Materials Science & Engineering A 632 (2015) 147–155

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of mechanical and thermal loading on boron carbide particles reinforced Al-6061 alloy

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ARTICLE INFO

Article history:
Received 13 October 2014
Received in revised form
7 February 2015
Accepted 7 February 2015
Available online 5 March 2015

Keywords:
Metal matrix composite
Boron carbide
Strength
Cold extrusion
Mechanical properties
Morphology

ABSTRACT

Metal Matrix Composites (MMC) considered as one of the 'advanced materials' have evoked growing interest during the last three decades due to their high performance and applications in strategic sectors. These composites exhibit unique and attractive properties over the monolithic alloys, but suffer from low ductility, which makes them not so attractive for some of the applications where high toughness is one of the design criteria. This limitation of MMCs has been overcome by resorting to various treatments such as mechanical and thermal loading. Considering very limited reports available on Al alloy reinforced with boron carbide (B_4C) particles, this paper presents (i) preparation of Al-6061 alloy reinforced with 1.5–10 wt% B_4C, (ii) subjecting them to mechanical and thermal treatments and (iii) characterization of all the above samples. Specific ultimate tensile strength and hardness of all the composites were higher than those of matrix. Also, these values increased with increasing amount of particles, with composites containing 8 wt% B_4C showing the maximum values in all the three conditions. These observations are supported by the uniform distribution of particles in the matrix as observed in their microstructure.

1. Introduction

There has been growing interest in the development of new materials and/or processes to meet the demands of various sectors, particularly in automotive and aerospace sectors. One such material is the metal matrix composite (MMC). The development of MMCs is reported as one of the major innovations in materials science in the last three decades [1]. This is an 'advanced material', which exhibits unique properties required for high performance in many applications including in strategic sectors such as aerospace and nuclear areas. These materials have been studied over the last three decades or so with more attention being given to light metals such as Al, Mg and Ti as matrix materials and a variety of reinforcing materials such as carbides of silicon (SiC), titanium (TiC) and boron (B_4C), oxides of aluminum (Al_2O_3), nitrides of silicon (Si_3N_4) and boron (BN) and even lighter ones such as graphite, mica, and glass both in discontinuous and continuous forms [2]. However, it has been observed that mostly Al and its alloys, both in cast and wrought form, have been used more extensively as the matrices for MMC synthesis. Although the MMCs can be produced by all the three states (solid state, liquid state or vapor state processes) [3,4], an analysis of these processing techniques involving various types of dispersoids particularly for the automotive applications revealed [3] that liquid metal processing (foundry technique) with particulate type of dispersoid is more attractive than others. This is because MMCs containing particles exhibit several advantages over the fiber reinforced composites particularly showing isotropic properties in addition to being economical, possibility of mass production as well as production of near net shaped components [1,4,5].

Stir casting offers better matrix–particle distribution due to stirring action of particles into the melt. The recent research studies reported that the homogeneous mixing and good wetting can be obtained by selecting appropriate processing parameters like stirring speed, time, and temperature of molten metal, preheating temperature of mold and uniform feed rate of particle [2].

The MMCs show favorable tendencies towards machining and workability using conventional methods. Gravity die casting and squeeze casting are adopted widely in metal industry for producing MMCs and alloys. The gravity die casting is popular because of its simplified process. By the judicious selection of matrix–dispersoid combination and processing method, it is reported [6–8] that these MMCs exhibit some attractive specific properties compared to those of ferrous and some non-ferrous monolithic materials. They include 20–50% increase in stiffness, 20–30% in

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http://dx.doi.org/10.1016/j.msea.2015.02.007
0921-5093/

ultimate strength (UTS), about 30% lower coefficient of thermal expansion, high thermal and electrical conductivities, improved damping properties, friction wear (2–5 times) and seizure resistance, over the matrix material. With a view to get improved properties in the MMCs produced particularly by foundry technique, both heat treatment and deformation by conventional metal forming techniques such as extrusion, forging and rolling have been resorted to [1,7,8]. Despite these, MMCs exhibit low ductility, which has been recently overcome by resorting to severe plastic deformation (SPD) processes [9–13]. It has also been reported [1] that the use of secondary processing of discontinuously reinforced composites would result in breaking up of particles, agglomerates, reduction or elimination of porosity, which would lead to the improvement in particle bonding thus resulting in improved mechanical properties.

Aluminum 6061 alloy possesses higher strength and corrosion resistance, responds favorably for both deformation and heat treatment and has excellent machinability and good wear properties amongst various aluminum alloys. In view of these attributes, along with their technological importance and exceptional increase in strength obtained after precipitation hardening, this alloy is widely used in many engineering applications such as construction, automotive and marine fields, where superior properties are essentially required [14]. It has also been found that this alloy is one of the popular choices as matrix material in the preparation of MMCs due to its better formability [15] including for boron carbide particle (B_4Cp) reinforced composites, although not much is reported for this system [15–17].

B_4Cp, a robust material, exhibits attractive properties, such as low specific gravity, high hardness, high elastic modulus with excellent neutron absorption, chemical and thermal stability, as well as corrosion resistance [15,18–20]. Also, it is the third hardest material after diamond and boron nitride with the hardness of 200VHN, which is higher than Al_2O_3 and SiC. It is also used for manufacturing bullet proof vests, armor tank, etc. In view of these, B_4C–Al system has been widely used as cermets and armor materials, which have significant industrial investment as high-strength applications. Furthermore, chemical compatibility between the matrix and the reinforcement, particularly when using liquid metal processes is important in the production of metal matrix composites, which is possible with this system [21]. Hence, B_4C reinforced aluminum matrix composite could gain more attraction with low cost casting route [22,23].

Further, despite the above mentioned attributes, B_4Cp have not been preferred as reinforcements in Al matrix compared to other ceramic fillers such as Al_2O_3 and SiC, probably due to higher cost of B_4C particles compared to other two ceramic particles mentioned and poor wetting [15,20]. Accordingly, limited studies have been carried out with B_4C particles as reinforcements in Al and its alloys to prepare both micro- and nano-composites as well as hybrid composites by various techniques and have been evaluated for physical, mechanical and tribological properties [14–47], while some are focused on the wettability and chemical reaction between aluminum and boron carbide [24], microstructure and interface of B_4Cp/Al composites fabricated by Boralyn process [25]. In addition there have also been some patents on Al alloy–B_4C composites presenting the fabrication methods and some applications [48–51].

Considering that Al alloy based B_4Cp composites being light weight functional material for emerging industrial applications have potential applications including strategic sectors structural neutron absorber, armor plate materials, brake disks for automotive industry and as a substrate material for computer hard disks [16,52,53], and only limited studies are made on Al 6061–B_4Cp composites prepared by casting route melt infiltration, but none seems to have evaluated the impact properties [14,15,21,37,40,42,45–47]. A detailed study was undertaken by the authors. Main objectives of such a study was to develop Al-6061 alloy based composites containing B_4C by liquid metallurgy using 'stir casting' technique or 'vortex' technique and subjecting it to both conventional plastic deformation (CPD-Extrusion) as well as severe plastic deformation (SPD-Twist Extrusion) processes and characterize all these three types of composites for their morphology and various properties.

This paper presents preliminary studies about the primary processing of Al-6061–(1.5–10 wt%) B_4C composite by 'stir casting' technique, and subjecting the matrix and its composites to T6-heat treatment (thermal loading) as well as to extrusion process (mechanical loading); study of the effect of mechanical loading and thermal loading of the cast composite on the tensile strength and hardness. The novelty of this study lies in the 'indigenous development of an induction melting furnace of 5 kW power, with motorized stirrer having variable speed' for the primary processing of the composites.

2. Experimental method

2.1. Materials

Al-6061 alloy having chemical composition listed in Table 1(a) was chosen as matrix. Other characteristics of this alloy include density of 2.7 g/cm^3, hardness of 95 BHN, ultimate tensile strength of 310 MPa, and % elongation of 17%. Various properties of boron carbide particles used in this study as reinforcement are shown in Table 1(b).

2.2. Methods

2.2.1. Primary processing

Al-6061 based composites were prepared using the simplest and most commonly used casting method (stir casting or vortex technique). The technique involved was as follows: an 'indigenously

Table 1
(a) Chemical composition of Al6061 alloy.

Element	Si	Mg	Cu	Cr	Fe	Ti	Zn	Mn	Al	Others
wt %	0.4–0.8	0.8–1.20	0.15–0.40	0.04–0.35	0.7 Max	0.15 Max	0.25 Max	0.15	Rest	0.15 Max

(b) Chemical composition of boron carbide particles.

Property	Value
Size (diameter in μm)	75
Density (g/cm^3)	2.52
Melting point (°C)	2445
Hardness (Knoop 100 g) (kg mm^{-2})	2900–3580
Fracture toughness (MPa m$-\frac{1}{2}$)	2.9–3.7
Young's modulus (GPa)	450–470