PRODUCTION OF Al-5Cu ALLOY COMPOSITES REINFORCED WITH FEW-LAYERED GRAPHENE BY POWDER METALLURGY METHOD

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Abstract

Aluminum based alloys have been widely used in the automotive, aircraft and defense applications because of good thermal and electrical conductivity, high tensile strength-to-weight ratio, high hardness, and ductility properties. Graphene, is an allotrope of carbon, attracts great attention worldwide due to its sp^2-hybridized two-dimensional honeycomb structure, low weight, thermal, electrical, and mechanical properties. In the present study, high purity few-layered graphene (FLG) which was synthesized via electric arc discharge method (EAD) were reinforced to the Al-5Cu alloy matrix using various weight fraction of 0, 0.1, 0.3, and 0.5, by mechanically alloying (MA). These nano-composite powders were consolidated by cold pressing under 450 MPa and they were subjected to sintering at 570 °C and 580 °C for 3 hours under argon atmosphere. The microstructure of composites materials was studied by optical microscope and scanning electron microscopy. The FLG was observed to be dispersed homogeneously in the Al-5Cu alloy matrix. An increase in the micro hardness for Al-5Cu alloy with 0.5 wt% FLG (123 HV) by 45% was observed compared to pure Al-5Cu alloy (85 HV) sintered at 570 °C. Moreover, wear properties of these composite materials were investigated by means and analysis of variance (ANOVA).

Keywords: Aluminum alloy, arc discharge, graphene, metal matrix composite, powder metallurgy

1. INTRODUCTION

Aluminum (Al) metal matrix composites are widely used in the automotive, aircraft and defense applications because of its good thermal and electrical conductivity, high tensile strength-to-weight ratio, high hardness, and ductility properties [1-2]. Various reinforcement materials such as Al_2O_3, SiC, B_4C, TiC,C with low density, good mechanical and chemical properties, high thermal stability and Young's modulus, good processability are used for Al metal matrix composites [3]. Graphene, which is one allotrope of carbon, due to its sp^2-hybridized two-dimensional honeycomb structure, low weight, thermal, electrical, and mechanical properties; has attracted great attention around the world. It can be considered as the ideal reinforcement for Al-based matrix composites with very high electrical (electron mobility, 1500 $cm^2\ V^{-1}\ s^{-1}$; resistance 10^{-6} Ωcm) and thermal conductivity (5.3×10^3 $Wm^{-1}K^{-1}$), low thermal expansion coefficient ($-6\times10^{-4}K^{-1}$), self-lubricating and excellent mechanical properties (tensile strength 130 GPa; elastic modulus 0.5 - 1 TPa.) [4].In this study, various weight fraction of 0, 0.1, 0.3, and 0.5 FLG which was produced by EAD method in our laboratory was reinforced to the Al-5Cu alloy matrix as reinforcement by MA. Structural and mechanical properties of composites were examined. Thus, it is aimed that the effect of FLG content on Al-5Cu alloy matrix was investigated.

2. MATERIALS AND METHODS

FLG reinforced Al-5Cu alloy matrix composites were produced from the Al (-200 mesh, 99%; Acros Organics), Cu (< 63 μm, ≥ 99%; Merck) and FLG as starting powders. High purity FLG was synthesized byEAD method by using an originally designed stainless steel reactor in our laboratory [5]. The FLG were reinforced to the Al and Cu powders alloy matrix using various weight fraction of 0, 0.1,0.3 and 0.5 by MA. A high-energy planetary ball mill with a stainless steel jar (250 mL) was used for MA. Stearic acid ($C_{18}H_{36}O_2$; 97% Merck) was added 2.5 wt% as a process control agent (PCA). These FLG reinforced Al-5Cu alloy matrix composite powders were formed as a bulk by using a uniaxial manual press at 450 MPa. Green bulk composites which were subjected to binder removal at 420 °C for 2 hours, were sintered at 570 °C and 580 °C with a 5 °C/min heating and cooling rate for 3 hours under Ar atmosphere. The particle size distribution of starting powders was conducted using Malvern Mastersizer 3000. Optical images of FLG reinforced Al-5Cu alloy matrix composites were determined with Nikon Eclipse microscope. The hardness of the FLG reinforced Al-5Cu alloy matrix composites was investigated for 15 seconds with a load of 200 g via a Qness Q10M microhardness tester. Wear properties were examined with steel balls a diameter of 5 mm by using Bruker UMT 2 wear tester. The load, wear distance, wear rate, and total wear distance applied to the bulk samples were 2 N and 3 N, 5 mm, 5 mm/s and 20000 mm, respectively. Moreover, wear properties were evaluated by using Minitab with ANOVA. The density of the sample was measured based on the Archimedes' principle.

3. RESULTS AND DISCUSSIONS

Figures 1(a-b) show particle size distribution and SEM images of Al and Cu powders as starting powders, respectively. Average particle size of Al was 21 μm, while Cu was measured as 23.6 μm. The SEM images which is shown **Figures 1(c-d)**of Al used as the starting powder are examined that is seen it has many unformed large and small particles. Cu powders also have a dendritic structure.

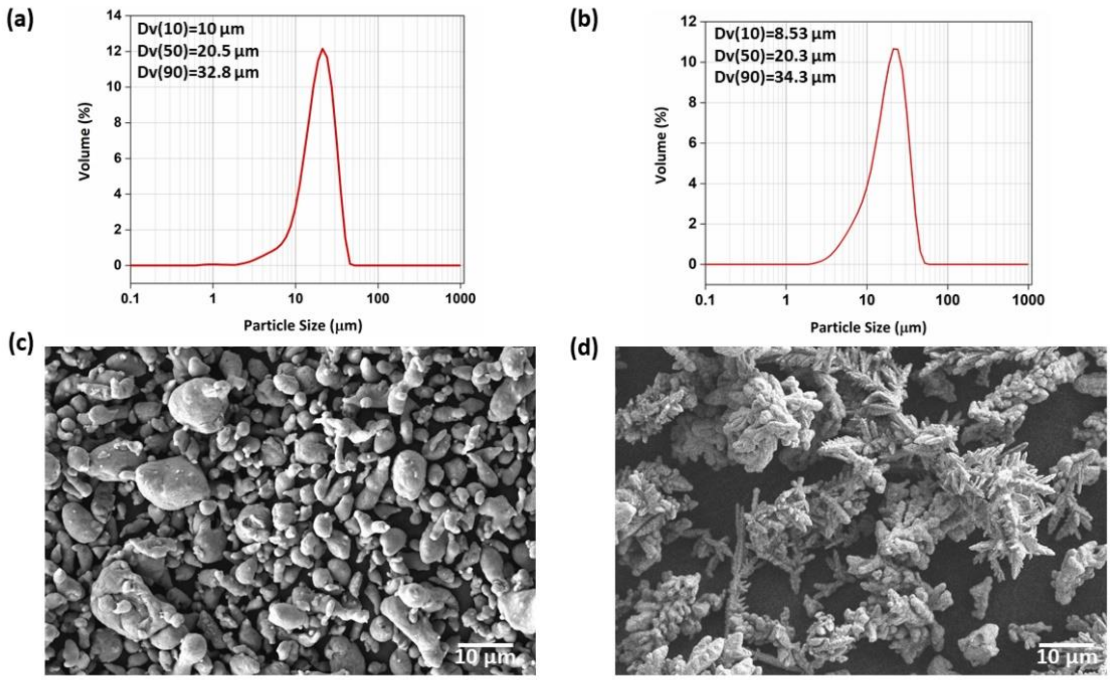

Figure 1(a-b) The particle size distribution, **(c-d)** SEM images of Al and Cu powders as starting powders, respectively

Figure 2(a) shows XRD pattern of 0.5 wt% FLG reinforced Al-5Cu alloy matrix powders. Characteristic peaks of Al and Cu was observed because the mixture is homogeneous in nanocomposite powders [6]. Since FLG were reinforced in trace amounts and dispersed homogeneously in the Al-5Cu alloy matrix, the peak of FLG was not seen in XRD patterns. The SEM image of 0.5 wt% FLG reinforced Al-5Cu alloy matrix powders is shown in **Figure 2(b).** While Al exhibits a ductile behavior in the ball milling, FLG also on the other hand, have a fragile structure. Ductile Al particles are repeatedly flattened during ball milling with cold welding, fracture and plastic deformation [7]. It is considered that FLG flatten the Al particles by creating a local tension. It can be said that the FLG are embedded in the Al-5Cu alloy matrix because of FLG residue is not visible on the matrix in the SEM images. Moreover, EDS analysis of 0.5 wt% FLG reinforced Al-5Cu alloy matrix composite powders is shown in **Figures 2(c-d)** with SEM image at different magnifications. The presence of Cu, which is the main alloying element, together with Al in the matrix alloy stands out. The C also shows the presence of FLG in the Al-5Cu alloy matrix.

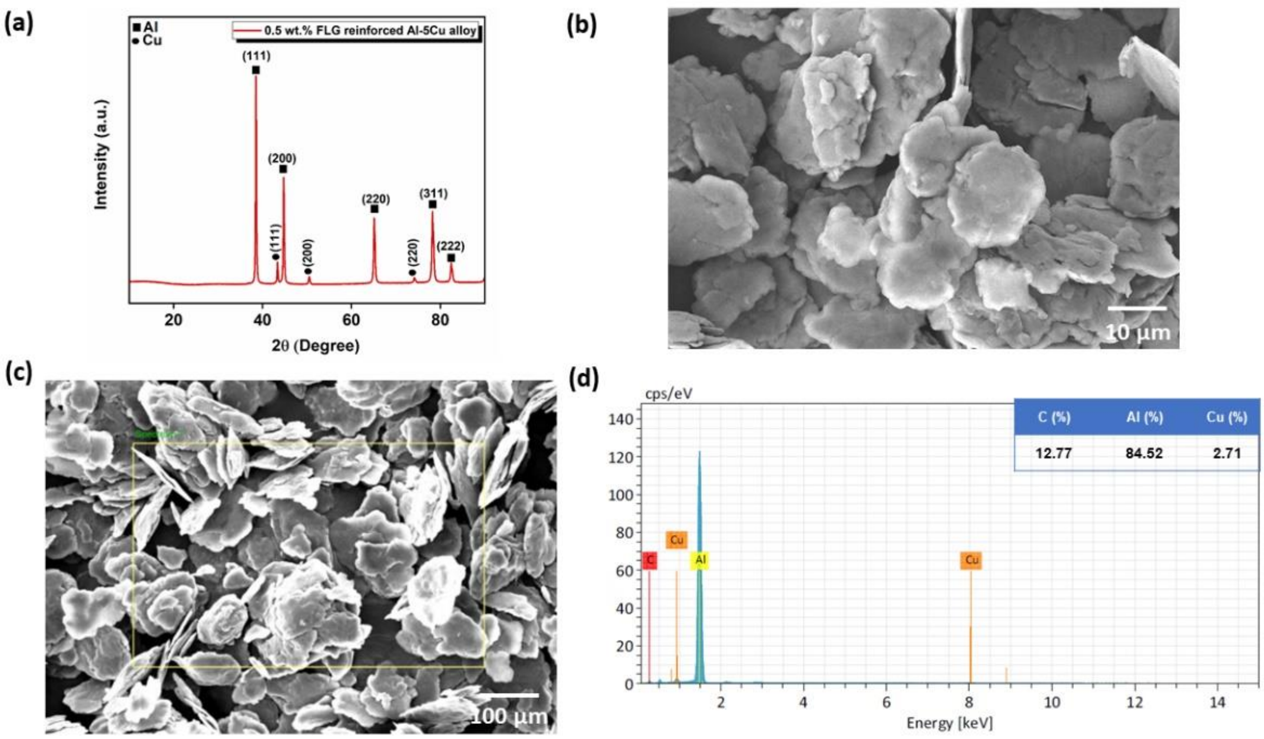

Figure 2(a) XRD pattern,**(b)** SEM image, **(c)** SEM image for EDS analysis and **(d)** EDS analysis of 0.5 wt% FLG reinforced Al-5Cu alloy matrix powders

Table 1 gives information about theoretical, Archimedes' and relative density of the sintered samples at different temperatures.

Table 1 Theoretical, Archimedes' and relative density of the sintered samples at different temperature

Sample	Theoretical density (g/cm^3)		Archimedes' density (g/cm^3)		Relative density (%)	
	570 °C	580 °C	570 °C	580 °C	570 °C	580 °C
Al-5Cu+0 wt% FLG	2.797		2.506	2.538	89.62	90.74
Al-5Cu + 0.1 wt%FLG	2.796		2.564	2.572	91.71	92.01
Al-5Cu+0.3 wt%FLG	2.793		2.590	2.599	92.74	93.07
Al-5Cu +0.5 wt%FLG	2.790		2.566	2.586	91.24	92.69

Figure 3 shows optical images of (a) 0, (b) 0.1, (c) 0.3 and (d) 0.5 wt% FLG reinforced Al-5Cu alloys composite matrix with 20X magnification for sintering at 570 °C. FLG were homogeneously dispersed on the Al-5Cu alloy matrix as shown in **Figures 3 (b-c-d).** Moreover, it was observed that there are some voids in the structure.

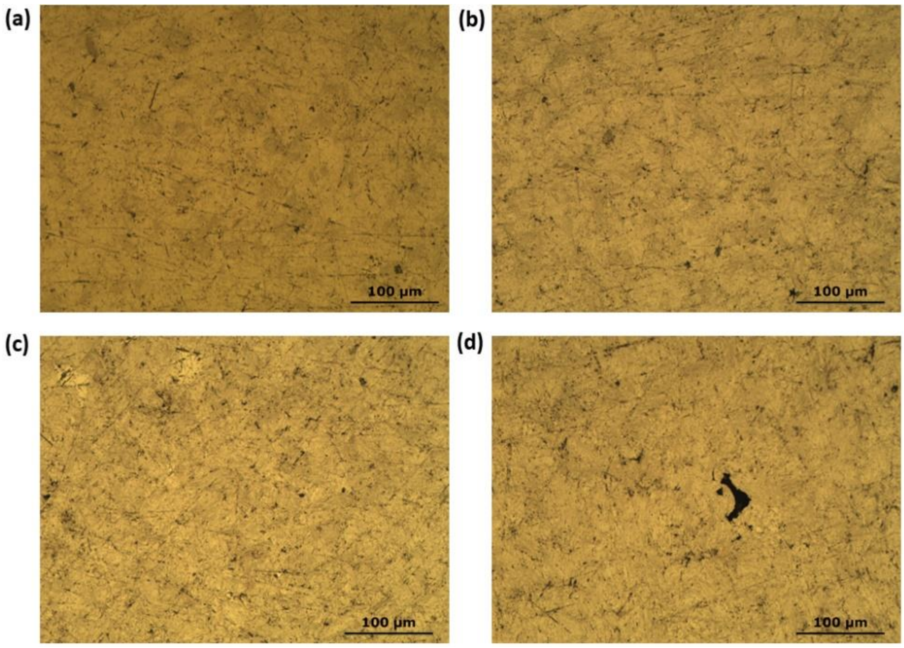

Figure 3 Optical images of **(a)** 0, **(b)** 0.1, **(c)** 0.3 and **(d)** 0.5 wt% FLG reinforced Al-5Cu alloys composite matrix for sintering at 570 °C

Figure 4 shows optical images of **(a)** 0, **(b)** 0.1, **(c)** 0.3 and **(d)** 0.5 wt% FLG reinforced Al-5Cu alloys composite matrix for sintering at 580 °C. It was seen that FLG were homogeneously dispersed in the Al-5Cu matrix alloy.

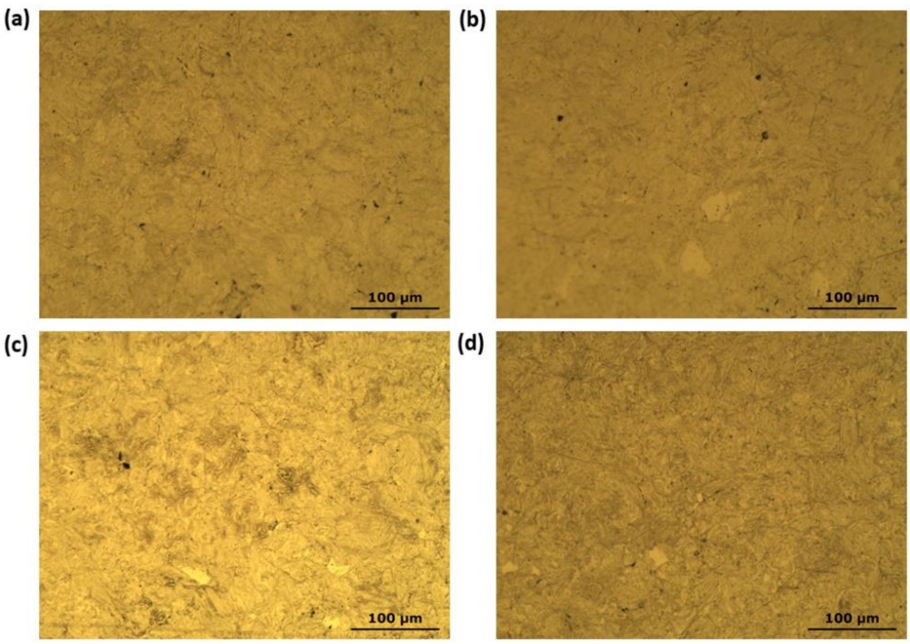

Figure 4 Optical images of **(a)** 0, **(b)** 0.1, **(c)** 0.3 and **(d)** 0.5 wt% FLG reinforced Al-5Cu alloys composite matrix for sintering at 580 °C.

Figure 5 shows the graph with error bar of hardness (HV) values for samples at different sintering temperatures. An increase in the hardness for Al-5Cu alloy with 0.5 wt% FLG (123 HV) by 45% was observed compared to pure Al-5Cu alloy (85 HV) sintered at 570 °C. Moreover, this increase was seen as 38% for sintering at 580 °C.

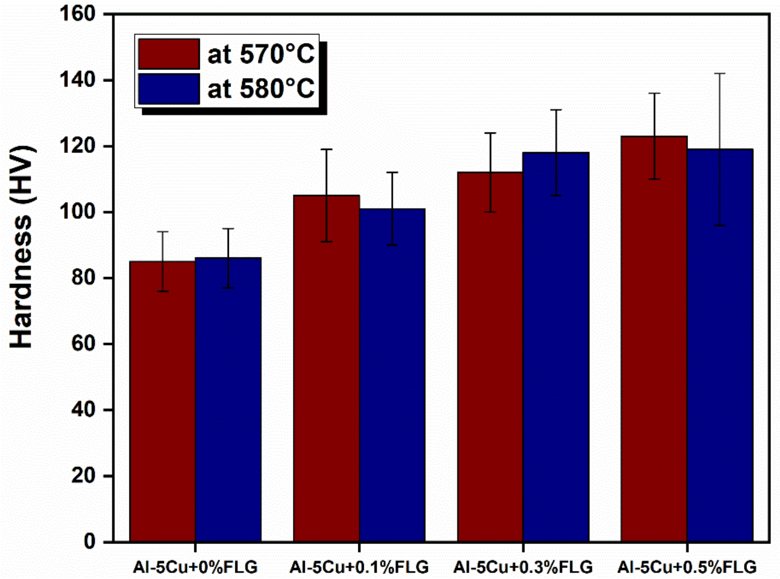

Figure 5 The graph with error bar of hardness (HV) values for samples at different sintering temperatures

Values of coefficient of the wear (COF), which was obtained by using wear tester, were given in **Table 2.** As the FLG content increases, the COF values decrease. Moreover, it was observed that as the applied load in the wear test increased, the COF value also decreased. The lowest COF, with a value of 0.491, was observed in the 0.5 wt% FLG reinforced Al-5Cu alloy-based composite sintered at 580 °C with a 3 N load applied.

Table 2 COF results of FLG reinforced Al-5Cu alloy matrix composites

Sample	Coefficient of the wear (COF)			
	570°C		580°C	
	2 N	3 N	2 N	3 N
Al-5Cu + 0 wt% FLG	0.602	0.556	0.588	0.556
Al-5Cu + 0.1wt% FLG	0.575	0.553	0.586	0.548
Al-5Cu + 0.3 wt% FLG	0.568	0.546	0.581	0.539
Al-5Cu + 0.5 wt% FLG	0.567	0.542	0.503	0.491

ANOVA was used to analyze the influence of process parameters (FLG composition and sintering temperature) on the COF for the FLG reinforced Al-5Cu alloy matrix composites. **Table 3** gives information about ANOVA results for COF. It is clearly seen that the FLG composition affects the COF value the most with a contribution of 42.9%.

Table 3 ANOVA results for COF

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution(%)
Composition (FLG%)	3	0.005566	0.005566	0.001855	3.13	0.074	42.87
Sintering Temperature (°C)	1	0.000856	0.000856	0.000856	1.44	0.257	6.59
Load (N)	1	0.000638	0.000638	0.000638	1.08	0.324	4.91
Error	10	0.005923	0.005923	0.000592			45.62

Note: DF – Degree of freedom, Seq. – Sequential, Adj. – Adjusted, SS – Sum of squares, MS – Mean of squares.

4. CONCLUSION

FLG reinforced Al-5Cu alloy matrix composites were successfully produced by powder metallurgy. It was observed that FLG were homogeneously dispersed in the Al-5Cu alloy-based matrix. With the increase of FLG content, a significant increase in hardness values was observed. An increase in the hardness for Al-5Cu alloy with 0.5 wt% FLG (123 HV) by 45% was observed compared to pure Al-5Cu alloy (85 HV) sintered at 570°C. In the ANOVA analysis performed, it was seen that the FLG content was more related to the COF values with a high rate of 42.9%. In future studies, the effect of the produced FLG content on composites can be investigated in more detail by applying different process and wear test conditions.

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