Brazing Diamond Grits onto a Steel Substrate Using Copper Alloys as the Filler Metals

S.-M. Chen and S.-T. Lin

Surface-set diamond tools were fabricated by an active metal brazing process, using bronze (Cu-8.9Sn) powder and 316L stainless steel powder mixed to various ratios as the braze filler metals. The diamond grits were brazed onto a steel substrate at 1050 °C for 30 min in a dry hydrogen atmosphere. After brazing practice, an intermediate layer rich in chromium formed between the braze filler metal and diamond. A braze filler metal composed of 70 wt % bronze powder and 30 wt % stainless steel powder was found to be optimum in that the diamond grits were strongly impregnated in the filler metal by both mechanical and chemical types of holding. The diamond tools thus fabricated performed better than conventional nickel-plated diamond tools. In service, the braze filler metal wore at almost the same rate as the diamond grits, and no pullout of diamond grits or peeling of the filler metal layer took place.

Keywords
active metal, brazing, copper alloy, diamond tool

1. Introduction

ALTHOUGH single-point diamond tools are occasionally used for precision machining, they suffer the drawbacks of high cost and brittleness. The usual way of overcoming such drawbacks is to fabricate abrasive diamond tools by impregnating fine diamond grits in a metal matrix. These diamond tools are used extensively for cutting, drilling, and surface grinding of stones, concrete, advanced ceramics, silicon wafer, and cemented carbides (Ref 1-7). There are various routes to the fabrication of diamond tools having distinct structures (Ref 3, 4, 6, 7), among which electroplating and brazing processes are usually employed to fabricate surface-set diamond tools by impregnating a layer of diamond grits onto the surface of metallic substrates. Thus, depending on the fabrication method, the hold on the diamond by the metal matrix can be mechanical, chemical, or a combination of both.

During service, the metal-diamond interface must withstand the moment to which the diamond grits are subjected. A purely mechanical hold on the diamond by the metal matrix is often insufficient and has to be assisted by a chemical one. Chemical bonding between the metal matrix and diamond grits can develop in an active metal brazing process, where the braze filler metal is usually composed of different constituents (Ref 8). Nickel is a common major constituent of braze filler metal, due to its strong affinity to diamond and high resistance to corrosion (Ref 6, 7). It is usually alloyed with chromium as the active metal (carbide former) and with additional metalloids such as phosphorus, boron, and carbon to reduce the melting temperature. Nevertheless, the nickel-based alloys currently used as the filler metals have eutectic temperatures higher than 1000 °C such that only natural diamond grits can be used in brazing practice, because synthetic diamond begins to lose strength beyond 800 °C (Ref 1). Additionally, due to the catalytic effect of nickel on the conversion of diamond into graphite and the high solubility of carbon in nickel at high temperatures, attack against the diamond grits is usually so severe that only diamond grits with grain size larger than about 10 μm can be used.

To solve the problems associated with nickel-based braze filler metals, alloys that have low melting temperatures and low solubilities for carbon, such as copper alloys, are thus potential candidates to be braze filler metals. Copper can be alloyed to reduce the brazing temperature, which in turn can minimize the deterioration of diamond grits and distortion of the metallic substrate. However, its inherent low hardness and poor wettability on diamond are widely believed to limit its success as a braze filler metal (Ref 1, 6, 7). Therefore, copper has to be alloyed with active metals to enhance its applicability as a braze filler metal. Copper alloys containing several percentages of active metals, such as chromium, titanium, tantalum, niobium, and vanadium, can improve the wetting and bonding characteristics between copper alloys and diamond by forming intermediate products that are a few microns thick (Ref 1, 9-12). For example, when copper was alloyed with 0.08 wt% Cr, the bonding strength between copper and diamond increased from 10 to 380 MPa, due to the formation of an intermediate Cr_3C_2 layer (Ref 9). Nevertheless, these active metals are usually added via vapor deposition to enhance their segregation to the diamond surface (Ref 1, 13). Such an approach suffers the drawbacks of being a multiple-step process and possibly causing uneven coating of the active metal on the diamond surface. Therefore, this research investigated the feasibility of brazing diamond grits in a single step, using mixed bronze and stainless steel powders as the braze filler metal. It was expected that active brazing of diamond grits onto the steel substrate and densification of the braze filler metal could be simultaneously achieved by liquid phase sintering.

2. Experimental Procedures

Natural diamond grits having sizes smaller than 80 mesh (about 180 μm) but larger than 100 mesh (about 150 μm) were used. The braze filler metals were prepared by mixing bronze powder (Cu-8.9Sn) and 316L stainless steel powder (Fe-17.5Cr-13Ni-2.7Mo-0.03C) to various ratios. The mean particle sizes of the bronze powder and the 316L powders were 75

S.-M. Chen and **S.-T. Lin,** Mechanical Engineering Department, National Taiwan Institute of Technology, Taipei 106, Taiwan, R.O.C.

and 14 μm, respectively. Table 1 shows the composition of the mixed powders used in this study, denoted as B-10SS, B-30SS, and B-50SS as abbreviations for bronze-10% stainless steel, bronze-30% stainless steel, and bronze-50% stainless steel, respectively. The braze filler metals were utilized in paste form, prepared by ball milling the mixed metal powder (80 wt%), polyethylene glycol (5 wt%), and water (15 wt%). Initially, a steel substrate (AISI 4130) was dipped into the filler metal powder paste and withdrawn. The diamond grits were also, as an alternative, applied to the steel substrate by sprinkling from a sieve device. Brazing practice was carried out in an alumina tube furnace, using a protective atmosphere of dry hydrogen (dew point: −50 °C). The thermal profile was: heat at a rate of 10 K/min to 1050 °C, hold for 30 min, and follow by furnace cooling. The brazed diamond tool was ground and polished with a phenolic bonded diamond grinding wheel. Both optical microscope and scanning electron microscope (SEM) were utilized to examine the morphologies of the as-brazed and as-polished diamond tools. Electron probe microanalysis (EPMA) was carried out to analyze the composition of the as-polished surface, under an accelerating voltage of 15 keV and an average electron beam diameter of 2 μm.

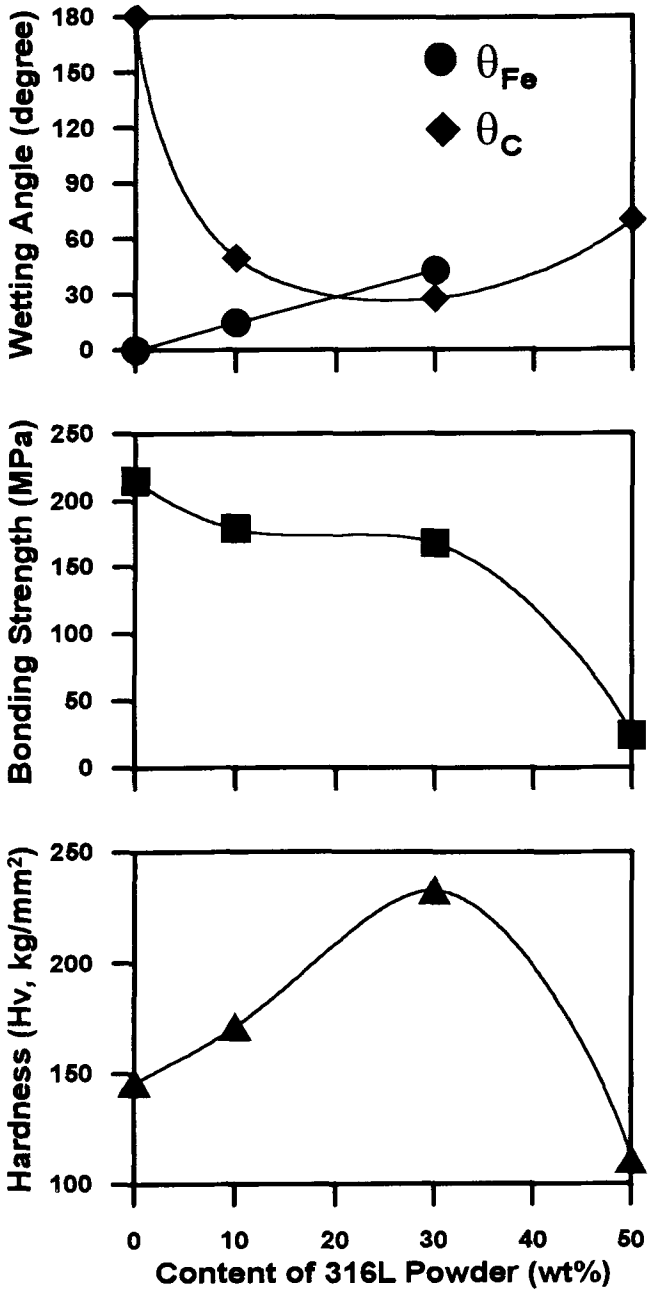


Fig. 1 Effects of relative fraction of 316L stainless steel powder in the braze filler metal on the wetting and bonding characteristics between the braze filler metal and the graphite or steel substrate, and on the hardness of the braze filler metal

Wetting and bonding characteristics between braze filler metal and diamond, and between braze filler metal and steel substrate, are important in affecting the diamond tool life. Strong bonding between the braze filler metal and diamond can prevent pullout of diamond grits during service, while strong bonding between the filler metal and steel substrate can prevent stripping or peeling of the braze filler metal layer during service. Thus, wetting and bonding tests were carried out. Graphite plate was used instead of large faceted diamond grain, because it has been shown that the wetting behavior between copper alloys and diamond is close to that between copper alloys and graphite (Ref 9-11). Wetting behavior between the molten filler metal and steel substrate or graphite substrate was examined using SEM. Bonding strength between the filler metal and steel substrate or graphite substrate was determined by tensile testing. The specimens were prepared by brazing two steel or graphite segments together using the braze filler metal in a sandwich-like structure. In addition, hardness of the braze filler metal was determined using the liquid phase sintered compact of mixed bronze and stainless steel powder. All of the specimens for the above-mentioned tests were prepared using the same thermal profile as that used in brazing the diamond grits.

3. Results and Discussion

3.1 *Properties*

Figure 1 shows the effects of braze filler metal composition on the wetting and bonding characteristics between the filler metal and steel substrate or graphite, as well as the hardness of the sintered filler metal compacts. The bonding strength between the braze filler metal and graphite substrate is not shown in this figure because cracks existed in the graphite substrate after brazing practice. It was also found that B-50SS was not sintered to a fully dense structure, so the following discussion is valid only for the braze filler metals containing lower fractions of stainless steel powder.

Table 1 Composition of three braze filler metals, prepared using mixed bronze and 316L stainless steel powders

Filler metal	316L content, wt%	Composition, wt%					
		Cu	Sn	Fe	Cr	Ni	Mo
B-10SS	10	82.0	8.0	6.7	1.7	1.3	0.3
B-30SS	30	63.8	6.2	20.0	5.3	3.9	0.8
B-50SS	50	45.6	4.4	33.4	8.8	6.5	1.3

The wetting and bonding characteristics between the braze filler metal and steel substrate deteriorated with the increase of stainless steel powder in the braze filler metal. Fracture of the sandwich-like specimens propagated mostly along the interface between the braze filler metal and steel substrate. The bonding strength was approximately between 170 and 220 MPa. Figure 2 shows a fracture surface of a sandwich-like specimen brazed using B-30SS as the filler metal. Clustering of particles less than 20 μm can be clearly observed. On the other hand, the wetting behavior between the braze filler metal and graphite was significantly improved with the increase of stainless steel powder in the braze filler metal. Such a trend is similar to a previous report which showed that addition of 0.12 wt% Cr to copper substantially reduced the wetting angle between copper and graphite, from 130° to 40° (Ref 11). The improved wetting behavior was attributed to the formation of an intermediate carbide layer at the metal-carbon interface (Ref 10).

The correct exposure of the diamond grits during service is vital to cutting efficiency, which is partially determined by the hardness of the braze filler metal. Braze filler metal that is too hard or wear resistant will not be removed rapidly enough to keep fresh diamond cutting edges exposed, which will result in the phenomenon of "glazing" (Ref 4). On the other hand, braze filler metal that is too soft or too easily eroded will cause premature loss of the diamond grits. The hardness of the sintered braze filler metal compact increased substantially with the increase of stainless steel powder in the braze filler metal. Highest hardness was achieved by the sintered B-30SS compact (233 kgf/mm^2 HV), although even this was much lower than the hardness of nickel-based alloys used in active metal brazing of diamond tools (>600 kgf/mm^2 HV) (Ref 14). In comparison, the hardness of the metal matrix for most hot-pressed diamond tools lies between 120 and 255 kgf/mm^2 HV (Ref 1). Additional alloying with tungsten or tungsten carbide can further increase the matrix hardness (Ref 15). The hardness of sintered B-30SS was much higher than that of 98% dense hot-pressed bronze compact (Hv 146 kg/mm^2 HV) or 96% dense sintered 316L stainless steel compact (Hv 164 kg/mm^2 HV), attributed to the solution hardening and/or precipitation hardening effects. Partitioning of elements of the initial powders occurred to a substantial extent during liquid phase sintering, even though clustering of particles that were originally 316L stainless steel powder can still be found in Fig. 2.

3.2 *Microstructure*

Figure 3 shows cross sections of brazed diamond tools that are approximately perpendicular to the interface between the braze filler metal and steel substrate. The diamond grits were properly embedded in the fully dense braze filler metals when B-10SS and B-30SS were used as the braze filler metals, but they were easily pulled out of the poorly densified braze filler metal during grinding when B-50SS was used. It can also be observed in this figure that wetting behavior of the braze filler metal on diamond grits was improved by changing the filler composition from B-10SS to B-30SS. Improved wetting enhanced the protruded height of diamond grits, which in turn could possibly promote higher cutting rates and cutting efficiencies.

Figure 4 shows the surface of a diamond tool, brazed using B-30SS as the filler metal, in the as-polished and as-etched states. This surface is approximately parallel to the interface between filler metal and steel substrate. There was no pullout of diamond grit during polishing, indicating that the diamond grits were strongly impregnated in the filler metal. Three discrete phases could be discriminated by their distinct morphologies in the filler metal matrix prior to etching: the phase surrounding the diamond grits, the phase composed of interconnected spheroidal grains, and the continuous phase that was in the liquid state during sintering. The phase surrounding the diamond grits was difficult to etch, while the interconnected spheroidal grains could be etched easily. This observation suggests that partitioning of chromium occurred during brazing. Analysis of the phase surrounding the diamond grits by line scanning in EPMA indicated that this layer was rich in chromium and had a thickness of about 13 μm. Such a layer is widely believed to be a carbide layer (Ref 8, 9, 13). For example, an intermediate Cr_3C_2 layer about 1.8 μm thick formed when Cu-0.33wt%Cr (Cu-0.4at.%Cr) was used as the braze filler metal (Ref 9). The intermediate layer can be further observed in the fracture surface near the interface between a diamond particle and the braze filler metal, as shown in Fig. 5. Fracture propagated close to the diamond surface but within the carbide layer, leaving clear pits.

To properly hold the diamond grits, both wetting and bonding criteria must be satisfied for diamond tools fabricated by brazing. Fabrication process also must not result in excessive loss of diamond due to chemical interaction with the metal, or reversion of diamond to the more stable graphite (Ref 1, 5, 9). Based on previous illustrations, the wetting and bonding characteristics between the braze filler metal and diamond grits were improved by the formation of an intermediate carbide layer near the diamond-metal interface. The hold on the diamond grits by the braze filler metal was achieved by atomic reaction at the interface, in addition to the mechanical support. Though atomic reaction occurred, the intermediate carbide layer could reduce the further loss of diamond because it behaved as a diffusion barrier. Nevertheless, the loss of diamond could still be severe for fine diamond grits. For example, if the layer surrounding the diamond grits shown in Fig. 4 was Cr_3C_2,

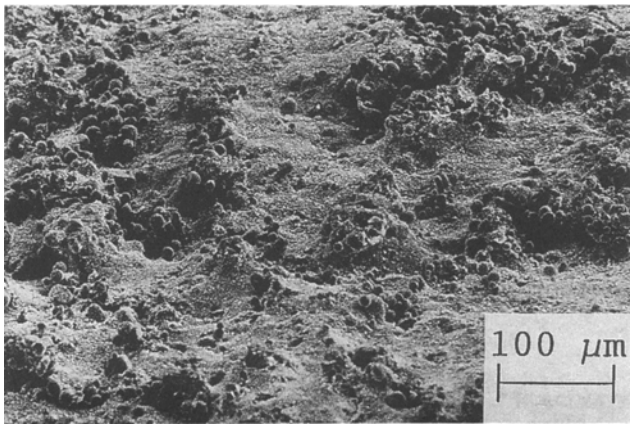
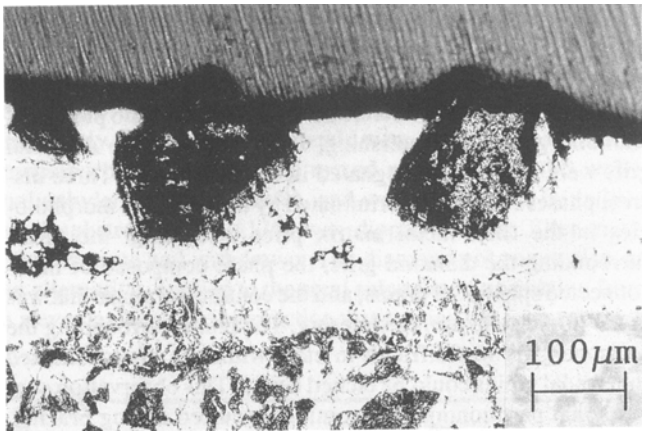
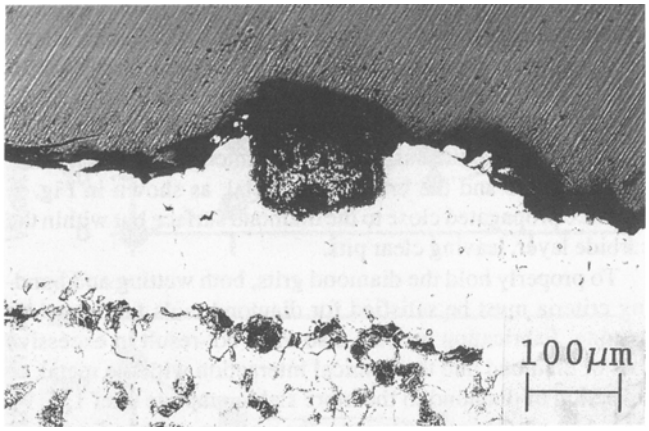


Fig. 2 Tensile fracture surface of the steel/filler metal/steel sandwich specimen, showing clear clusters of spheroidal particles



(a)

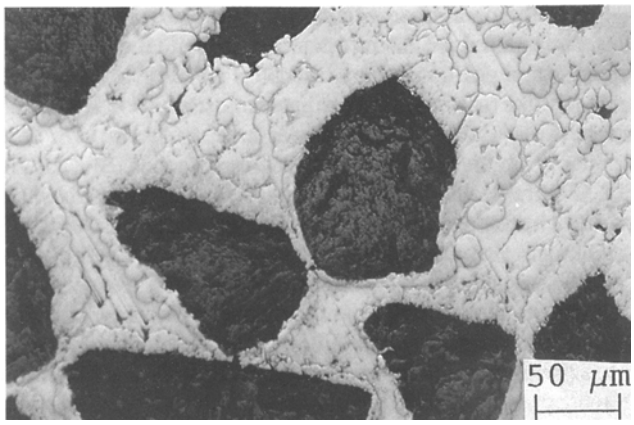


(b)

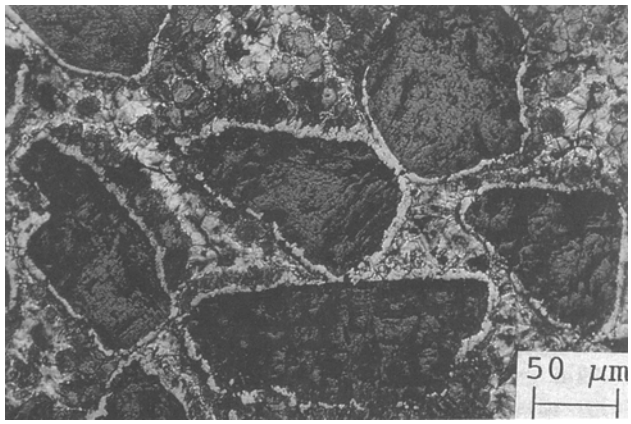
(c)

Fig. 3 Cross sections of brazed diamond materials. (a) B-10SS. (b) B-30SS. (c) B-50SS. The dark items in (a), (b) and, (c) are diamond particles.

formation of a 13 μm thick carbide layer consumed about 3.7 μm of diamond from its surface. Therefore, further optimization of processing temperature or processing time is required if diamond grits smaller than 10 μm are to be used.



(a)



(b)

Fig. 4 (a) As-polished and (b) as-etched microstructures of a diamond tool brazed using B-30SS as the filler metal

3.3 *Performance Comparison*

Surface-set diamond tools processed by electroplating or by brazing were compared with respect to their tool lives. The electroplated metal was nickel, while the braze filler metal was B-30SS. Figure 6 shows a typical configuration of the nickel-plated diamond tools. The nickel matrix near the diamond grits exhibited a concave profile, caused by the nonconducting characteristic of diamond. Therefore, if the protruded height of the diamonds is large, the diamond grits can be easily pulled out of the nickel matrix long before the diamond grits are worn out. To avoid such a problem, the diamond grits have to be embedded so deeply that the embedded portions are usually unavailable for cutting before the tools become glazed. In addition, a low protruded height of diamond grits may cause buildup of heat when the tools are rubbed against the workpiece. On the other hand, for the brazed diamond tools, the diamond grits were impregnated to a shallow depth and the braze filler metal exhibited a wetting coverage on the diamond grits, as shown in Fig. 3(b). This promoted high diamond exposure and greatly eliminated the loss of diamond particles through pullout. Furthermore, the diamond grits were bonded with about 30% of the crystals covered with the braze filler metal, which might allow greater scarf clearance, higher cutting speed, and lower heat buildup.

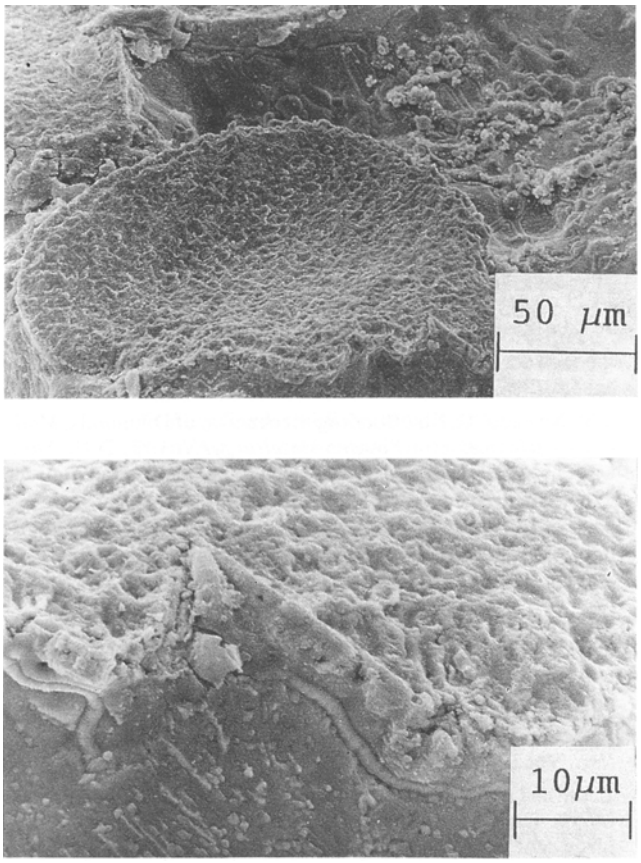


Fig. 5 Microstructure of the fracture surface near the carbide layer

Grinding wheels capable of forming curve profile were fabricated by these two processing routes to grind against granite plates. The granite plates, which originally had right angle edge, were ground into quarter-circle curved edge 20 mm in radius. Grinding was carried out at a rotation frequency of 6000 rpm in a wet condition, using a manually operated machine (Master 3000, Marmoelettromeccanica, Italy). The machine ran at a rate of 10 ± 2 m/min. The average tool lives for the electroplated and brazed tools, based on three tested specimens each, were 36 and 52 m, respectively. Relatively speaking, the brazed diamond tools yielded smoother ground surface with less noise.

Impregnation of diamond grits by electroplating produced a simple mechanical entrapment of the diamond grits on the plated nickel layer and a mechanical type of adhesion between the plated nickel layer and the steel substrate. Depending on the surface cleaning conditions, the adhesion strength between the plated nickel layer and the steel substrate is usually less than 140 MPa (Ref 16). Therefore, stripping or peeling of the plated nickel layer could take place when the shearing stress in service is too high. Figure 7 compares the electroplated and brazed diamond tools that experienced a continuous dry grinding operation against granite for 3 min at a rotation frequency of 3600 rpm. Peeling of the plated nickel layer was so severe for the electroplated diamond tools that the plated layer virtually disintegrated long before the diamond grits were worn out. The braze filler metal did not strip or peel because interfacial bonding strength between the braze filler metal and the steel substrate was high. Furthermore, wearing of the braze filler metal proceeded at the maximum rate as the wear rate of the diamond grits, such that the diamond grits were not dislodged prematurely from their positions and the microstructures of the diamond tools in the worn state were similar to that shown in Fig. 4. Examination of the ground diamond grits under higher magnification, as shown in Fig. 8, indicated that microfracture of the diamond grits occurred during service such that numerous new sharp cutting edges were exposed. This might explain why brazed diamond tools achieved smoother ground surface and less noise.

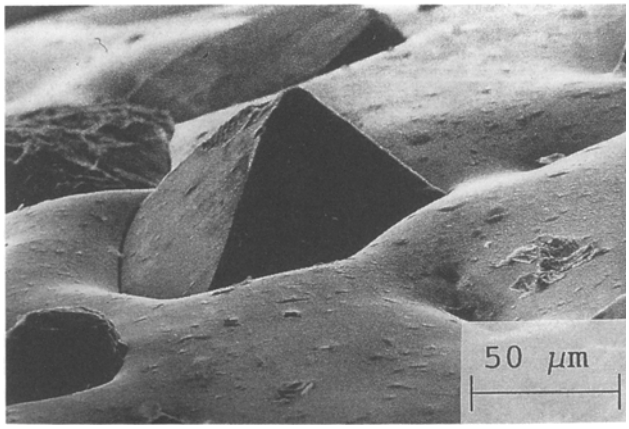


Fig. 6 Microstructure of an electroplated diamond tool surface. Note the nonwetting of the electroplated nickel on the pyramid of diamond.

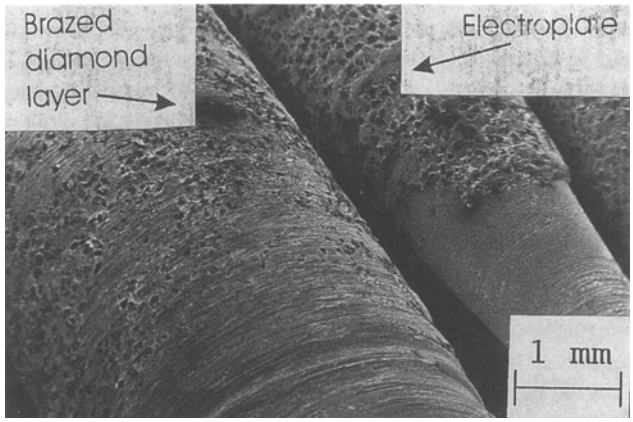


Fig. 7 A comparison of the electroplated and brazed diamond tools after dry grinding. Severe peeling of the plated nickel layer had occurred for the electroplated diamond tool, while the diamond grits and the braze filler metal layer were strongly bonded together for the brazed diamond tool.

4. Conclusions

An active metal brazing process, using copper alloys prepared by mixed bronze powder and 316L stainless steel powder as the braze filler metal, was found to be a viable route for fabricating surface-set diamond tools. The process produced very

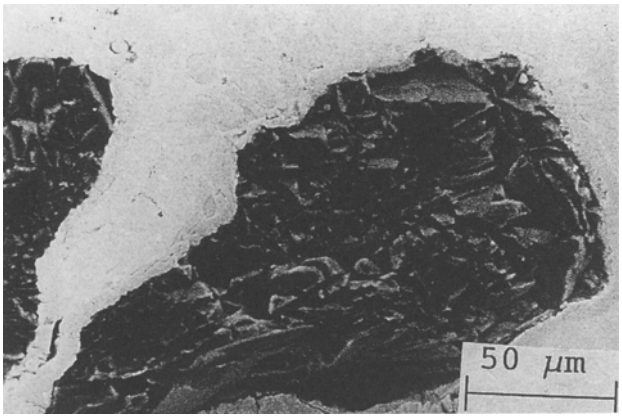


Fig. 8 Examination of a ground diamond grit at high magnification, showing the existence of fine cutting edges in the diamond grit

efficient diamond tools yielding increased productivity and part consistency. The braze filler metal was composed of 70 wt% bronze powder and 30 wt% 316L stainless steel powder. After brazing, a fully dense braze filler metal matrix evolved that was composed of three distinct phases, among which was a chromium-rich intermediate layer about 13 μm thick that formed between the metal matrix and diamond grits. A combined chemical and mechanical type of holding on the diamond grits was attained, which was the origin of enhanced grinding performance when the braze material was compared with the electroplated diamond tools in side-by-side tests.

References

1. J. Konstanty, The Materials Science of Stone Sawing, *Ind. Dia. Rev.*, Vol 51, 1991, p 27-31
2. J.R. Chalkley and D.M. Thomas, The Tribological Aspects of Metal-Bonded Diamond Grinding Wheels, *Powder Metall.*, Vol 12, 1969, p 582-597
3. T. Fujimori, Y. Yamamoto, and A. Okada, Improvement of Strength and Cutting Performance of Industrial Diamond, *J. Mater. Sci. Soc. Jap.*, Vol 32, 1995, p 39-49
4. M. Igharo and J. Russell, Development of Diamond Impregnated Cutting Tools, *Surf. Eng.*, Vol 10, 1994, p 52-55
5. M. Jennings and D. Wright, Guidelines for Sawing Stone, *Ind. Dia. Rev.*, Vol 49, 1989, p 70-75
6. J.T. Lowder and E.M. Tausch, Method of Manufacturing Diamond Abrasive Tools, U.S. Patent 3,894,673, 15 July 1975
7. J.T. Lowder and E.M. Tausch, Diamond Abrasive Tool, U.S. Patent 4,018, 576, 19 April 1977
8. Z.Y. Xu and Z.D. Lin, Bonding Mechanism of Diamonds, *Modern Developments in Powder Metallurgy*, Vol 17, D.N. Aqua and C.I. Whitman, Ed., Metal Powder Industries Federation, 1984, p 273-288
9. P.M. Scott, M. Nicholas, and B. Dewar, The Wetting and Bonding of Diamonds by Copper-base Binary Alloys, *J. Mater. Sci.*, Vol 10, 1975, p 1833-1849
10. D.A. Mortimer and M. Nicholas, The Wetting of Carbon by Copper and Copper Alloys, *J. Mater. Sci.*, Vol 5, 1970, p 149-155
11. D.A. Mortimer and M. Nicholas, The Wetting of Carbon and Carbides by Copper Alloys, *J. Mater. Sci.*, Vol 8, 1973, p 640-648
12. E. Benz, Vacuum Brazing as a Production Method, *Ind. Dia. Rev.*, Vol 51, 1991, p 249-250
13. Z. Lin and R.A. Queeney, Interface Bonding in a Diamond/Metal Matrix Composite, *Modern Developments in Powder Metallurgy*, Vol 20, P.U. Gummeson and D.A. Gustafson, Ed., Metal Powder Industries Federation, 1988, p 443-450
14. S.T. Lin, "Active Metal Brazing of Diamond Tools," NTIT-ME-110, National Taiwan Institute of Technology, Taipei, Taiwan, April 1996
15. Metallurgy of Diamond Tools, *Ind. Dia. Rev.*, Vol 45, 1985, p 248-250
16. K.G. Budinski, *Engineering Materials: Properties and Selection*, 3rd ed., Prentice Hall, 1989, p 540