Performance of Cu–TiC alloy electrodes developed by reaction milling for electrical-resistance welding

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Abstract

The performance of a nominal-composition Cu–5 vol.% TiC alloy, prepared via powder metallurgy, was evaluated when such material was used as electrodes for electrical-resistance welding. Starting from Cu, Ti and graphite powders, flakes of the alloy were synthesized by reaction milling in a high-energy mill; alloy bars 6 mm diameter were then produced by hot extruding such flakes. Electrodes performance was evaluated by means of the following indexes: tip shortening, tip widening, and mass loss. Electrolytic copper electrodes were used as reference. The results obtained clearly demonstrate that the Cu–TiC electrodes prepared from powders synthesized by reaction milling have a remarkably better performance than those manufactured from electrolytic copper.

Keywords: Welding; Electrodes; Mechanical alloying; Reaction milling; Copper alloys; Dispersion-strengthening

1. Introduction

The electrical-resistance welding process reached full development in the production of aviation assemblies, car chassis and bodies, metallic furniture, and other applications, after World War II. This welding process uses Cu and Cu alloys as the electrode material. Electrical-resistance welding involves passing a high current at a low voltage through a circuit closed by the pieces to be welded; these pieces are maintained in close contact with the two electrodes by means of an applied pressure, see Fig. 1. The heat generated by the Joule effect is enough to produce local fusion of the pieces under pressure, leading to an autogenously forged union. Thus, electrode materials must exhibit high electrical and thermal conductivities, combined with high strength, at elevated temperatures.

The elevated-temperature strength of metal alloys can generally be improved by the inclusion of a low volume fraction (0.02–0.05) of finely dispersed ceramic particles [1]. Insoluble particles are required to allow thermal and electrical conductivities to remain within acceptable practical limits. These dispersoids must be thermodynamically stable, homogeneously distributed in the metal matrix and of nanometric size. The elevated-temperature strength of a metallic matrix reinforced with nano-dispersoids is controlled by two principal mechanisms: interactions between dispersoids and grain boundaries [2] and interactions between dislocations and matrix/dispersoid interphases [3].

Reaction milling is an effective approach to introduce nanometric dispersoids in a Cu matrix [4,5]. Mechanical alloying and its particular form of reaction milling have been recently reviewed by Lu and Lai [1]. Mechanical alloying is a ball mill process invented around 1966, where a powder mixture is subjected to high-energy collisions from the balls. The two most important events involved in mechanical alloying are the repeated welding and fracturing of the powder mixture, permitting the solid-state synthesis of materials which are usually not possible to obtain by traditional techniques. Alloys with different combinations of metals, even using a starting mixture of low- and high-melting temperature

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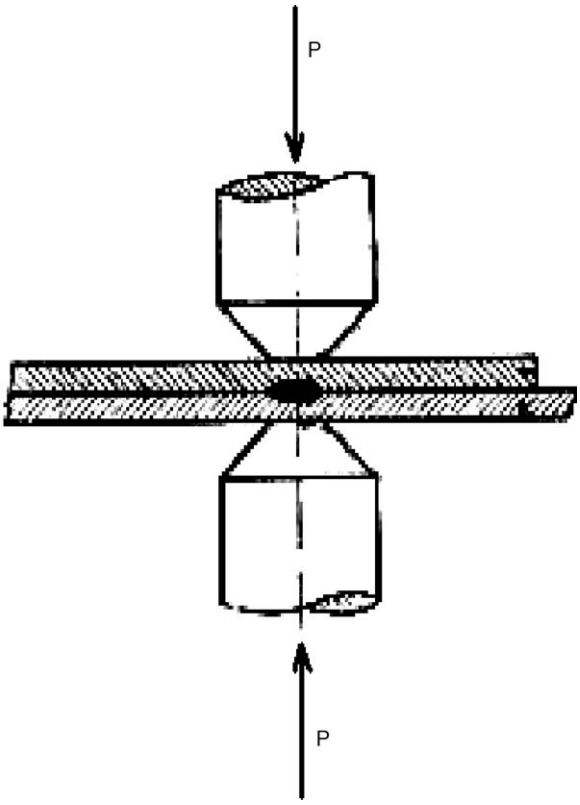

Fig. 1. Electrical-resistance welding of two plates performed between two electrodes under pressure.

elements, have been developed. Although in general, the raw materials used in mechanical alloying should include at least one fairly ductile metal, to act as host or binder to hold together the other components, many studies have confirmed that brittle metals can also be mechanically alloyed. The final products developed by milling itself are flakes whose internal microstructure is constituted by micro or nano-size crystalline grains, or by amorphous composites, or by combinations thereof; solid solutions have also been documented [1]. Because of attrition, such microcrystalline grains develop a high dislocation density. Subsequently, the flakes obtained by mechanical alloying are consolidated by thermomechanical approaches, such as sintering or hot extrusion [4,5].

Reaction milling, developed around 1975, is performed using a chemical reaction that occurs, during the mechanical alloying process, between milling additives and the powder particles to be milled [1]. Thus, the liquid grinding media and the gas atmosphere must be carefully chosen to promote the reaction of C, O or N with selected metals in order to obtain finely dispersed carbides, oxides or nitrides, respectively. The dispersion of suitable nanometric ceramic particles developed by reaction milling, like the above referred oxides, carbides or nitrides, into the metallic matrix, leads to an effective anchoring/pining of dislocations, subgrains and grains, and, also, to an increase of the temperatures at which recovery, recrystallization and grain growth phenomena occur. Thus, high-temperature material strength is increased.

The objectives of the present work are as follows: (a) to synthesize, by reaction milling, composite flakes consisting of approximately 5 vol.% of TiC nanoparticles dispersed in a copper matrix, and then, to prepare dense bars via hot extrusion of the flakes, and (b) to study the performance of these bars as electrodes for electrical-resistance welding. A comparative study of the performance of those Cu–TiC electrodes with that of electrodes manufactured from massive electrolytic copper is also carried out.

2. Experimental

Dendritic powders of electrolytic Cu (90 wt.% below 40 μm), Ti powders (below 45 μm) and graphite powders[1] (6 μm mean size) were employed as raw materials to form a Cu–5 vol.% TiC alloy (nominal composition), using hexane as milling media. The powders (Cu–2.3 wt.% Ti–0.3 wt.% C) were mechanically milled in a stainless steel attritor based in the Szegvari-type one (100 mm diameter and 1.500 cm^3 volume), using an AISI 316 steel container with bearing steel balls (4.76 mm diameter) made of the same material. Milling conditions were as follows: ball to powder weight ratio = 10:1 g/g; rotational speed = 500 rpm; milling time = 10 h. The flakes obtained by milling were encapsulated under low vacuum and then consolidated by extrusion at 1023 K, using an extrusion ratio of 10:1.

Microstructural analysis was performed on Cu–TiC alloy samples using a Phillips CM 200 Transmission Electron Microscope (TEM), fitted with an EDS system (EDAX). X-ray diffraction analysis (XRD) was carried out with a spectrometer Siemens, model D 500, using Cu Kα radiation under 40 kV and 40 mA.

To evaluate the resistance of the material to high-temperature softening, the consolidated samples were annealed for 1 h at different temperatures (673, 923 and 1173 K), and Rockwell B hardness was then measured at room temperature. Moreover, for evaluating creep behaviour, hot compression tests at 773 and 1123 K were performed in an Instron TT-DM model machine. Two cross-head compression speeds, 0.005 and 0.05 cm/min, which corresponded to initial true-strain rates of 0.85×10^{-4} and 0.85×10^{-3} s^{-1}, respectively, were used. The compression samples were cylinders 9.8 mm height and 6.5 mm diameter; graphite was used as lubricant.

International Annealed Copper Standard (IACS) electrical conductivity of the Cu–5 vol.% TiC alloy was measured by the four-point method.

Electrical-resistance welding of two metal plate pieces (SAE 1020 steel, 0.5 mm thick) was used for testing the performance of a pair of Cu–TiC alloy electrodes. Bars of 6 mm diameter mounted in adapting holders, as shown in Fig. 1, were used as electrodes. In the equipment employed, the two

[1] Microcrystalline powders kindly provided by Southwestern Graphite Company.

electrodes of a given pair work along the vertical axis; the lower electrode arm is in a fixed position, while the upper electrode arm is moved until contacting the welding point by applying an external pressure during the welding time period. The following experimental conditions were used: nominal current intensity = 34 A; current application time = 3 s; and intermediate cooling time = 15 s. A pair of massive electrolytic Cu electrodes, also under the shape of 6 mm diameter bars, was used for establishing a performance reference in welding tests as above indicated. Temperature measurements performed with an optical pyrometer gave a value of about 623 K at electrode tips.

Three indexes were employed to evaluate the performance of the electrodes: (1) electrode tip shortening; (2) electrode tip-diameter increase; and (3) electrode mass loss. The measurements were made after 80 welding operations; only when each set of 80 operations was completed, electrodes were extracted from their holders. Electrode tip length was defined as the portion of electrode length that stayed visible outside the holder.

3. Results and discussion

3.1. Materials behaviour

The hardness values obtained for the massive electrolytic Cu used as reference and for the as-extruded Cu–5 vol.% TiC alloy were of 32 and 62 RB, respectively. Moreover, the curves of hardness versus temperature of 1 h annealings reported in Fig. 2, clearly show that the Cu–TiC alloy retains its hardness up beyond 923 K, as previously reported by Palma et al. [6]. The fact that each one of the curves in Fig. 2 exhibits a maximum at 673–923 K suggests that annealing hardening by precipitation occurs. Such results were in good agreement with those previously reported by Palma et al. [6], for a similar alloy Cu–TiC alloy independently prepared and tested in the same conditions.

The results of hot compression tests are presented in Fig. 3. The curves for an initial true-strain rate of $0.85 \times 10^{-4}\ s^{-1}$ reveals that the strength of the Cu–5 vol.% TiC alloy at 773 K is higher than that of electrolytic Cu, in qualitative agreement with hardness results of Fig. 2. Moreover, Fig. 3 shows that the flow stress curves of the Cu–5 vol.% TiC alloy increases when strain rate is increased, as expected for high temperatures.

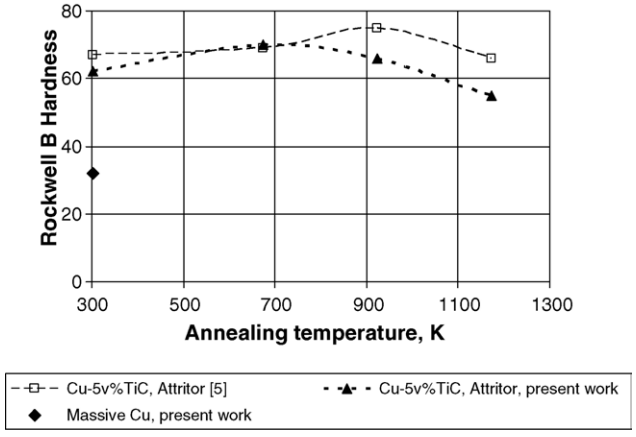

Fig. 2. Room-temperature hardness of the Cu–5 vol.% TiC alloys after an annealing of 1 h at different temperatures. The room-temperature hardness of electrolytic (massive) Cu is also shown.

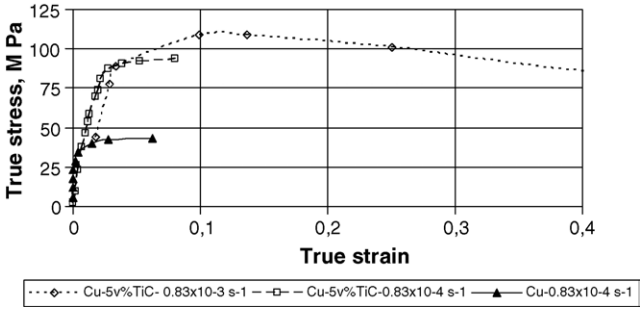

Fig. 3. Compression test curves for electrolytic Cu–5 vol.% TiC alloy and Cu, performed at 773 K for the initial true-strain rates indicated.

Electrical conductivity measurements of the Cu–5 vol.% TiC alloy gave a value of 76.9% IACS. Thus, this material accomplishes the requirement of a minimum value of 75% IACS indicated in reference [7] for electrical-resistance welding.

3.2. Electrodes performance

The results obtained after 80 welding operations for the three indexes used for evaluating the compared electrode performance of bars of electrolytic Cu and Cu–5 vol.% TiC alloy, are summarized in Table 1. Fig. 4 shows the Cu and Cu–5 vol.% TiC electrodes after 80 welding operations. Irrespective of the electrode material, the lower electrode of a

Table 1
Values of the electrode-performance indexes after 80 welding operations

Electrode		Performance indexes		
Material	Position	Tip shortening (%)	Tip-diameter increase (%)	Mass loss (%)
Cu	Upper electrode (moving)	37	26	12.2
	Lower electrode (fixed)	64	42	11.5
Cu–5 vol.% TiC	Upper electrode (moving)	7	21	3.1
	Lower electrode (fixed)	15	22	3.3

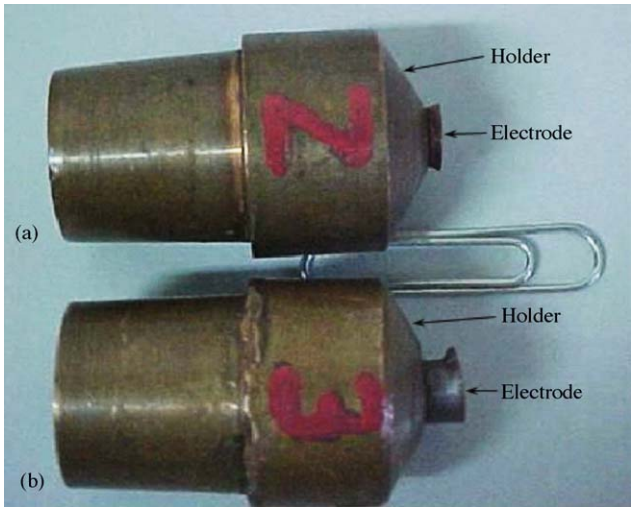

Fig. 4. Electrodes in their adapting holders after 80 welding operations: (a) electrolytic (massive) Cu and (b) Cu–5 vol.% TiC alloy.

pair, the fixed one, exhibited a higher deformation and mass loss than the upper electrode, the moving one.

The effect of the number of welding operations on the percentage of tip shortening for Cu and Cu–5 vol.% TiC electrodes is shown in Fig. 5. Table 1 and Figs. 4 and 5 show that the Cu–5 vol.% TiC alloy electrodes present a better performance than the Cu ones. In fact, the Cu–5 vol.% TiC electrodes exhibit a lower tip shortening, tip-diameter increase, and mass loss. Remark that concerning the lower electrodes, the mass loss index of the Cu–5 vol.% TiC alloy is about 3.5 times smaller than that of electrolytic Cu. These index results are coherent with the higher compression flow stress at $0.83 \times 10^{-4}\,s^{-1}$ of the Cu–5 vol.% TiC when compared to that of electrolytic Cu, as already shown in Fig. 3.

3.3. Microstructure

The microstructure of the Cu–Ti–C extruded alloy is shown in Fig. 6. EDS analyses showed that the dark particles observed in this micrograph correspond to TiC dispersoids, ranging from 5 to 15 nm in size. Note that TiC is not only

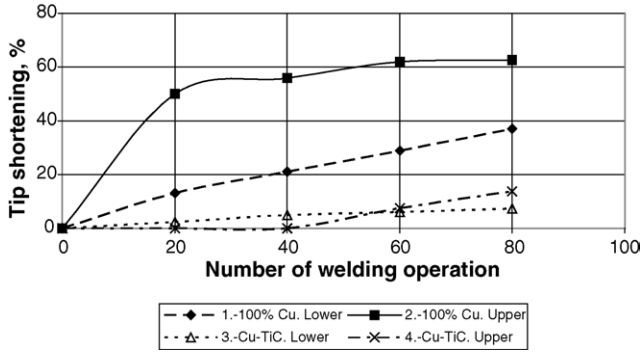

Fig. 5. Effect of the number of welding operations on the tip shortening percentage for Cu and Cu–5 vol.% TiC lower and upper electrodes.

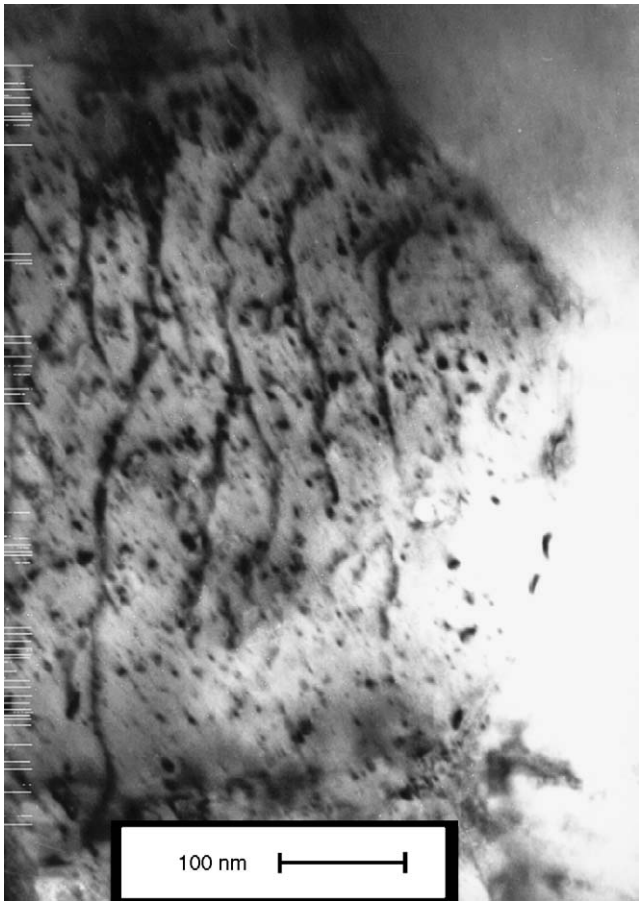

Fig. 6. Transmission electron micrograph of the as-extruded Cu–5 vol.% TiC alloy. TiC nanometric particles are seen into grains and on dislocations.

concentrated in dislocations, but it seems to be in part homogeneously distributed in the whole copper matrix. Moreover, TiC has also been detected by XRD measurements, see Fig. 7.

Therefore, such a better performance of the Cu–5 vol.% TiC electrode is microstructurally explained because of the presence of TiC nanoparticles. Those ceramic dispersoids would limit the movement of grain and subgrain boundaries, and of dislocations. In particular, dispersoids with coherent phases, such as TiC, mainly restrict grain-boundary mobility. We have observed that these TiC crystals are coherently orientated into the copper matrix in a similar Cu–Al–Ti–C alloy prepared by reaction milling [6].

The grain size of the copper matrix ranges from 100 to 150 nm, with the coarser grains presenting subgrains.

The use of copper-based alloy electrodes prepared by reaction milling would only be justified when their high performance exceed, in economical terms, the relatively high manufacturing costs of the process involved, having also in mind scenarios of other electrode materials competitors. The benefits of a better performance would in particular mean a larger time between tool replacements; in contrast, costs should consider that copper powders and its additions must be milled for many hours in rather small capacity mills, and

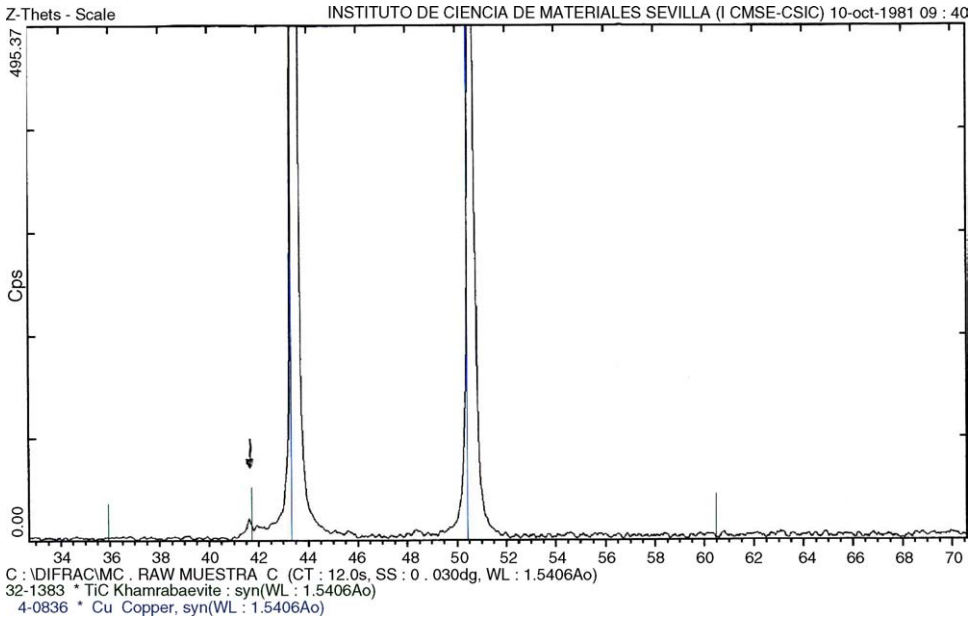

Fig. 7. XRD pattern for the Cu–TiC alloy. The vertical arrow shows diffraction TiC peak, at 2θ-value of 41.7° corresponding to (2 0 0) planes. The two main peaks correspond to copper.

then encapsulated and hot extruded for obtaining electrode bars.

4. Conclusions

The performance of dispersion-strengthened Cu–5 vol.% TiC alloy electrodes after 80 consecutive point welding operations is remarkably higher than that of electrolytic Cu electrodes.

The better performance of the Cu–5 vol.% TiC alloy synthesized by reaction mechanical alloying in a high-energy mill and consolidated by hot extrusion, is explained by considering the homogeneous distribution of nanometric TiC dispersoids in the alloy Cu matrix.

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