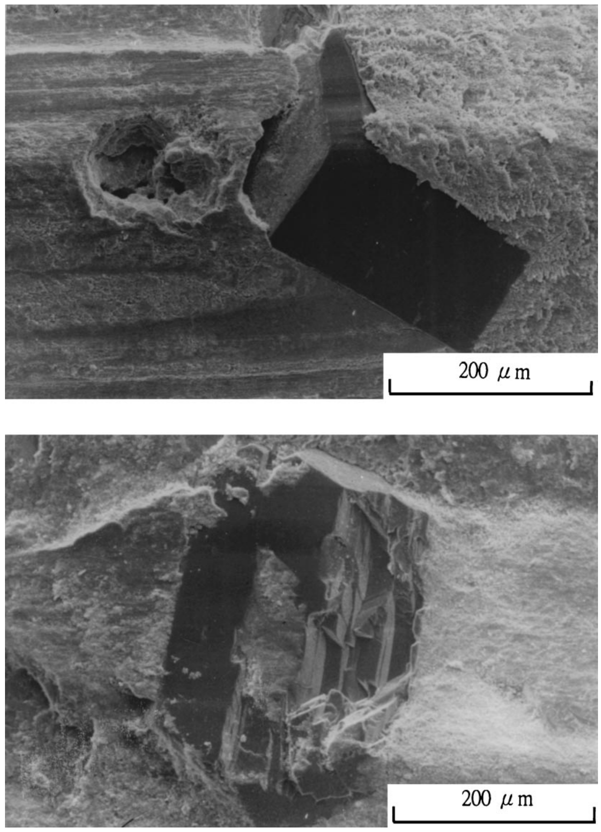


*Figure 7* Micrographs of the as-ground surface of tool, showing the mode of diamond loss during service.

(10 vol% diamond). It can be inferred from the micrographs that the diamond particle was gradually ground off initially, resulting in blunting of the cutting edge. When the area of the blunted surface became relatively large, severe interfacial friction between diamond particles and granite took place during testing, causing the diamond particle to be exposed to a large bending moment. In this circumstance, the diamond particle can either be pulled out of the matrix phase should the interfacial bonding force (bonding strength multiplied by bonding area) be low, or be broken should the interfacial bonding force be high. In fact, the tools fabricated in this study primarily exhibited fracturing of diamond particles. Pull-out of diamond particles was also observed, only always with a thin film attached to the surface of diamond particles, similar to those micrographs shown in Fig. 4. Fracturing of diamond particles resulted in the exposure of new irregular cutting edges. Such a mode of diamond loss certainly would promise a longer tool life than loss by pull-out of diamond particles during service.

## 4. Conclusion

Pressureless sintering is a viable route to the fabrication of high performance diamond particle composite blocks. Enhanced interfacial bonding between the diamond particles and the matrix phase was achieved when Ti was added as an active element into the bonding matrix. When granite is a material to be machined, the transverse rupture strength of the composite block, instead of the hardness of the matrix phase, is a primary factor affecting the tool life. Though without a direct comparison, the general properties and wear mode of diamond particles suggested that the composite blocks fabricated in this study will have performance superior to cobalt-bonded composite blocks fabricated via hot-pressing.


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