Abrasion resistant active braze alloys for metal single layer technology

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The technology of brazing a single layer of abrasive on to the surface of a grinding tool, metal single layer (MSL) technology, provides an alternative way to make use of the superabrasives diamond and cubic boron nitride in machining ceramic materials or superalloys, cutting of construction materials, etc. For certain applications of MSL bonded wheels, the grinding or cutting process is very abrasive and the wear resistance of the braze alloy often dominates the wheel failure. The wear resistance of the braze alloy typically used for MSL can be improved by incorporating hard dispersoids. The present study examines the effect of particulate molybdenum, tungsten, SiC, WC, and TiC dispersoids on the wear resistance of Cu–Sn–Ti active braze alloys. Among these, TiC was identified as most effective in enhancing the abrasive resistance of the braze alloy. It was found that a braze alloy of 75Cu–25Sn–12·5Ti–7·5Zr–10TiC–0·2C (by weight) exhibits high wear resistance and excellent performance in cutting tests on green concrete.

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INTRODUCTION

Designers are changing over to ceramic materials and ceramic reinforced materials for improvements in wear resistance, corrosion resistance, and higher thermal strength. Many high performance alloys, cermets, composites, and in particular ceramics can not be machined by any technology other than grinding.[1,2] Thus there is a continual need for improved grinding technology.

For an abrasive to function propertly, it must be harder than the material being ground. Based on this criterion, the superabrasives diamond and cubic boron nitride (CBN) are highly suitable materials to make grinding wheels. Diamond is suited to grind WC, natural stone, granite, concrete, and ceramics, but unsuitable for the grinding of ferrous materials as a result of its chemical instability and reaction with the workpiece.[3,4] Moreover, the tendency for graphitisation of the diamond at high temperature (above 800°C) may also prohibit manufacture using diamond tools at elevated temperatures. Compared with diamond, CBN is less reactive in the presence of ferrous alloys and is thermally stable at elevated temperatures (~1300°C). Although a less hard and often more expensive superabrasive than diamond, CBN is widely used in the grinding of ferrous materials such as tool steel. Grinding with diamond and CBN can, therefore, complement each other.

Metals are commonly used to bond superhard abrasives, such as diamond and CBN, to form the abrasive section of a grinding tool. Single layer tools are either obtained by attaching the abrasive using brazing or made by electroplating.[5] The metal alloys used for wheel bonding consist of various compositions of copper, tin, iron, chromium, nickel, etc. Two of the most popular compositions used in brazing superabrasive wheels are Au–Cu eutectic with 2–4·5 wt-%Ti and Cu–Sn–Ti alloy. Also quite common, especially in the production of diamond wheels, is a nickel electroplated bond which is deposited on the metal tool body from a suitable electroplating bath. This deposit bonds the diamond grains distributed over the wheel surface usually in the form of a single layer. There are many disadvantages to the electroplating process. The first is its high production cost. In order to guarantee full coverage of the diamond wheel, a considerable amount of diamond must be kept in the electroplating bath and the cost of the superabrasives is high, of the order of thousands of dollars per kilogram. Second, controlling the accuracy of certain wheels with complex grinding contours is difficult in the electroplating process. Third, there is no chemical reaction between the diamond and the nickel; the bond is inherently weaker than that formed by chemical reaction. Therefore, a high volume fraction of nickel must be deposited around the diamond crystals and a large quantity of heat may be generated in the swarf removal process during grinding. An alternative method is to use metal single layer (MSL) bonds produced by brazing.[6]

In MSL technology, the grinding wheel has a steel core and a layer of diamonds which are brazed with a special alloy.[7] The first step is to mix a carbide forming substance such as titanium or chromium with the traditional braze alloy powder and form a slurry paste with a temporary binder. The paste is then applied to a tool substrate and at least a monolayer of diamond particles on the coating material. Finally, the preform is brazed at a temperature sufficient to form a metal carbide on the diamond and to braze the diamond to the tool substrate. Since an active braze exhibits good wetting characteristics, in the process of brazing molten braze forms a meniscus at the diamond periphery providing even stronger bonding of the diamond crystals to the substrate.

The life of the MSL bond grinding wheel is strongly dependent on the aggressiveness of the material being ground. Certain machining processes such as cutting green concrete are very abrasive. The wear resistance of the braze alloy plays an important role in determining the life of an MSL wheel. Wear of the braze alloy results in undercutting of the diamond crystal support and hence premature removal of the diamond particles. A wear resistant braze alloy improves the life of MSL bonded cutting wheels. Because the braze alloy can not be solution treated in a vacuum brazing process, introducing hard particles is one of the most convenient ways to improve the wear resistance of the bond metal.

In reactive brazing, the active element reacts with the superabrasive crystals as well as the added hard particles. This could result in consumption of the active element and deterioration of the wettability of the braze alloy. Moreover, the size and morphology of the hard particles also plays an important role in determining the strength, toughness, and abrasive resistance of the braze alloy. The purpose of the present study was to demonstrate improvement in the wear resistance of 70Cu–21Sn–9Ti (wt-%) active braze alloy by introducing hard particles. Effects of dispersoids such as molybdenum, tungsten, TiC, SiC, and WC were tested in these experiments. The most wear resistant braze alloy was further examined for its performance in green concrete cutting.

EXPERIMENTAL

The braze alloy was prepared by mixing metal powders, reinforcements, and organic binder gel to form a slurry paste. Particle size and morphology of the metal powders and reinforcements are shown in Table 1. The abrasive selected for the present study was 20/30 mesh (0·841–0·595 mm) natural diamond. Specimens with different chemical compositions were vacuum brazed at selected temperatures in the range 880–920°C. Each specimen was examined by stereomicroscopy to find any solidification cracks and to measure the meniscus shape around the diamond. An optical microscope was used for general metallurgical observations. A shear test was performed on the brazed 20/30 mesh diamond crystal to evaluate the bonding strength between the diamond and the braze alloy. A Vickers microhardness test of the braze alloy with a load of 200 g was also performed. After completing this first stage examination, qualified braze alloys were subjected to further wear and erosion tests in order to evaluate their properties more accurately.

Wear tests were performed by abrading the cross-section of a 7·16 mm diameter rod with 180 grade SiC paper at a constant normal load of 10 N in a typical pin on disc type of test. The accumulated weight loss of the specimen was measured after each minute of testing. The erosion test was performed with a steady nitrogen gas flow at $5\cdot5 \times 10^5$ Pa, a 6·35 mm distance, and a 30° impingement angle for 60 s. Dry SiC particles, 320 grit (32–44 μm), with a flow rate of $1\cdot07$ g min^{-1} were used as erosion particles throughout the experiment. Similarly, the weight loss of the test specimen was measured. Although the braze alloys have different densities, the results of the erosion test and wear test were measured by mass loss. In order to make all data comparable, every datum was calibrated by the braze alloy density and converted to volume loss. The measured braze alloy densities shown in the appendix were used to determine the volume losses.

To verify the abrasive resistance of the new alloy, a more abrasive cutting test was also performed. Two cutting wheels were tested. Each MSL diamond cutting disc was 228·6 mm in diameter and 1·59 mm thick. Green concrete blocks with dimensions of 304·8 × 304·8 × 7010 mm were used with a depth of cut of 25·4 mm. Two braze alloys were evaluated using this test:

(i) 77Cu–23Sn–10Ti (by weight); 77Cu–23Sn prealloyed bronze powder was mixed with titanium hydride powder and 40/50 mesh IMG diamonds from Tomei Co. were applied as the abrasive

(ii) 75Cu–25Sn–12·5Ti–7·5Zr–10TiC–0·2C (by weight); 40/50 mesh IMG 'artificial diamonds' from Tomei Co. were used as the abrasive.

A Cambridge scanning electron microscope was used for failure analysis of the MSL wheels after the cutting test, using an operating voltage of 25 kV. The chemical composition of the phases in the braze alloys was analysed using a Jeol JXA–733 Superprobe equipped with a wavelength dispersive spectrometer. The spot size used in the analysis was 1 μm. In X-ray analysis of the braze alloys, the specimen was prepared by melting the alloy powder mixture at the brazing temperature to form a bulk metal. The polished bulk metal was examined using X-rays.

Table 1 Size and morphology of powders used

Powder	Size	Morphology
Cu–Sn bronze	325 mesh, <44 μm	Spherical
TiH_2	<10 μm	Irregular
Zr	325 mesh, <44 μm	Irregular
C black	<1 μm	Irregular
TiC	325 mesh, 10–44 μm	Irregular
SiC	<10 μm	Irregular
WC	325 mesh, <44 μm	Irregular
Mo	<10 μm	Irregular
W	325 mesh, <44 μm	Irregular

RESULTS AND DISCUSSION

Theory of developing abrasion resistant braze alloy by introducing hard particles

Archard's equation is a simple yet valuable expression for the volume of ductile material removed by wear[8,9]

$$V_w = K A_w P / H \qquad (1)$$

where V_w is the volume of material removed by wear per unit sliding distance, K is a dimensionless number known as the Archard wear coefficient, A_w is the normal contact area, P is the normal pressure, and H is the indentation hardness of the softer material. The wear resistance R_w is simply defined as the reciprocal of the wear volume

$$R_w = 1/V_w \qquad (2)$$

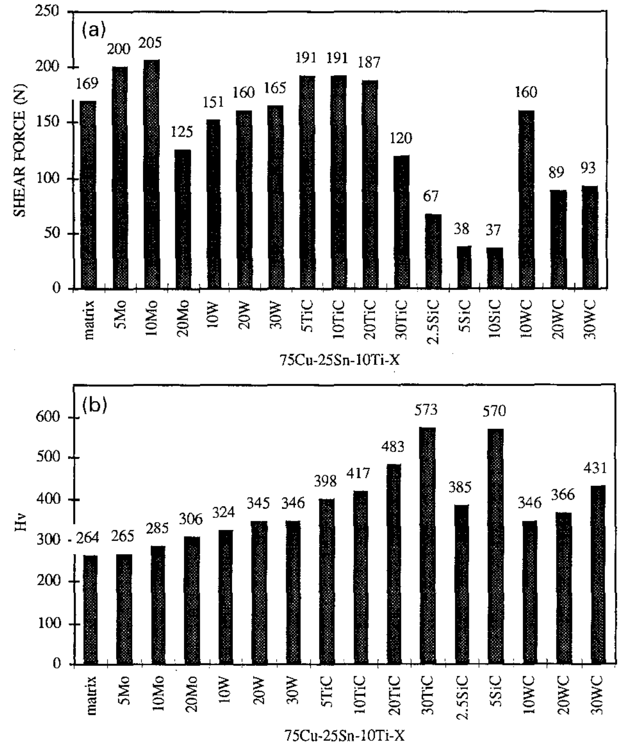
The wear property of a material is improved by producing a hard second phase in the matrix. The effect of the size ratio of the swarf to the hard particles in the matrix is important in determining the effectiveness of the added hard particles.[10,11] The small coherent particles are often sheared during plastic deformation. For large incoherent particles (larger than 1 μm), Orowan bypass can readily take place. However, fine incoherent particles, e.g. in the size range 10–100 nm, can provide an effective barrier to dislocation motion. As a result, hard precipitates or particles such as carbides can be useful in decreasing abrasive wear if they are well bonded within the matrix. Provided that the reinforcement is well bonded to the matrix, ceramic reinforced metal matrix composites generally show much better resistance to unlubricated sliding wear than the unreinforced matrix.[12–18] However, a small increase in the coefficient of friction and a considerable decrease in ductility of the composite was observed in these cases.

It is also important to note that brittle material has an additional mode of abrasive wear, namely microfracture. This occurs when the applied stress exceeds the fracture strength of the material. If the condition is high stress abrasion, widespread fracture of the reinforcing phase occurs and the wear resistance may be no different from that of the unreinforced phase.

The erosive wear performance is strongly dependent on the interparticle spacing and the choice of dispersoid. The composite will not exhibit good erosion resistance unless it contains a very high volume of ceramic.[12] This is because the erosion of brittle materials is distinctly different from that of ductile materials. The mechanism of material removal involves cracks initiated by brittle fracture. The erosion rate of ceramics is given by[10]

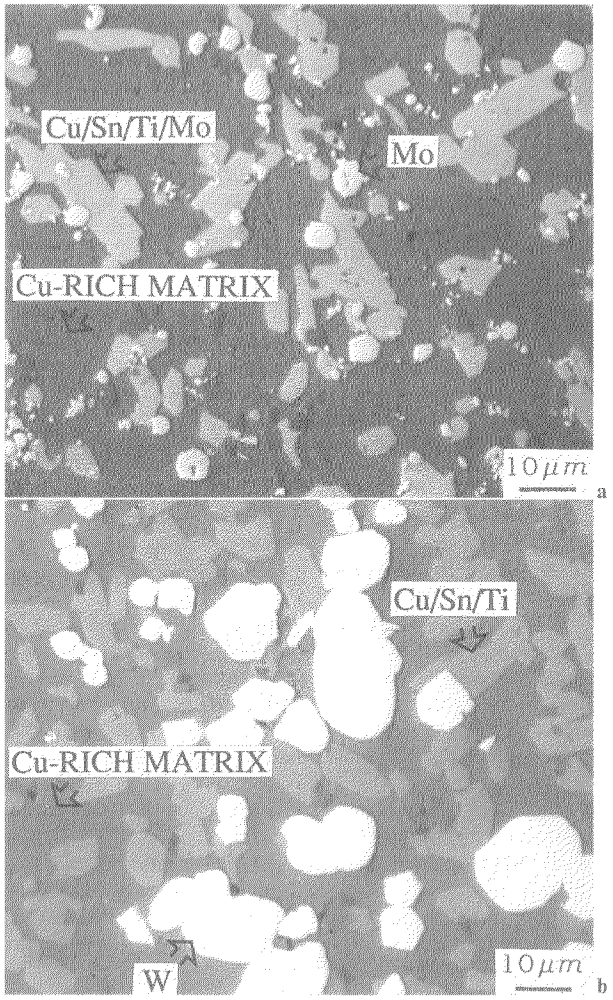
$$V_e \propto v_0^{3\cdot2} d^{0\cdot66} \rho^{1\cdot3} K_{IC}^{-4\cdot3} H^{-0\cdot25} \qquad (3)$$

where v_0, d, and ρ are particle velocity, diameter, and density respectively, H is material hardness (Knoop hardness in kilograms/millimetre squared), K_{IC} is material toughness, and V_e is the volume loss by erosion per unit



a shear test; *b* microhardness test

1 Results of given tests for various particle additions



a 75Cu–25Sn–10Ti–10Mo; *b* 75Cu–25Sn–10Ti–20W

2 Microstructure of given braze alloys brazed at 900°C for 30 min

mass impacted. Equation (3) explains why introducing some very hard ceramic particles will not produce improved erosion resistance. The fracture toughness of the material plays the most important role in determining the erosion rate. This formula demonstrates that the hard, brittle second phase particles can actually be detrimental to erosion resistance.

Developing abrasion resistant copper base active braze alloys

Metal matrix composites containing a high volume fraction of carbide, nitride, boride, and/or oxide particles are frequently the materials of choice for applications which require high wear resistance. Suitable particles introduced into the braze can not be judged based on their hardness alone. Chemical stability, metallurgical compatibility, and toughness should also be considered. Some refractory metals, such as molybdenum and tungsten, which possess excellent erosion resistance, were also included in the test.[10]

The 75Cu–25Sn–10Ti braze with molybdenum, tungsten, TiC, SiC, and WC additions was evaluated. Figure 1 shows the averaged shear and microhardness test results for 75Cu–25Sn–10Ti–X braze alloys. Each datum in Fig. 1 is the averaged value of 10 measurements. Some experimental data deviating from their average value were observed in both the shear and microhardness tests. The deviation in the shear test originates from different cross-sections of the diamonds. However, the average values can be used as an indication of bond strength between the diamond and various braze alloys, although the inhomogeneous microstructure of the braze alloy is responsible for variations in hardness values.

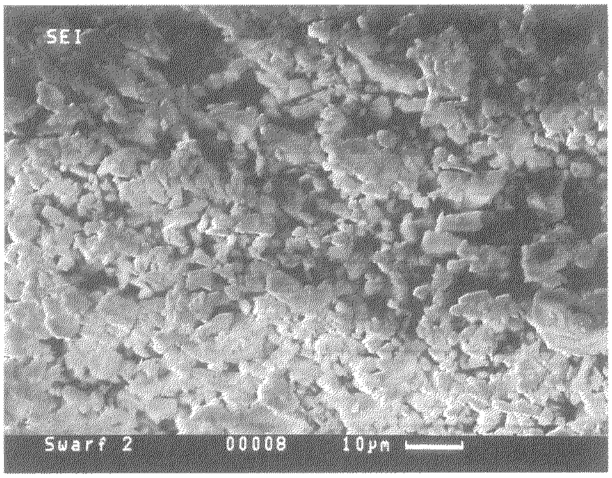
Figure 2*a* shows the scanning electron microscopy (SEM) backscattered images of 75Cu–25Sn–10Ti–10Mo. Three phases, the copper rich matrix, the Cu–Sn–Ti–Mo phase, and molybdenum can be seen in Fig. 2*a*. Based on the electron microprobe analysis, the chemical composition of the copper rich matrix is 88·6Cu–10·8Sn–0·5Ti–0·1Mo and the solubility of molybdenum in the copper rich matrix is very limited. However, the chemical composition of the Cu–Sn–Ti–Mo phase is 10·9Cu–52·7Sn–34·3Ti–2·1Mo; part of the molybdenum reacted with the braze alloy and formed a new phase. The hardness improvement of the braze with molybdenum additions is not very large despite its high elastic modulus. If the molybdenum addition is greater than 15·4 wt-%, i.e. $20/(75+25+10+20)\times 100$, the bond between the diamond and the braze deteriorates.

Figure 2*b* shows the SEM backscattered images of 75Cu–25Sn–10Ti–20W. Similarly, three phases, the Cu rich matrix, the Cu–Sn–Ti phase, and tungsten, can be seen in Fig. 2*b*. However, the chemical composition of the copper rich matrix is 88·2Cu–11·5Sn–0·3Ti and the chemical composition of the Cu–Sn–Ti phase is 8·4Cu–54·8Sn–36·8Ti. There is no dissolution of tungsten in the copper rich matrix; tungsten will not react with the braze alloy, but adding tungsten powder will increase the braze alloy hardness while maintaining acceptable bonding force between the diamond and the braze. Adding TiC below 15·4 wt-% provided the best result. The braze with TiC additions possesses both the highest hardness and the highest bond strength. A poor bond is observed for all specimens containing SiC particles. The optimal value of WC particle additions is below 8 wt-%.

Titanium is thermodynamically favoured to reduce WC or SiC.[19] It is reported that titanium can react with SiC and form TiC and Ti_5Si_3 sequentially via[20]

$$SiC(s) + Ti \rightarrow TiC(s) + Si(s)$$

$$3Si + 5Ti \rightarrow Ti_5Si_3(s)$$



3 Morphology of Al_2O_3 swarf after grinding test

Consequently, SiC is not an appropriate dispersoid for this application.

Based on experiments, TiC displays the best metallurgical compatibility in titanium containing copper base braze alloys. It is also reported that additions of TiC can greatly improve the abrasion resistance of iron alloys.[21] As the volume fraction of TiC increases, the mean free path between the carbide particles decreases. The ability of the abrasive to deform the softer matrix and to remove it through a wear mechanism is much reduced. Therefore, it is expected that higher volume fractions of TiC display better abrasion resistance under the conditions of material removal via microploughing and microcutting. However, the bond strength deteriorates as the concentration of TiC particles exceeds 15·4 wt-%. Consumption of the active element and a decrease of the ductility of the braze are two possible explanations for this phenomenon. Significant hardness improvement can not be achieved by a low volume fraction of ceramic particle addition. A large volume fraction of ceramic particles can cause the bond strength to deteriorate. Therefore, there is an optimal quantity of each ceramic particle. Several compositions (by weight) were selected for further wear and erosion tests:

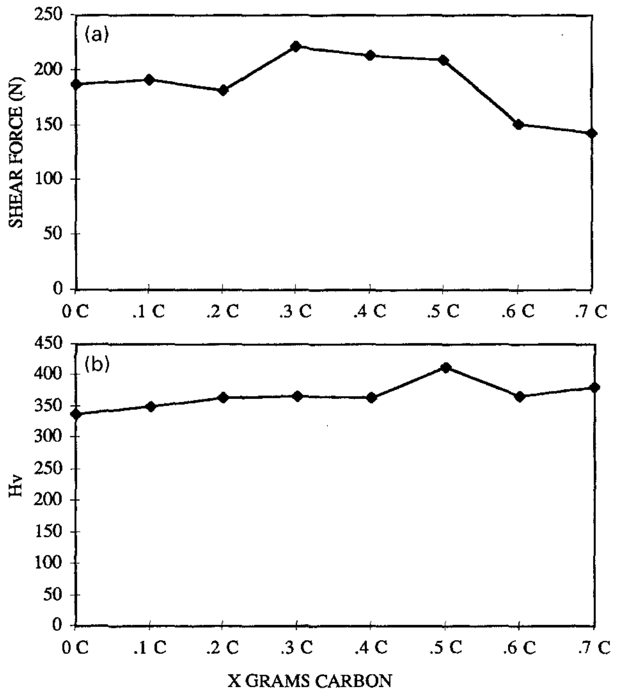
(i) 75Cu–25Sn–10Ti–(5–20)TiC
(ii) 75Cu–25Sn–10Ti–(10–30)W
(iii) 75Cu–25Sn–10Ti–10WC
(iv) 75Cu–25Sn–10Ti–10Mo

The strength of ceramic particles can lessen as their size increases as a result of the greater possibility of crystal flaw. However, the size of the hard particles should be larger than that of the swarf of the ground material in order to obtain the maximum protection from matrix wear. Figure 3 shows the Al_2O_3 swarf after the MSL grinding test; its size is less than 10 μm. Therefore, 325 mesh (smaller than 44 μm) particles were chosen throughout the experiments.

The ceramic particles tend to cluster during brazing. Agglomeration of the ceramic particles is also observed in Al–SiC composites.[22] Chung and Hwang[23] suggested that the agglomerated SiC particles appear to have been crushed during wear and become loose. The relatively low binding force among the clustered particles certainly reduces their effectiveness in enhancing wear resistance. Based on the test results, the clustering tendency of TiC can be reduced with addition of larger TiC particles.

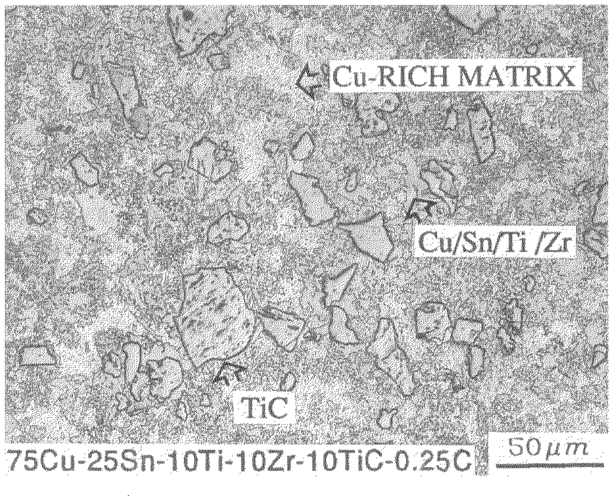
Another way to increase the hardness of the braze is to form carbide precipitates via chemical reaction. There are two potential causes of suppression of carbide formation. First, a strong carbide forming element, titanium in this case, can also react with other element(s) in the braze and form intermetallic compound(s), i.e. these reactions compete with each other. Second, the Cu–C binary phase diagram shows very limited solubility of carbon in copper.[24] This indicates that the flux of carbon atoms in copper is low at the brazing temperature and the process will be rate controlled by diffusion of carbon atoms. A series of experiments was conducted to verify the kinetics of these reactions. The test results show that carbide formers, such as chromium, tungsten, and silicon are not effective in improving the hardness of the braze processed at 900°C. Zirconium was the only element which had a measurable effect in enhancing the hardness of the braze. However, ZrC can not be observed using an optical microscope and the formation of zirconium carbide is not observed experimentally. It was also found that the hardness of the braze alloy is enhanced by the addition of fine carbon powder. Therefore, the finest carbon black powder (<1 μm) was used in further experiments.

The hardness of the braze can be further improved by combining both TiC particle additions and carbide formation by chemical reaction. Figure 4 shows the shear test

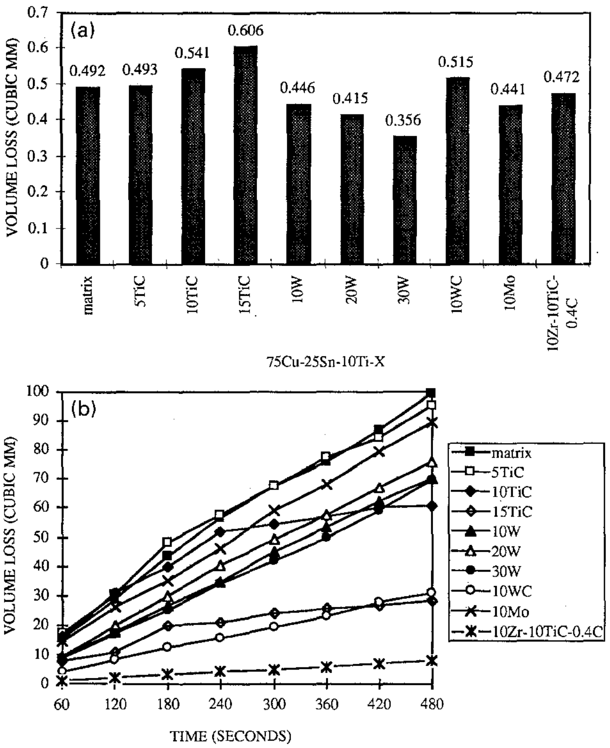


a shear test; *b* microhardness test

4 Results of given tests for 75Cu–25Sn–10Ti–10Zr–10TiC–(0–0·7)C brazed at 900°C for 30 min

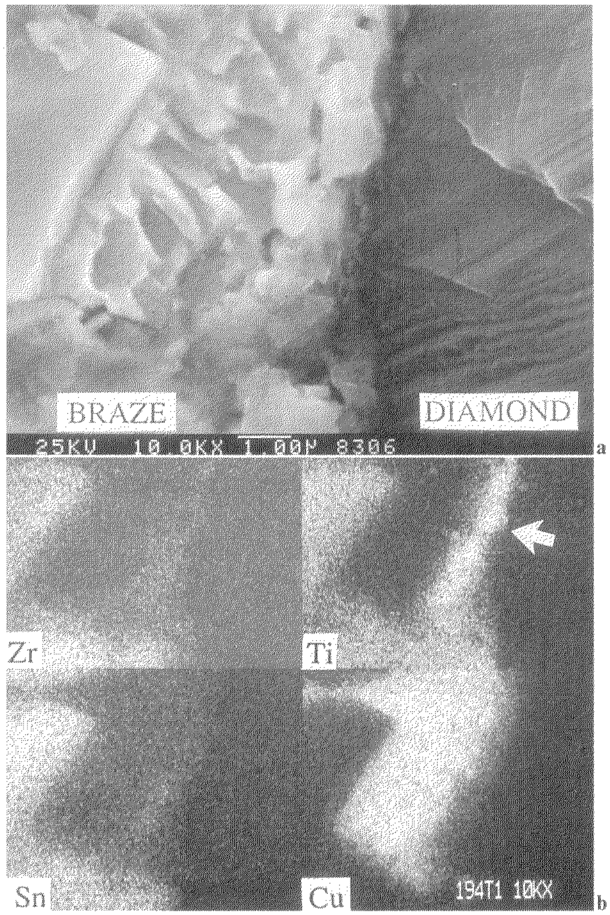


5 Microstructure of 75Cu–25Sn–10Ti–10Zr–10TiC–0·25C brazed at 920°C for 30 min



a erosion test; *b* wear test

6 Results of given tests for 75Cu–25Sn–10Ti–X braze alloys



a morphology; *b* dot mapping of Zr, Ti, Sn, and Cu

7 Given results of EDX analysis for 75Cu–25Sn–12·5Ti–7·5Zr–10TiC–0·2C brazed at 920°C for 30 min

and microhardness test of 75Cu–25Sn–10Ti–10Zr–10TiC–(0–0·7)C. Excellent bonding between the diamond and the braze alloy can be obtained if the carbon content is below 0·38 wt-% (0·5 by weight in Fig. 4). However, the increase in hardness obtained by adding carbon into the braze alloy is not very large. Figure 5 shows the microstructure of 75Cu–25Sn–10Ti–10Zr–10TiC–0·25C braze alloy and TiC particles were identified by wavelength dispersive spectrometry. The TiC distribution in 75Cu–25Sn–10Ti–10Zr–10TiC–0·25C (Fig. 5) is much more uniform than that in 75Cu–25Sn–10Ti–(5–20)TiC. Therefore, it is expected that the new 75Cu–25Sn–10Ti–10Zr–10TiC–0·25C alloy will demonstrate better mechanical properties than those of the Cu–Sn–Ti–TiC alloy.

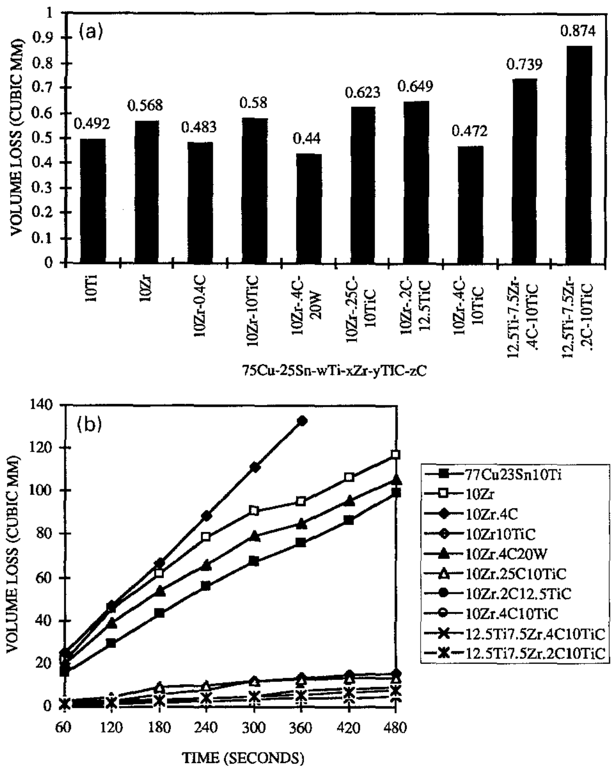
Further wear and erosion tests of the above alloys were performed. Figure 6 shows the erosion and wear tests of 75Cu–25Sn–10Ti–X; 75Cu–25Sn–10Ti–10Zr–10TiC–0·4C had the best wear resistance. The wear resistance of Cu–Sn–Ti–Zr–TiC–C alloys is about 10 times better than that of Cu–Sn–Ti. Wear test data for Cu–Sn–Ti with 10TiC and 15TiC additions (Fig. 6*b*) do not change in a linear fashion because the microstructure of these alloys is not homogeneous. Clustering of the particles is responsible for this variation.

Introducing hard, brittle particles, however, did not improve the erosion resistance of the braze alloy, because the erosion rate of composites is strongly related to both fracture toughness and hardness as discussed above. Based on previous results, tougher particles, such as tungsten, improve the erosion resistance more effectively than TiC dispersoids.

Figure 7 shows energy dispersive spectrometry (EDS) analysis of the interface between 75Cu–25Sn–12·5Ti–7·5Zr–10TiC–0·2C and the diamond. At least three phases can be identified from Figs. 5 and 7. They are TiC particles, copper rich matrix phase, and a Cu–Sn–Ti–Zr phase. Based on the EDS analysis of the above polished bulk braze alloy, copper, TiC, and a small amount of ZrC were identified. Only a limited amount of zirconium reacts with the carbon. This may result from the low brazing temperature which is not high enough for formation of zirconium carbide. Unfortunately, other phases can not be identified after reviewing all currently existing crystal structure files.[25]

Based on the EDS dot mapping of zirconium, titanium, tin, and copper (Fig. 7*b*), zirconium has a much stronger tendency to associate with tin than copper does. An important effect of adding zirconium to the braze is that the tin content in the copper rich phase can be decreased. If the zirconium content had decreased, a high tin bronze phase would be formed in the test. This can result in a more brittle braze than the current one. Because pure copper has excellent ductility, a continuous high purity copper phase is beneficial to the toughness of the braze. The resulting material could form an ideal composite by combining hard, brittle phases with a ductile matrix if the interfacial bond is strong enough.

The 75Cu–25Sn–10Ti–10Zr–10TiC–0·4C alloy had the highest abrasion resistance of any alloy tested. The viscosity of this braze was, however, too high to form a good meniscus shape around the larger diamonds, e.g. 20/30 mesh (0·841–0·595 mm). Phase separation and microvoids were also observed. Viscosity is a critical issue for brazing, especially in the case of MSL technology. The viscosity should be low enough to form a good meniscus shape around the diamond, but should not be so low that it will not hold the braze alloy on the wheel during brazing. Two possible methods may be used to reduce the braze viscosity: one is to increase the brazing temperature, the other to slightly alter the chemical composition of the braze alloy without appreciably affecting its mechanical properties. Based on the experimental results, it was seen that increasing



a erosion test; *b* wear test

8 Results of given tests for 75Cu–25Sn–*w*Ti–*x*Zr–*y*TiC–*z*C braze alloys

the brazing temperature is not an effective way to reduce the viscosity of the braze alloy in the case of introducing hard particles. Therefore, changing the composition of the braze alloy was necessary to reduce the viscosity of the braze alloy.

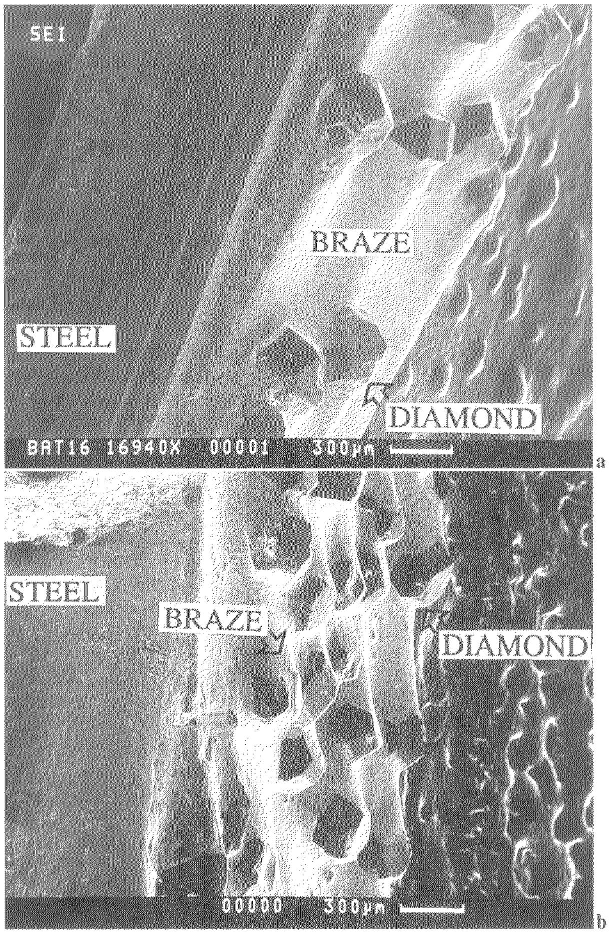
In order to obtain better wetting of the larger diamonds, a series of experiments was conducted. Based on these tests, reducing the carbon content in the braze was seen to be a good way to lower its viscosity. Further optimisation of this alloy was performed. Figure 8 shows the erosion and wear test for 75Cu–25Sn–*w*Ti–*x*Zr–*y*TiC–*z*C braze alloy. The wear resistance of modified Cu–Sn–Ti–Zr–TiC–C alloys is comparable to that of the original alloy. All alloys exhibited improved abrasive wear resistance in the experiment; 75Cu–25Sn–12·5Ti–7·5Zr–10TiC–0·2C brazing at 920°C shows good wear resistance as well as excellent wetting characteristics. Therefore, this alloy was chosen for the green concrete cutting test.

Green concrete cutting test

Two MSL cutting blades were used in the test, for which results are summarised in Table 2. The cutting process is highly abrasive; the MSL blade with a Cu–Sn–Ti bond failed after less than 300 m of cutting and at this point the blade was stripped of abrasive crystal. The MSL blade with Cu–Sn–Ti–Zr–TiC–C alloy was stopped after 411·5 m of cutting.

Table 2 Cutting test results for two different metal bond MSL diamond wheels

Braze alloy	Length of cutting, m	Failure mode
Cu–Sn–Ti	<300	Debonding of diamonds and wear of wheel substrate
Cu–Sn–Ti–Zr–TiC–C	411·5	Wear of wheel substrate



a Cu–Sn–Ti bond after 300 m of cutting; *b* Cu–Sn–Ti–Zr–TiC–C bond after 411·5 m of cutting

9 Micrographs showing morphology of given MSL wheels after cutting test

Figure 9 shows the surfaces of the two MSL wheels after the cutting test. Results for the Cu–Sn–Ti braze can be seen in Fig. 9*a*. As fabricated, both MSL wheels were equivalent in diamond weight. However, the diamond concentration in Fig. 9*b* is much higher than that in Fig. 9*a*. The wavy surface in the fractographs indicates that the wear resistance of the Cu–Sn–Ti braze is inferior to that of the Cu–Sn–Ti–Zr–TiC–C braze alloy. However, the Cu–Sn–Ti–Zr–TiC–C braze remained well bonded to the diamond crystals after 411·5 m of cutting. All of the remaining diamond crystals were still firmly bonded by the braze alloy and there is no evidence of the diamond crystals debonding.

The reason for the Cu–Sn–Ti–Zr–TiC–C bond working more effectively than the Cu–Sn–Ti bond can be mainly attributed to the improved wear resistance of the braze alloy. Wear of the braze alloy during the cutting process results in reduction of the bonded surface area and exposure of the diamond crystals. Finally, the braze alloy can not hold the diamond any more and the diamond crystals are removed. The wear resistant braze alloy extends the wheel's life and changes the failure mode of the MSL cutting wheel from debonding of the diamond to wear of the steel substrate. Moreover, it is expected that the wheel's life can be further improved by choosing an improved, i.e. harder, substrate material.

CONCLUSIONS

1. The abrasion resistance of the braze can be greatly improved by introducing hard and blocky particles. Based on wear test data, it is concluded that TiC is superior to

Table 3 Theoretical and measured densities of braze alloys

Composition by weight	D_t, g cm^{-3}	D_m, g cm^{-3}	$(D_m/D_t - 1) \times 100$, %
75Cu–25Sn–10Ti	7·8332	7·9193	1·10
75Cu–25Sn–10Ti–5TiC	7·6346	7·6604	0·34
75Cu–25Sn–10Ti–10TiC	7·4146	7·566	2·04
75Cu–25Sn–10Ti–15TiC	7·3082	7·3642	0·77
75Cu–25Sn–10Ti–10W	8·2407	8·0575	−2·22
75Cu–25Sn–10Ti–20W	8·6202	8·5339	−1·00
75Cu–25Sn–10Ti–30W	8·9741	8·9796	0·06
75Cu–25Sn–10Ti–10WC	8·158	8·2095	−0·63
75Cu–25Sn–10Ti–10Mo	7·9878	8·1367	1·86
75Cu–25Sn–10Ti–10Zr	7·7021	7·5727	−1·86
75Cu–25Sn–10Ti–10Zr–0·4C	7·6733	8·1201	5·82
75Cu–25Sn–10Ti–10Zr–10TiC	7·3776	7·4147	0·50
75Cu–25Sn–10Ti–10Zr–20TiC	7·1204	7·0989	−0·30
75Cu–25Sn–10Ti–10Zr–10TiC–0·4C	7·3268	7·6506	4·42
75Cu–25Sn–10Ti–10Zr–10TiC–0·25C	7·3457	7·574	3·11
75Cu–25Sn–10Ti–10Zr–12·5TiC–0·2C	7·2834	7·4612	2·44
75Cu–25Sn–12·5Ti–7·5Zr–10TiC–0·4C	7·2572	7·6354	5·21
75Cu–25Sn–12·5Ti–7·5Zr–10TiC–0·2C	7·282	7·5525	3·71
75Cu–25Sn–10Ti–10Zr–20W–0·4C	8·3592	8·6812	3·85
75Cu–15Ti–10Ag	7·8859	7·793	−1·18
75Cu–15Ti–10Ag–10TiC	7·4721	7·2937	−2·39
75Cu–15Ti–10Ag–15TiC	7·3055	7·2112	−1·29
75Cu–15Ti–10Ag–25W	8·9422	8·3493	−6·63
68·8Ag–26·7Cu–4·5Ti (ticusil)	9·4814	9·2556	−2·38
65·96Ag–26·22Cu–7·72Ti	9·1433	9·3891	2·69

W, Mo, WC, and SiC in improving the wear resistance of Cu–Sn–Ti active braze alloy.

2. Improving the erosion resistance of the braze alloy can not be achieved by simply introducing hard particles with less than 15 wt-%TiC dispersoids into the Cu–Sn–Ti alloy. However, tougher particles, such as tungsten, improve the erosion resistance more effectively than TiC dispersoids.

3. Based on experimental results, the 75Cu–25Sn–12·5Ti–7·5Zr–10TiC–0·2C braze displays wear resistance 10 times superior to that of the 77Cu–23Sn–10Ti alloy. With this braze, the cutting performance of MSL blades is improved in the green concrete cutting test.

APPENDIX

Theoretical and measured density of braze alloy

If the braze alloy is assumed to be an ideal solution, with no volume change after brazing, the theoretical density of the braze alloy can be calculated from the equation

$$D_t = \Sigma\, v_i D_i \quad \text{. . . . .} \quad (4)$$

where D_t is the theoretical density of the braze alloy in grams/centimetre cubed, v_i is the volume fraction of component i, and D_i is the density of component i in grams/centimetre cubed. Values of D_t used to calculate the theoretical density of various braze alloys are:

Ag	10·5
Cu	8·9
Graphite	2·3
Mo	10·2
Sn	7·3
Ti	4·5
TiC	4·9
W	19·3
WC	15
Zr	6·5

The experimental measurement of the density can be performed using the equation

$$D_m = W_{air}/V = W_{air}/(W_{air} - W_{water}) \quad \text{. . . . . .} \quad (5)$$

where D_m is the measured density of the braze alloy in grams/centimetre cubed, V is the volume of the braze alloy in centimetres cubed, W_{air} is the weight of the braze alloy in air in grams, and W_{water} is the weight of the braze alloy in water in grams.

There is a possible error when equation (4) is applied to measure the braze alloy density. If there is porosity in the specimen, the measured density will deviate from the real density. Therefore, all specimens were examined using an optical microscope to ensure that there was no porosity. Using equations (4) and (5) the densities of braze alloys with different compositions can be obtained and are given in Table 3.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of Norton Co., Worcester, MA, USA and wish to express their appreciation to colleagues in the Superabrasives Department for assistance enabling this work to be carried out.

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