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Mechanical properties of hot-pressed Al-4.5 wt. % Cu/WC composite

Samaneh Bernoosi[1], Rasoul Azari Khosroshahi[1*], Reza Taherzadeh Mousavian[2]

1. Faculty of Materials Engineering, Sahand University of Technology, Tabriz, Iran
2. Young Researchers and Elite Club, Ilkhchi Branch, Islamic Azad University, Ilkhchi, Iran

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** Corresponding author: rakhosroshahi@sut.ac.ir ; Tel: +98 9144127857*

Abstract
In this study, the elemental powders of aluminum and copper were initially subjected to mechanical alloying using an attrition ball mill under argon atmosphere to produce an Al-4.5 wt% Cu powder alloy. The WC nanoparticles were then added to the powder alloy and milled in a planetary ball mill to explore the role of the WC nanoparticles on the mechanical properties of the fabricated composite powder. The experimental results revealed that a solid solution of Al-Cu could be formed after MA and a good dispersion of the WC nanoparticles in the aluminum matrix was obtained as characterized using X-ray diffraction and scanning electron microscopy, respectively. The results of hardness and compression tests of the hot pressed composites indicated that the MA followed by the hot-press processes was successful to fabricate an alloy and a metal matrix composite with considerable mechanical properties. However, a decreasing trend in the hardness and strength of the composites with the WC contents of more than 5wt% was observed. The maximum values of 260 HV and 575 MPa were obtained for a composite containing 5 wt% of nano ceramic particles.

Keywords: *Al-4.5 wt% Cu, Metal matrix composite, Mechanical alloying, Microstructural characterization, WC nanoparticle.*

1. Introduction

In recent years, many studies have been done on the aluminum metal matrix composites as they have low weight and high special strength, and can be easily manufactured at low cost. These properties as well as the properties that the ceramic particle reinforcement would provide (such as good plastic forming capability, excellent heat and wear resistance and bulk mechanical properties), made composites with particulate reinforcement very promising materials in applications such as aerospace (helicopter, rotor vanes in the aero-engine), and automotive industries (brake drum, drive shaft, cylinder block), sports and army [1-9].

Nanocrystalline composites containing ceramic nanoparticles as reinforcement could be strengthened by both grain size reduction and nanoparticle effects. The strength of the particulate Metal Matrix Composites (MMCs) is affected by volume fraction, size, shape, and distribution of the particles. However, achieving optimized properties depends on good dispersion of the particles in the matrix [10-14]. As the nanoparticles tend to agglomeration to reduce their specific area, the homogeneity of dispersion becomes an obstacle. Mechanical Alloying (MA) was introduced as a solution to overcome this problem [10-15]. Razavi Tousi *et al*. [16] have achieved a homogeneous distribution of reinforcement in the aluminum matrix after 10 h of MA. MA is also a good route for the fabrication of the solid solution of alloys without an excessive increase in the temperature and gaining a nanostructure alloy. This low temperature causes the least reaction between the matrix and reinforcement, therefore, undesired interfacial reaction will be decreased, leading to improved mechanical properties [17-24]

Hence, the porosity content and matrix-particle interface, as well as reinforcement distribution affect the mechanical properties, the consolidation process should be well designed during fabrication of MMCs. There are a few researches available in the literature [25-27], using WC as the reinforcement in the matrix of an aluminum alloy. The main aim of this work is to produce an Al-4.5 wt% Cu solid solution matrix reinforced with nano WC particles using the MA and hot-press processes. For comparison, the mechanical properties of the sintered composite specimens containing various weight fractions of reinforcement as well as those with the pure Al and alloyed matrix samples were studied.

2. Experimental procedures

The elemental powder mixtures of Al, Cu (Table 1) and stearic acid (1 wt%, as the process control agent), were milled for 40 h in an attrition ball mill to form an Al-4.5 wt% Cu alloy; the rotation speed and ball to powder ratio were 270 rpm and 10:1, respectively. The milled alloy was mixed with different weight fractions (1, 3, 5 and 7%) of WC nanoparticles (Table 1) and milled in a planetary ball mill for 2h to investigate the effect of weight fraction of reinforcement on the mechanical properties of the fabricated composites. Consolidation of the milled powder was done using the initial cold pressing method followed by uniaxial hot pressing at 723°K and 800 MPa. The conditions of hot pressing are listed in Table 2.

Table 1. Elemental powder specification used in manufacturing of the composite

Elemental powder	Cu	Al	WC
Purity	99.8%	99.5%	99%
Average size	<20μm	50-60μm	<100nm

Table 2. Hot press condition for consolidation of the cold-pressed samples

Powder charged in mold	3.3 g
Compacting force	800 Mpa
Pressing temperature	450°C
Pressing duration	90 minutes
Dimension of sample	Cylinder with 10mm diameter, 1.7mm height
Lubricant	Mixture of oil and graphite

The fabricated alloyed and composite powders were characterized by Scanning Electron Microscopy (SEM, CamScan2300) to evaluate the morphological changes of the particles during MA. In addition, Energy Dispersive X-ray Spectroscopy (EDS) measurements were conducted to investigate the distribution of the nano WC particles, as well as copper powders. The crystallite size and lattice micro-strain of the milled powders were determined by X-ray diffraction phase analysis (D8 ADVANCE-BRUCKERS) following the Williamson-Hall approach [28], using a Cu-Kα radiation in the 2θ range of 10–90.

The microhardness test was applied according to the ASTM standard E384 on the consolidated samples using an Aksashi/ LECO M400-G1 microhardness tester under a load of 50 g for a dwell time of 10 seconds. An average value of five tests for each specimen was reported.

The compression test was applied according to the ASTM E9-89aR00 using an

ADAMEL DY26 compression/tension tester with a strain rate of 0.2 mm/ min at the height to diameter ratio (h/d) of 1.4. The average value of three tests for each specimen was reported.

3. Results and Discussion

3.1. Morphological evolution

As shown in Figure 1a, the as-received Al powder has near platelet shape. Due to the ductile nature of the Al and Cu (the alloying agents), they were resistant to plastic deformation. Thus, the cold welding process becomes dominant; this increases the duration of the ball milling. At the beginning of MA, the powder mixture became flattened and enlarged (Fig. 1b), the deformation took place at this stage, and the flat-type morphology was formed. By further milling to 20 h (Fig. 1c), fracturing and rewelding occurred and poor welded Al-Cu appears like flakes [29]. At the last stage, i.e. after 40 h of milling (Fig. 1d), the fracturing process overcame the cold welding one so that the work-hardened fragile flakes became finer and the morphology was changed to the equiaxed form. Figure 2 reveals that the size distribution of the milled powders after 40 h is finer than that of the 20 h milled powder.

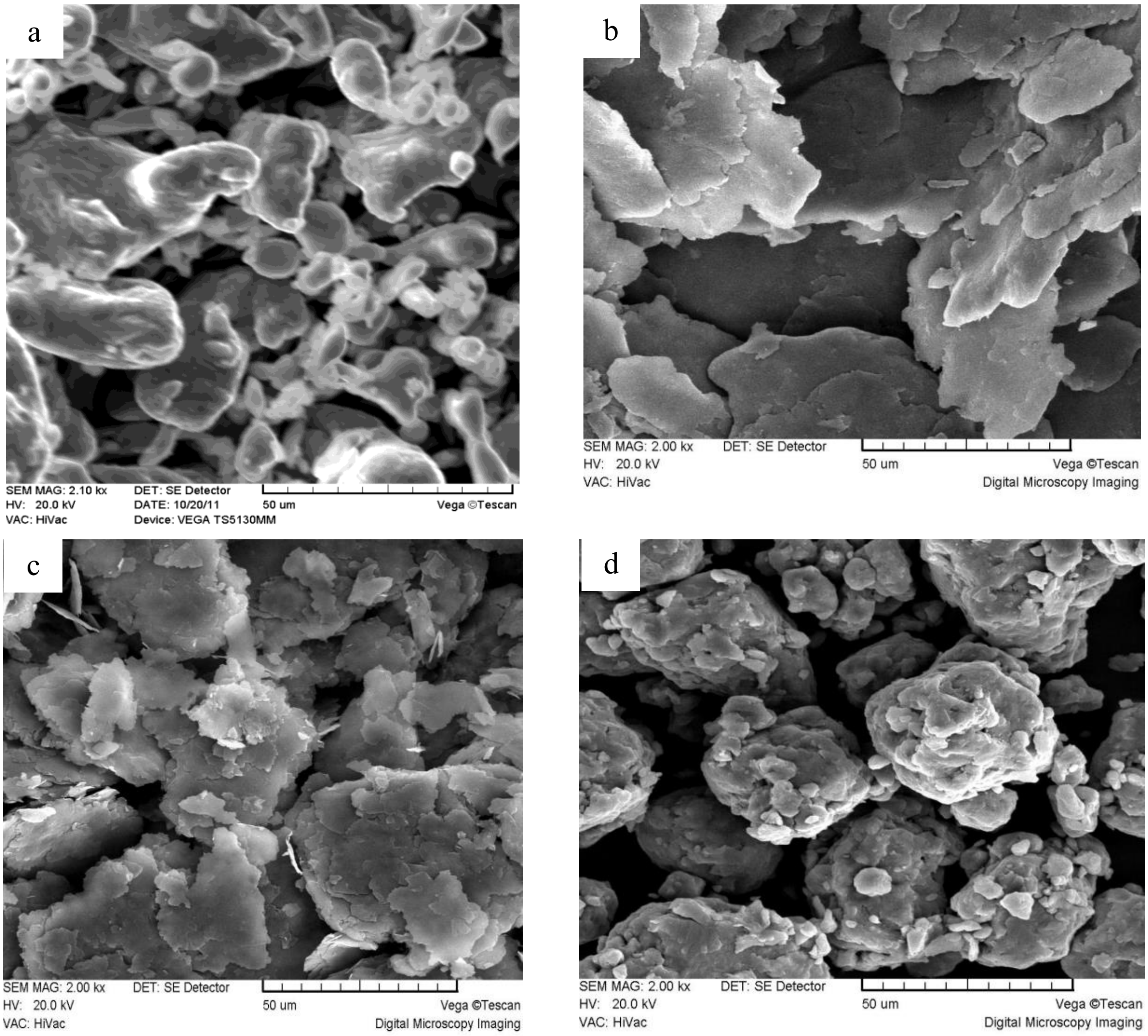

Fig. 1. Morphologies of the as-received Al powder (a), and milled products for 10 h (b), 20 h (c), and 40 h (d)

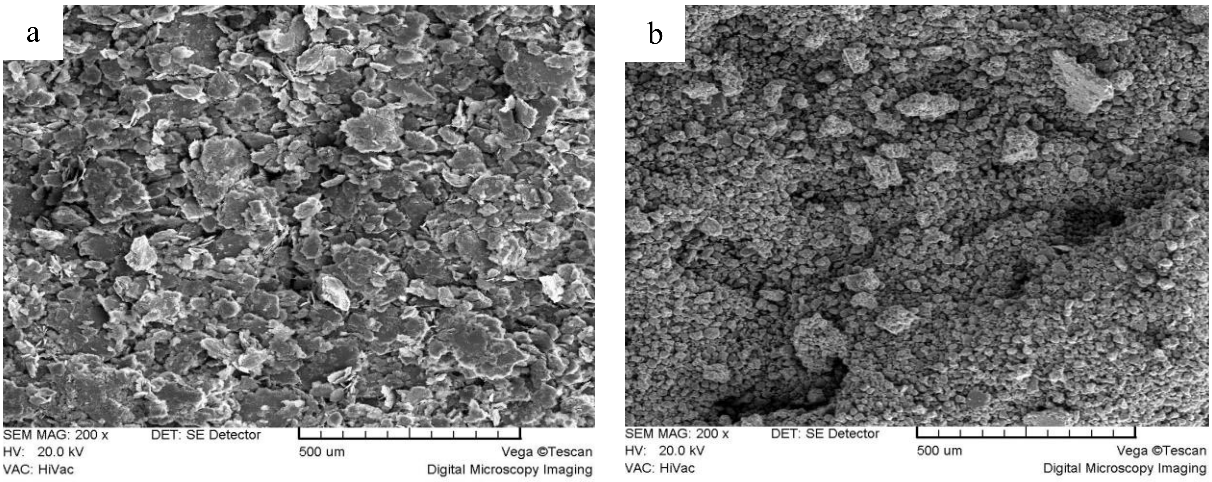

Fig. 2. SEM micrographs of the milled products for 20 h (a) and 40 h (b)

3.2. Structural analysis

Figure 3 shows the XRD patterns of the mechanically alloyed powders after various milling times. It can be seen that as the milling time increases, the Al peaks are gradually broadened and their intensities decrease, which is believed to be due to an increase in the lattice strain and a decrease in the crystallite size. The stress generated by plastic deformation causes the formation of sub-grain boundaries and therefore, grain refinement will be observed with increasing of the lattice distortion [30, 31]. After 40 h of milling, the peaks of Cu disappeared and the Al peaks shifted slightly to higher angles; the lattice parameter of the Al was increased due to the dissolving of the Cu atoms into the Al crystal structure to form a solid solution of Al-4.5 wt% Cu. The production of the fcc-Al (Cu) solid solution by MA was also investigated elsewhere [32].

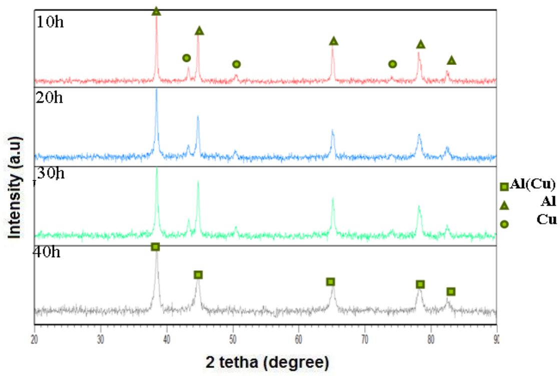

Fig. 3. XRD patterns of the milled product as a function of the milling times

The crystallite size and lattice strain of the milled powders were measured by both the Scherrer and Williamson-Hall methods (Table 3). By increasing the milling time, the induced strain increased and the grain size decreased. This event has been reported by several researchers as well [32, 33]. A remarkable increase in the lattice strain in the first 10 h of milling followed by a further slight one reflects the generation of dislocations and lattice defects in the grains. By increasing the milling time, the grains got saturated and therefore the dislocations changed their form and orientation to balance the energy within the grains [34], which resulted in the refinement of the grains [35]. Al crystallite size of the mechanically alloyed powder was found to be ~25 nm after 40 h of milling.

Table 3. Crystallite size and strain induced by MA in various milling times

Milling time(h)	$D_{Scherrer}$ (nm)	$D_{Williamson\text{-}Hall}$ (nm)	Strain%
10	47	231	0.06
20	26	31	0.44
30	24	30	0.45
40	22	25	0.5

The SEM image and the related EDX analysis of the sintered composite contain 3 wt% nano WC as shown in Figure 4. It exhibits a good dispersion of WC and Cu particles in the aluminum matrix. A near uniform dispersion of the reinforcement in the matrix and a good bonding strength will result in satisfactory mechanical properties [33]. Therefore, the secondary process after MA is very critical in order to gain good bonding strength as well as having nano-sized grains. From Figure 4b, it can be observed that the aluminum phase covers almost the entire surface of the composite. Inter-lapping of the aluminum and copper is noticeable, which leads to the assumption of the presence of Al_2Cu. In order to justify the EDX results, an X-Ray diffraction phase analysis was applied for a detailed characterization of the Al_2Cu.

Figure 5 shows the XRD pattern of hot pressed Al 4.5 wt% Cu/ 3 wt% WC composite. This Figure indicates the presence of the WC, Al and Al_2Cu phases. There is no evidence of the Cu peak, meaning that during hot pressing, all the Cu powders engaged in the formation of Al_2Cu. In addition, this Figure indicates that the corresponding peaks of WC remained unchanged, meaning that no interfacial reaction occurred between the matrix and WC.

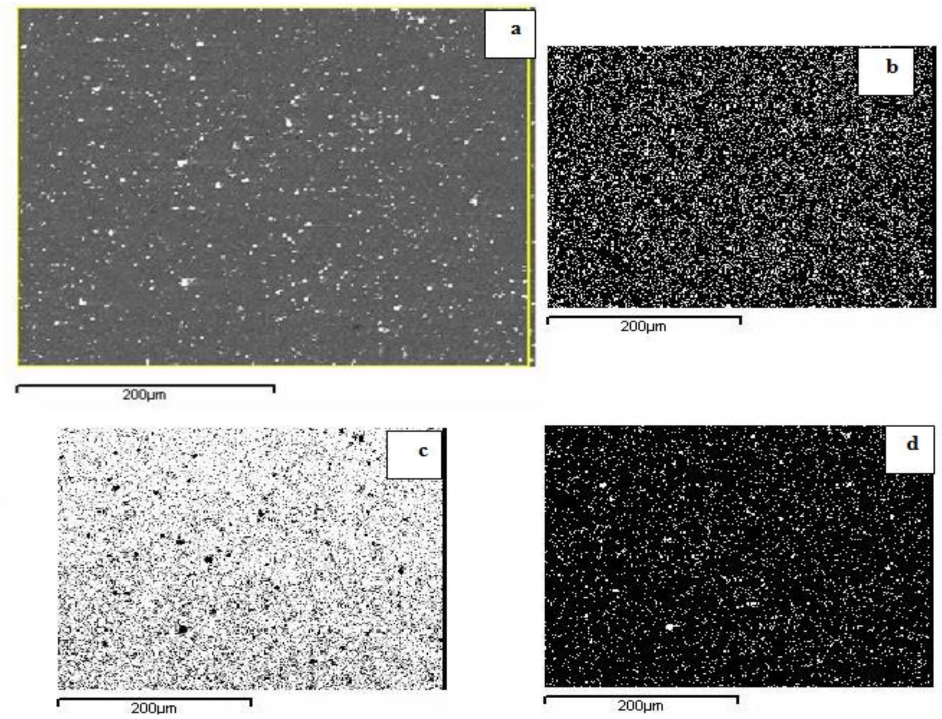

Fig. 4. (a) SEM micrographs of the sintered Al-4.5 wt % Cu-7 wt % WC composite, EDX analysis of Al (b), Cu (c), and W (d)

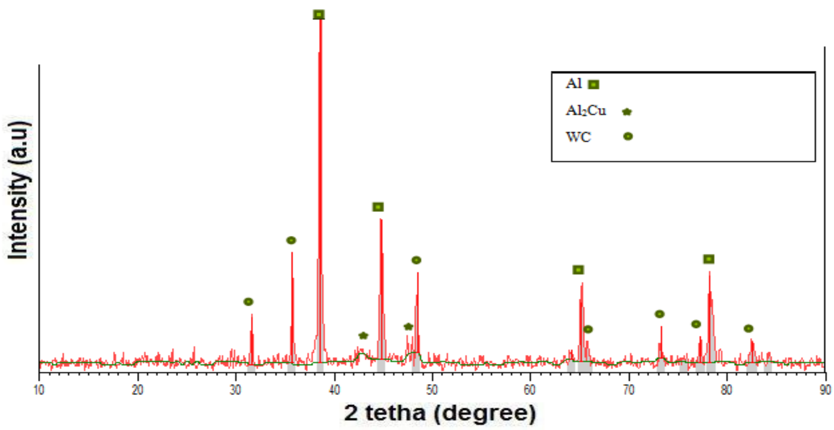

Fig. 5. XRD pattern of the sintered Al-4.5 wt % Cu-7 wt % WC composite

3.3. Mechanical properties

3.3.1. Microhardness

Values of microhardness and density of the produced composites are listed in Table 4. The hardness of the Al-4.5 wt% Cu alloy was considerably increased due to the solid-solution preparation and grain size reduction during MA. The addition of the nanoparticles to the matrix further enhanced the hardness of the composite, while the compressibility of the powders was decreased. The presence of the particles of finer diameter size led to an increase in the specific surface area; therefore, the inter-particle friction and porosity would be increased, leading to poor grain junction and compressibility [36].

Table 4. Microhardness and density of the hot pressed composites

Material	Microhardness (HV)	% Relative Density
Al	41	99
Al/4.5 wt. % Cu (M)	164	98
M+1 wt. % WC	207	96
M+3 wt. % WC	234	93
M+5 wt. % WC	260	92
M+7 wt. % WC	232	92

A reduction in the microhardness was observed in a sample containing 7 wt% WC, indicating that the unfavorable porosity effect, as well as the excessive agglomeration of the nanoparticles was dominant, although this sample had a higher amount of hard ceramic nanoparticles.

3.3.2. Compression test

The strain-stress curves, as well as the values of yield and failure stresses of the composites are tabulated in Table 5. During the compression test, no buckling deformation was observed. The high amount of reinforcement surrounding the ductile matrix led to a decrease in the ductility and an increase in the strength of the composite specimens. In addition, the porosity led to an initial failure of the specimen preventing the formation of plastic deformation zones. Therefore, an increasing trend in the compression strength is observed by increasing the amount of reinforcement, which is not followed for a specimen containing 7 wt% WC. This result is in agreement with the density and hardness results. As explained, the two factors (ceramic reinforcement and porosity) caused a decreasing trend in the ductility of the composites. The ductility of the pure aluminum obtained was 27%, while after alloying it reached up to 14% and the sample containing 7 wt% nano WC had only 2% ductility. The optimum amount of the WC reinforcement in our study was found to be 5 wt%, meaning that a decreasing trend in strength will be observed for more than this value. The last note that can be deduced from this table is the difference between values of the yield and failure stresses of all the samples. This amount was decreased for the samples, which have higher amounts of ceramic particles, meaning that the plastic deformation zone was limited for samples containing 5 and 7 wt% of nano WC.

Table 5. Results of the compression test

Material	Yield Strength (MPa)	Failure stress (MPa)	Ductility (%)
Al	45	105	27
Al/4.5 wt. % Cu (M)	290	410	16
M+1 wt. % WC	385	475	11
M+3 wt. % WC	455	510	9
M+5 wt. % WC	575	605	5
M+7 wt. % WC	545	560	2

4. Conclusions

The main findings of the present study are as follows:

1. An Al-4.5 wt% Cu solid solution was formed after attrition ball milling for 40 hours. Diffusion of Cu into the Al was found to be the dominant process during ball milling.
2. A near uniform dispersion of the WC as nano reinforcement in the matrix was obtained after 2h of ball milling.
3. The Al crystallites were decreased, but their associated lattice strain was increased with increasing the milling time to 40h.
4. The presence of the ceramic nanoparticles will lead to a lower relative density, a lower

ductility and a higher yield and failure strength. However, this trend is not followed by the sample containing 7 wt% nano WC.

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