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Microstructure and mechanical properties of hot extruded 6016 aluminum alloy/graphite composites

Mohamed M. El-Sayed Seleman[a,b,*], Mohamed M.Z. Ahmed[a,b,c], Sabbah Ataya[a,b,d]

[a] Department of Metallurgical and Materials Engineering, Faculty of Petroleum and Mining Engineering, Suez University, 43518 Suez, Egypt
[b] Suez and Sinai Metallurgical and Materials Research Center of Scientific Excellence (SSMMR-CSE), 43518, Suez, Egypt
[c] The British University in Egypt, Mechanical Engineering Department, El-Sherouk City, 11837, Cairo, Egypt
[d] Department of Mechanical Engineering, College of Engineering, Al Imam Mohammad Ibn Saud Islamic University, Riyadh 11432, Saudi Arabia

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The incorporation of graphite particles into AA6016 aluminum alloy matrix to fabricate metal/ceramic composites is still a great challenge and various parameters should be considered. In this study, dense AA6016 aluminum alloy/(0–20 wt%) graphite composites have successfully been fabricated by powder metallurgy process. At first, the mixed aluminum and graphite powders were cold compacted at 200 MPa and then sintered at 500 °C for 1 h followed by hot extrusion at 450 °C. The influence of ceramic phases (free graphite and in-situ formed carbides) on microstructure, physical and mechanical properties of the produced composites were finally investigated. The results show that the fabricated composites have a relative density of over 98%. SEM observations indicate that the graphite has a good dispersion in the alloy matrix even at high graphite content. Hardness of all the produced composites was higher than that of aluminum alloy matrix. No cracks were observed at strain less than 23% for all hot extruded materials. Compressive strength, reduction in height, ultimate tensile stress, fracture stress, yield stress, and fracture strain of all Al/graphite composites were determined by high precision second order equations. Both compressive and ultimate tensile strengths have been correlated to microstructure constituents with focusing on the in-situ formed ceramic phases, silicon carbide (SiC) and aluminum carbide (Al_4C_3). The ductile fracture mode of the produced composites became less dominant with increasing free graphite content and in-situ formed carbides. Wear resistance of Al/graphite composites was increased with increasing graphite content. Aluminum/20 wt% graphite composite exhibited superior wear resistance over that of AA6016 aluminum alloy.

1. Introduction

Recently, there are increasing demands for lightweight, low-cost materials which have sufficient strength with high wear resistance for many industries. The incorporation of graphite particles into metal matrix to fabricate a self-lubricating composite is considered as an interesting innovation [1,2]. Carbon has several allotropes and one of them is soft graphite (Gr) with hexagonal crystal structure. It is an effective solid lubricant additive [3] due to its anti-corrosion, high-temperature endurance and self-lubricating properties [4–6]. It was reported that [7–9] the presence of graphite in composite materials leads to an increased wear resistance subjected to sliding wear.

The metal matrix may also be selected to impart good electrical and thermal conductivities to the produced composites. Aluminum (Al) is recommended as a metal matrix constituent for production of such composites [10–13]. Since graphite particles are lighter than matrix alloys, the Al/graphite composites are used to reduce the overall weight of components. Aluminum and graphite are widely acceptable materials for automotive and aerospace applications. Furthermore, the aluminum matrix composites containing graphite have a large scale application in land vehicles and electrical contacts. Due to their wide range of characteristics such as low friction, low density, low thermal expansion coefficient and remarkable high thermal conductivity [10,14,15]. Al/graphite composites have

* Corresponding author at: Department of Metallurgical and Materials Engineering, Faculty of Petroleum and Mining Engineering, Suez University, 43518 Suez, Egypt.
E-mail address: mohamed.elnagar@suezuniv.edu.eg (M.M. El-Sayed Seleman).

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numerous applications in electronic industry. These are electronic packaging, heat sinks, heat spreaders, base plates, coolers, discs and rings. For electronic packaging applications, mainly two properties should be considered and controlled, namely high thermal conductivity and low thermal expansion of the composites, to meet thermal dissipation requirements. Chen and Huang [10] studied the influence of graphite percentage and its orientation on the properties of Al/graphite composites through hot pressing technique. They reported that as the graphite volume fractions increased from 10 to 90 vol.% in the aluminum matrix, thermal conductivity increased, while thermal expansion coefficient and density decreased. The related properties are favorable for many electronic and thermal applications.

Different processing techniques can be used to fabricate Al/graphite composites. They can be grouped into two main routes depending on the state of matrix during the manufacturing process, namely liquid [16–19] and solid processing routes [20–24].

In liquid techniques, the low density of graphite particles as compared to that of aluminum matrix causes floating of graphite particles on the aluminum melt resulting in non-uniform distribution of graphite in the produced composites [19]. However, good dispersion of graphite in aluminum melt was obtained by Barekar et al. [18] using a melt conditioned high-pressure die casting process with the help of innovated high-shear dispersive mixing action of a twin screw. For solid processing routes, spark plasma as an expensive technique was used to produce Al/graphite composites [25]. Moreover, there are considerable trials to produce Al/ceramic composites using friction stir processing (FSP) by dispersing the ceramic phase in shape of particles [26,27] or nanotubes [26,28]. Application of hot extrusion as a processing method to reinforce aluminum with boron carbide (B_4C) particles after mechanical milling has been studied by Alizadeh et al. [29]. They reported that the mechanical properties of Al/B_4C composites were enhanced with increasing B_4C content; however, the elongation was decreased.

In the present study, in order to avoid the formation of heterogeneous structure, powder metallurgy route consisting of cold compacting, sintering and hot extrusion is suggested instead of conventional liquid-based process to produce Al/graphite composites. No studies have been reported on hot extrusion, microstructure features, mechanical properties and fracture characterization of 6016 Al alloy containing a wide range of graphite content up to 20 wt%. Furthermore, researches on the deformation processing of soft particles such as dispersed graphite in Al alloy matrix during hot extrusion are limited. Thus, this investigation aims to explore the possibility of producing 6016 Al alloy/graphite composites containing high graphite content up to 20 wt%. Moreover, deep investigation of mechanical properties in terms of hardness, compressive strength, tensile properties and wear resistance behavior was conducted. In addition, the deformation behavior of graphite dispersed composites, the fracture and worn surfaces of the Al alloy matrix and the composites were also examined.

2. Experimental

2.1. Starting materials

The starting materials were commercial grade 6016 Al alloy and high purity graphite powders. Aluminum and graphite powders were supplied by Prolabo, Paris. According to the supplier, aluminum content was not less than 97% and the graphite purity was of 99.90% with ash content of 0.05%. The chemical composition of Al alloy powder is listed in Table 1. The particle shape of Al alloy powder was examined by SEM as shown in Fig. 1(a), which indicates that the particles of the aluminum powder are slightly rounded with an average size of 100 μm. SEM examination of graphite powder shows that the particles are mostly in a mixture of granular and flake shapes, as shown in Fig. 1(b).

Table 1
Chemical composition of AA6016 Al alloy powder (wt%).

Si	Mg	V	Fe	Mn	Cr	Zn	Cu	Ti	Al
1.50	0.50	0.03	0.79	0.10	0.14	0.02	0.03	0.03	Bal.

2.2. Processing of the composites

The designed Al/graphite composites have 0, 5, 10, 15 and 20 wt% graphite content. The powder batches were mixed in a double cone rotating mixer for 1 h at a speed of 45 rpm, to achieve homogenous mixtures of loose aluminum and graphite powders. The powder blends (40 g) were cold compacted at 200 MPa in a single acting die-set having 25.4 mm internal diameter. The produced green compacts were sintered at 500 °C for 1 h in a controlled atmosphere (argon). The as-sintered composite materials were not fully dense and had relatively low strength. Then, all sintered materials were hot extruded (extrusion ratio: 10) at 450 °C using a 20 ton vertical press. A conical die was used with a die angle of 45° and an exit diameter of 8 mm.

2.3. Characterization techniques

The phases in starting powders and final produced materials were analyzed using X-ray diffractometer (Siemens D5000) with Cu*K*α radiation at 40 kV and 30 mA. The diffractometer was operated within range of $2\theta = 10°–100°$. The density of hot extruded Al alloy matrix and Al/graphite composites were measured using Archimedes method. Furthermore, the theoretical densities of all designed composites were calculated based on the rule of mixture.

Hardness of all extruded materials was measured on Vickers hardness tester (model HWDV-7S) at an applied load of 500 g for a holding time of 15 s. In order to determine the tensile properties and compressive strength, extrusion bars ($d = 8$ mm) were machined to produce tensile and compression test specimens to be loaded parallel to the extrusion direction. Tensile test specimens were machined to the short size specimen ($L_o = 5d$) in accordance with the ASTM B925-03 using the available extrusion bar dimensions, as shown in Fig. 2(a). Specimens used for compressive strength tests were machined to a height $H_o = 10.5$ mm and diameter $D_o = 7$ mm, as shown in Fig. 2(b). Such specimens have a height-to-diameter (H_o/D_o) ratio of 1.5 to avoid buckling if $H_o/D_o > 2$ and excessive friction in case of $H_o/D_o < 1$. The tests were carried out using a universal testing machine Instron-4208 at the quasi-static strain rate of 0.001 s^{-1}.

The influence of graphite content on the dry sliding wear resistance of the hot extruded 6016 Al/graphite composites was assessed using a pin-on disc wear test at a constant load of 3 N and a sliding distance of 2.68 km. Microstructure, fracture and worn surfaces, collected debris of the extruded Al alloy and Al/graphite composites were investigated using scanning electron microscope (SEM, Quanta FEG-250) equipped with advanced energy dispersive spectroscopy (EDS). Two SEM detectors, low k-Volt high-Contract Detector (VCD) and Everhart-Thornley Detector (ETD), were applied to distinguish the different microstructure constituents and topography where the latter is a second electron low magnification detector.