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Studies on Mechanical Alloying of Copper-Tungsten Carbide Composite for Spot Welding Electrode

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This article presents a study on the properties and performance of copper-based composite reinforced with recycled tungsten carbide powder as spot welding electrode. The copper-tungsten carbide composite electrode was prepared by mechanical alloying and powder forging before being machined into truncated cone-face geometry. The welding operation was conducted on galvanized steel using a pedestal-type spot welding machine. Composites with higher density and electrical conductivity were obtained after mechanical alloying for shorter time. In contrast, a higher hardness is shown in the composite, which was mechanically alloyed to longer time. The strength of the welded steel coupon was found to increase with decreasing milling time due to an increase in density and electrical conductivity. The wear behavior of the composite revealed that the deformation of the spot weld electrode increased with increasing milling time.

Keywords mechanical alloying, metal matrix composites, welding

1. Introduction

Resistance spot welding is a principal method for joining sheet steel components in building construction, home appliance, and automotive industries. In this welding process, metal sheets are pressed by a pair of copper-based electrodes and an electric current is applied across the electrodes (Ref 1). Because of the mating (or faying) surface, the applied electric current is high enough to provide sufficient heat onto the surface contact point of the metal sheets. Over time, this repeated heating and pressing operation may contribute to electrode deformation, breakdown, softening, and mushrooming (Ref 2). When this occurs, a large current is required to accomplish the task due to the enlargement of the welding tips. This will continue until the deformed electrode is replaced. The situation could worsen when galvanized (or zinc-coated) steel is welded (Ref 3).

Because of the cost of replacing and/or refacing worn electrodes, it is the continuing desire for the industry to increase the operational life of a resistance spot welding electrode at a reasonable cost. Improvement in electrode performance translates into lower cost and greater efficiency of the welding operation. This has led to an ever increasing interest in producing hard particles or dispersion-reinforced copper-based composites, as they are commonly known to offer a unique combination of high strength and hardness with excellent electrical conductivity (Ref 4, 5). The high thermal and electrical conductivities of copper make it suitable for spot welding electrode application, yet its low melting point increases the electrode wear rate and makes it necessary for another material with high melting point to be introduced as reinforcement.

The most widely used method for the production of composite reinforced with dispersed particles is based on casting and powder metallurgy (P/M) techniques (Ref 6). In P/M, the reinforcement particle and metal phases can be blended together, pressed and sintered with or without application of pressure. Two mixing methods can be used for manufacturing dispersion-strengthened composite. The first method involves mechanical mixing of matrix and reinforcement powder. It is relatively simple but does not ensure a uniform distribution of the dispersed particles. The second process is high-energy milling or mechanical alloying (MA) that has been used successfully to produce various powder systems since 1970 (Ref 7, 8).

Mechanical alloying of copper composite system has been studied extensively, particularly the effect of milling parameter on composite properties (Ref 9, 10). To the author's knowledge, there are no detailed studies on MA in the Cu-WC system, and on the relation between milling time and welding behavior of the spot welding electrode material. This article presents a study on properties of mechanical-alloyed copper composite reinforced with recycled tungsten carbide. The spot welding behavior of the composite is also being investigated and reported.

This study is mainly concerned with copper composite reinforced with tungsten carbide particulate. Refractory compound of tungsten carbide, which is mainly used in powder metallurgy parts including cutting tool tips, dies, and wear parts (Ref 11), shows superior hardness, abrasive wear strength, and high melting point and it is an attractive additional agent for dispersion strengthening of copper. The combination of these two elements should provide a serviceable material for spot welding electrode applications. However, tungsten carbide is an expensive material. For the benefit of material replacement and saving the cost of raw material, and eventually the cost of overall welding operation, the present work deals with

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development of copper composite spot welding electrode reinforced with low-cost tungsten carbide powder which is ground from worn cutting tool tips.

2. Experimental Procedures

Commercial grade copper powder (99.9% purity, 24 μm) supplied by Merck and recycled tungsten carbide cutting tool powder (12.57 μm) were used in this work to produce tungsten carbide-reinforced copper composite. The WC powder was obtained by grinding worn and used tungsten carbide cutting tools in a high-energy planetary mill for particle refinement and followed by sieving (Ref 12). Following grinding, copper and tungsten carbide powder were mixed together to obtain Cu-15 vol.%WC composition and then they were mechanically alloyed in a high-energy planetary mill. The ball-to-powder ratio and speed were fixed at 5:1 and 200 rpm, respectively. The mixture was extracted at 4, 8, and 12 h of milling time.

Powders of 5.5 g were charged into a cylindrical tool steel die, with 10 mm diameter, and pressed at 50 MPa in a single action on a Universal Tensile Machine. The preform was sintered in air at 700 °C for half an hour in a furnace. Subsequently, the preform was transferred to the Universal Testing Machine and forged at a speed of 8 MPa/s in a closed die under a pressure of 130 MPa.

Density measurement of the forged composite was carried out using immersion method according to the ASTM standard B28-96 (1999) and the obtained density was then compared with the theoretical density of the composite (Ref 12). According to this standard, the envelope density of the compact sample was obtained, which takes into account of both open and closed pores. The sample was first impregnated with light paraffin oil in a vacuum chamber for 15 min to fill all open pores. Excess oil on the surface was removed by wiping gently with an absorbent paper. Care must be taken not to extract the oil already impregnated into the pores. To weigh the oil-impregnated sample in water, a stainless steel wires twist was used to suspend the sample. Care must be taken to ensure that the sample and the support wire were free of air bubbles when immersed in the water. The Archimedes density was calculated as:

$$\rho = \rho_{water}\left(\frac{W_{air}}{W_{oil} - W_{water}}\right) \times 100 \qquad \text{(Eq 1)}$$

where ρ is the density of compact, ρ_{water} is the density of the water at room temperature, W_{air} is the weight of sample in air, W_{oil} is the weight of oil infiltrated sample in air, and W_{water} is the weight of oil infiltrated sample in water.

Hardness measurement was made using the Vickers test machine under an applied load of 200 N. The electrical conductivity of the composite was measured using a Wheatstone bridge technique and the value was compared with electrical conductivity of a standard sample, by giving a conductivity value of %IACS (International Annealed Copper Standard). Microstructure observation was carried out under a Horiba light optical microscope and a Phillips scanning electron microscope was used to observe fracture surface on welded sample.

The welding operation was performed with a pedestal-type spot welding machine on galvanized steel pairs (coupons) at welding current of 7000 A with welding load of 80 kg. Welding time of 9, 16, and 22 cycles was selected since this range is suitable for the steel thickness, as suggested by the machine manual. Before the welding operation, the composites were machined by turning the top surface to a form of truncated cone and then polished with sandpaper to ensure good contact with the steel workpieces. The machined electrode was inserted into holder constructed specially for the spot welding operation. The metal sheet used for welding investigation was a 0.70 mm thick hot-dip galvanized steel with a layer of zinc coating.

The strength of welded steel coupons was measured using tensile shear test (Instron Test Instrument, Model 8500) whereby the load was applied parallel to the spot weld interface. Maximum breaking load and diameter of fracture surface of welded steel coupons were recorded and fracture surface was observed under a scanning electron microscope (SEM). At the end of 25 consecutive welding numbers, the deformed surface of the electrodes was examined under SEM. Selected welded coupon was sectioned close to the weld nugget normal to the plane of the sheet and, subsequently, hot mounted in bakelite for metallographic preparation. Polished samples were etched in alcoholic ferric chloride to reveal the weld nugget microstructure. Characterization of weld nugget was performed using optical microscope.

3. Results and Discussion

3.1 Composite Properties

After forging, a thin dark layer is seen to cover the compacts. This oxide is formed because the hot forging was conducted in ambient atmosphere. Measurement of density, hardness, and conductivity was accomplished after removing the oxide skin from the compacts.

Table 1 provides the material properties of the forged Cu-15 vol.%WC composite, i.e., density, hardness, and electrical conductivity, obtained from 10 individual samples. Apparently, density decreases with an increase in milling time. According to Joshi et al. (Ref 9) this trend appears to be closely related to the hardness of powder since a gradual increase in powder hardness with milling was observed. The above explanation could be implied in this study since longer duration of milling process has refined the tungsten carbide particle, as observed in Fig. 1, and increased the hardness of the powder. Densification of the hardened powder during forging becomes more difficult and hence causes a decrease in composite's density.

Probably the oxide was incorporated during mechanical alloying because of the exposure of atmosphere during lamellar formation on the surface of particle (Ref 13). The oxide might impede solid-state diffusion during forging process and lead to the decrease in adhesion between powder particles. It is seen

Table 1 Density, electrical conductivity, and hardness for Cu-15 vol.%WC composite for various mechanical alloying durations

Milling time, h:	4	8	12
Density, %TD	65	63	57
Hardness, Hv	62	79	84
Electrical conductivity, %IACS	58	54	50

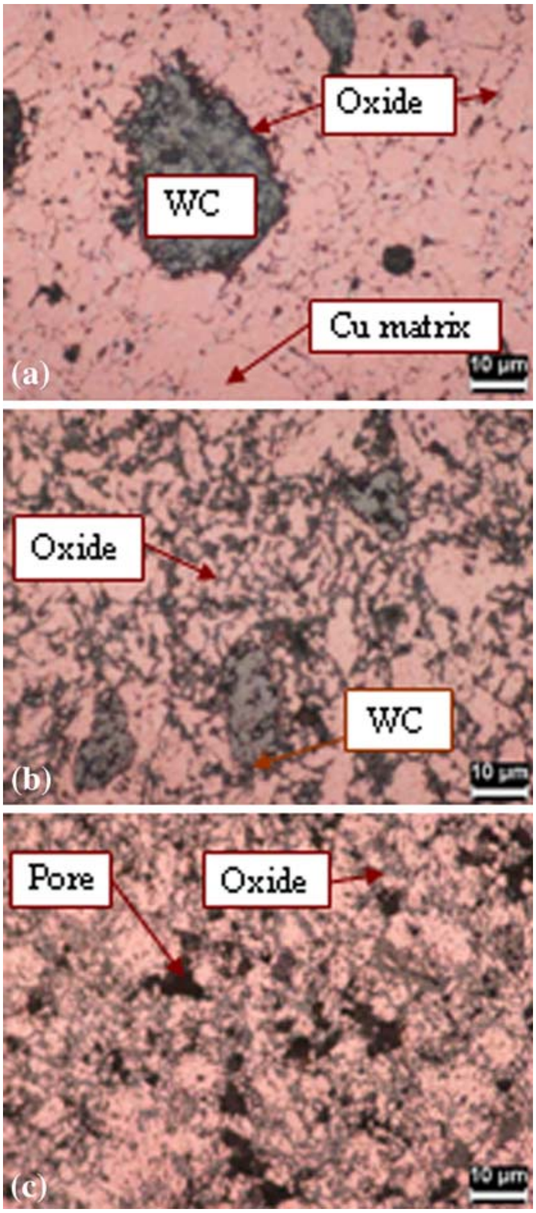

Fig. 1 Optical micrographs of Cu-15 vol.%WC composite prepared from powder mechanically alloyed with various duration: (a) 4 h, (b) 8 h, and (c) 12 h

Table 2 Results of tensile shear test of steel coupons welded using Cu-15 vol.%WC electrode composite

Milling duration, h	Welding time, cycle:	9	16	22
4	Failure load, N	285	587.5	700
	Solidified zinc diameter, mm	3.95	4.85	5.08
8	Failure load, N	200	325	587.5
	Solidified zinc diameter, mm	3.68	4.80	4.85
12	Failure Load, N	100	225	400
	Solidified zinc diameter, mm	2.83	3.65	4.25

that prolonging milling process caused more oxidation as indicated by thicker oxide layer because of the higher number of particle collision.

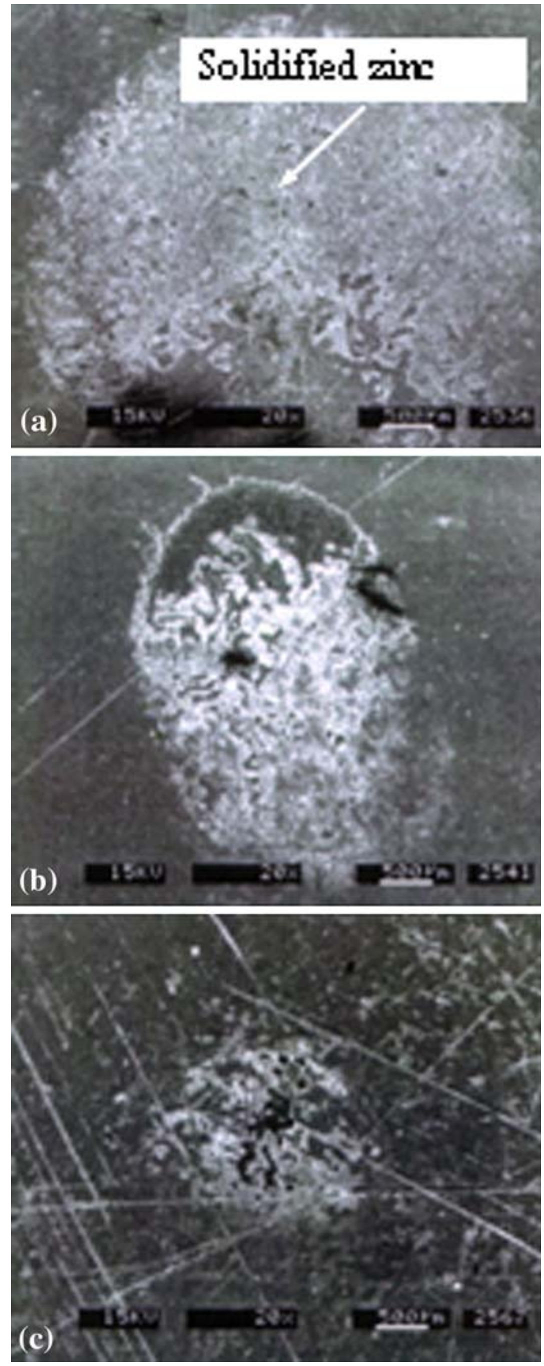

Fig. 2 Fracture surface of spot weld produced by Cu-15 vol.%WC composite electrode prepared from powder mechanically alloyed with various duration: (a) 4 h, (b) 8 h, and (c) 12 h

As shown in Table 1, the hardness increases with an increase in mechanical alloying times. The increment in hardness as a result of longer milling time can be explained by the refinement of tungsten carbide particle and copper grain size as observed in Fig. 1. For the same volume fraction of tungsten carbide content, the refinement of tungsten carbide particulate appears to decrease the interparticle distance. This in turn raises the yield strength of the copper matrix, and hence improves the material's resistance to deformation (Ref 14).

Table 1 also indicates that incorporating 15 vol.% WC results in a drop of electrical conductivity to a level of

50-58%IACS since tungsten carbide has electrical conductivity lower than copper (Ref 15). The reduction in electrical conductivity with the addition of WC particles is generally attributed to the reduction in the conductive cross-sectional area of the composite. Oxides also tend to reduce the conductivity of the composite because the copper matrix is discontinued (Ref 15, 16). For composites prepared from 8 and 12 h milled powder, the presence of oxide was critical because it forms a continuous layer in copper matrix in certain regions (Fig. 1). It is also noted that the change in conductivity with milling time shares a similar trend with the change in density. This observation is in agreement with the results reported by Li et al. (Ref 17) who suggested that grains in intimate contact without insulating phase, such as pores, are continuous to an electric field.

3.2 Welding Characteristics

The failure load of the welded galvanized steel coupons in the tensile shear test which is obtained from 10 sets of steel coupons is shown in Table 2. The diameter of the fracture surface is also included. Figure 2 shows that the rough area on the fracture surface corresponds to the molten and solidified zinc layer and not to weld nugget.

The electrode material has low electrical conductivity (50-58%IACS); thus, the electrical current conducted in the steel-steel interface is below the current required for the weld nugget formation but it is sufficient for melting the zinc-coated layer. The lack of weld nugget facilitated the separation of welded steel coupons, which gave explanation for the low failure load, i.e., in the range of 100 to 700 N. This range corresponds to 155 to 338 MPa, respectively. Although weld nugget did not form, the load did not approach zero because of the strength of the brazed joint that resulted from the melting of zinc layer (Ref 18). This statement is also plausible if the joint strengths in the present work are compared to the strength of zinc. According to Ref 19, the ultimate strength of zinc is in the range of 110 to 200 MPa. Therefore, it can be concluded that the measured joint strength of less than 200 MPa is due to the joining of zinc because the joint strength values are almost similar to the strength of zinc. On the other hand, the measured joint strength that is more than 200 MPa resulted from the bonding between steel sheets.

To confirm that welding between the steel sheets is achieved, metallurgical examination was done on high-strength joints. As shown in Fig. 3(a), the welded area consists of two zones with different microstructure. The fusion zone shows darker etching region than the base metal, which, in general, is typical for spot welded steel microstructure. Some interesting features concerning nugget development can be noted from micrograph in Fig. 3(b). The grain size varies from the galvanized steel base metal to fusion line with more formation of martensite structure. As a conclusion, high-strength joints in this work are accomplished because of the weld nugget formation between the steel sheets as supported by the microstructural evidence.

The failure load and solidified zinc diameter decreases with increasing powder milling time. It can be seen that 4 h milled electrode gives the highest failure load and largest solidified zinc diameter. These results are related to the properties of electrode material, density, and electrical conductivity. Referring to the electrical conductivity, it can be seen that 4 h milled electrode gives the highest densification and electrical conductivity. High electrical conductivity increases the heat energy at steel-steel interface, which in turn increases the braze joint diameter and failure load. The above explanation is consistent with the results presented in tensile shear test for steel coupons welded at longer welding time. Higher welding time increases the solidified zinc diameter since heat energy is proportionate to the welding time (Ref 18).

The micrograph of electrode surfaces after 25 weld number is shown in Fig. 4. All electrodes underwent extensive "mushrooming," or face enlargement, and peripheral crack are also evident in 8 and 12 h milled electrode. Obviously, the electrodes prepared from powder with longer milling time exhibited larger diameter of deformed face even though their hardness is higher. The severe deformation characteristic in electrodes prepared from powder with longer milling time does not agree with Aslanoglu et al. (Ref 8), who reported that high-hardness material imparts high resistance to deformation in service environment. The electrode wear behavior in this investigation might be related to the density of the electrode material. As reported by Li et al. (Ref 17) pores are weak points in the structure of electric conductor subjected to mechanical impact. In addition, there is a direct relation between the density and thermal conductivity, a material property that is related to the quantity of heat absorbed and dissipated (Ref 20). Since the 12 h milled electrode has the lowest density, it is expected to have the lowest thermal conductivity, and eventually results in the hottest surface during welding. High electrode

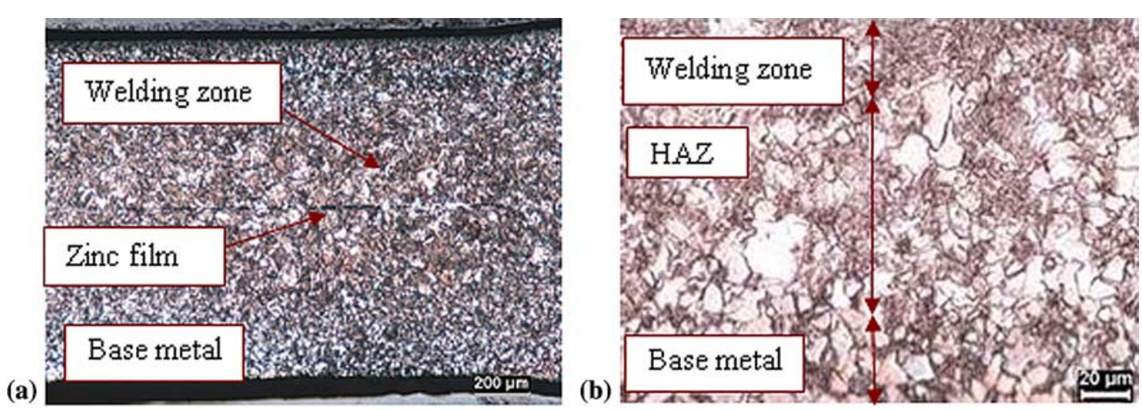

Fig. 3 Metallurgical cross section of weld joint by optical micrograph: (a) 50× and (b) 500×

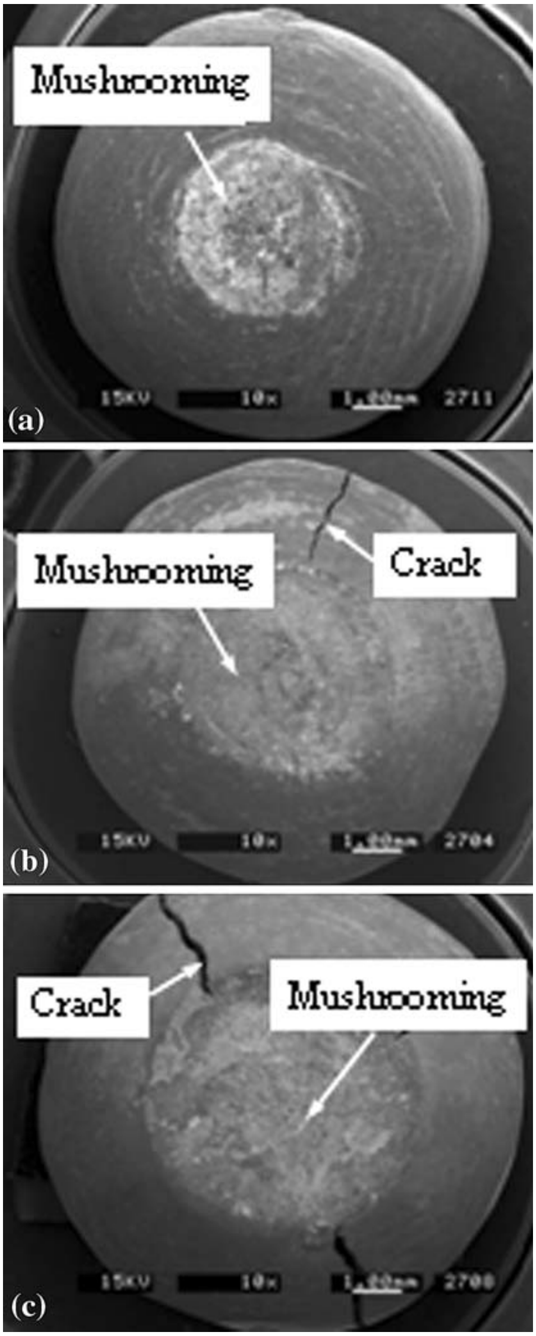

Fig. 4 Micrograph of worn electrode face: (a) 4 h milled composite, (b) 8 h milled composite, and (c) 12 h milled composite

face temperature in 12 h milled electrode might be responsible for more rapid electrode wear by softening the electrode face structure, making them more susceptible to faster and greater deformation. The crack observed in the deformed electrode probably originated from thermal shock due to the intense heat during welding.

4. Conclusion

The properties and actual welding performance of spot welding electrode prepared from copper composite reinforced with recycled tungsten carbide have been examined. Experimental results show that increasing milling time increases the hardness of the composite electrode due to refinement of tungsten carbide reinforcement particle and copper matrix grain. However, density was found to decrease with increasing milling time due to formation of oxide which inhibited the consolidation of powder during forging. In addition, higher milling time resulted in lower electrical conductivity because the oxide makes the copper matrix discontinuous. In summary, the composite density is the predominant factor as it greatly affects the spot welding electrode's performance. The 4 h milled electrodes with the highest densification show the best weld strength and electrode deformation resistance, which indicates that increasing the densification would produce an electrode with better properties.

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