EFFECT OF HEAT TREATMENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF EXTRUDED SiC/6061 COMPOSITE

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Abstract
The effect of heat treatment on microstructure and mechanical properties of extruded SiC/6061 aluminium alloy matrix composite was investigated. The heat treatment (annealing at 540 °C for 1.5 hours, water quenching and artificial aging at 170 °C for 7 hours) caused dissolution of Mg_2Si particles and decomposition of small SiC particles. The 0.2 % yield strength and the ultimate tensile strength of extruded composite were increased by application of heat treatment due to precipitation of β´´ phase particles. On the other hand, the ductility of composite was decreased. The fracture surface of as-extruded composite was consisted of numerous dimples. It was a result of micro voids nucleation at interface between matrix and SiC particles and second-phase particles. The fracture of heat treated composite was similar, micro voids were nucleated mainly on SiC particles, which were cracked during tensile test.

Keywords: particulate reinforced composite, SiC, extrusion, mechanical properties, fracture

1 Introduction

Discontinuously reinforced aluminium alloy matrix composites are a good choice for engineering applications due to their excellent properties such as low density, good strength, high stiffness, superior wear resistance and low coefficient of thermal expansion [1-3]. Among reinforcements, SiC particles are suitable due to maintain good thermal and chemical stability during production of composites and good strength at service conditions [4]. Properties of SiC aluminium matrix composites are affected by the microstructure, distribution of SiC particles, SiC particles volume fraction and magnitude of reinforcement [5-7].

The most widely used process for production of the composite semiproduct is powder metallurgy. Main advantages of powder metallurgy are the lower sintering temperatures if compared with other methods, absence of chemical reaction between the reinforcement and matrix and the uniform dispersion of the reinforcement [8-10].

The most common secondary processing of SiC aluminium matrix composites is hot extrusion process [11, 12]. Hot extrusion has ability to create the final composite product of more complex shapes. Brittle materials can be produce too, because the material only encounters shear and compressive stresses. The extrusion of powder mixture ensures homogenous distribution of reinforcement in matrix [13]. Hot extrusion of SiC aluminium matrix composites leads to break up of particle agglomerates and improve the mechanical properties of these materials [14]. On

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the other hand, presence of brittle and nondeformable reinforcements can result in the undesirable phenomena, such as debonding of interface, surface cracking, and fracture of reinforcement in the extruded composites [15].

The aim of this work is to analyse the effect of age-hardening heat treatment on change in microstructure, mechanical properties and fracture mechanism of SiC/6061 composite in as-extruded condition.

2 Experimental materials and procedures

The experimental material was aluminium alloy matrix composite reinforced by SiC particles. The standardized chemical composition of matrix (EN 573-3) is given in **Table 1**. Semiproduct for extrusion was homogenized mixture of EN AW 6061 aluminium alloy powder with 20 volume percent SiC particles. This mixture was compacted by processed by CIP (cold isostatic pressing) to billet of appropriate dimensions. The billet was heated up to extruding temperature of 480°C and then extruded to final product.

Table 1 The chemical composition of matrix 6061 aluminium alloy [wt. %][16]

Mg	Si	Cu	Mn	Cr	Zn	Fe	Ti	Al
0.8-1.2	0.4-0.8	0.15-0.4	max. 0.15	0.04-0.35	max. 0.25	max. 0.7	max. 0.15	bal.

Analysis of composite microstructure, distribution and size of SiC particles in extruded product were observed on polished metallographic samples in transverse sections by light microscopy (LM) and scanning electron microscopy (SEM). The chemical composition of particles was identified by EDX analysis. Mechanical properties of extruded composite products were evaluated by tensile tests. Fracture surfaces of analyzed composites after tensile tests were investigated using light and scanning electron microscopy. The fracture surfaces were coated by nickel coating to protect the fracture surface against plastic deformation and to enhance metallographic sample edge retention.

Furthermore, extruded composite products were heat-treated using solution annealing at temperature of 540 °C for 1.5 hours, subsequently water quenched and artificially aged at temperature of 170 °C for 7 hours.

3 Results

Microstructure

Light microscopy, scanning electron microscopy (SEM) techniques were used to characterize the particle distribution in matrix of composite. Typical micrographs from transverse section of the composite in the as-extruded condition containing SiC particles are shown in **Fig. 1**. The SiC particles have an average size of about 7 μm, as it was stated in work [17]. It can be seen that while the spatial distribution of SiC particles appeared homogeneous, it was still quite clumped. Detailed micrograph (**Fig. 1b**) showed SiC particles to be like irregular blocks. Some SiC particles are broken due to the severe deformation stress generated during extrusion process.

The dark and light gray second-phase particles were also observed in the 6061 Al alloy matrix in the as-extruded condition. EDX analysis showed (**Fig. 2)** that the fine dark particles observed by SEM (as shown by arrows in **Fig. 2a**) contain Mg and Si. Gray particles of irregular shape (as shown by arrow in **Fig. 2c**) contain Cu, Fe and Si.

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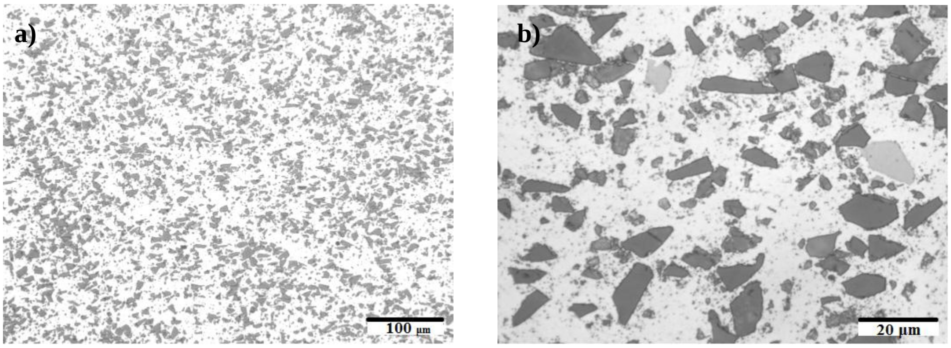

Fig. 1 Microstructure SiC/6061 composite in the as-extruded condition; (a) lower magnification (b) higher magnification

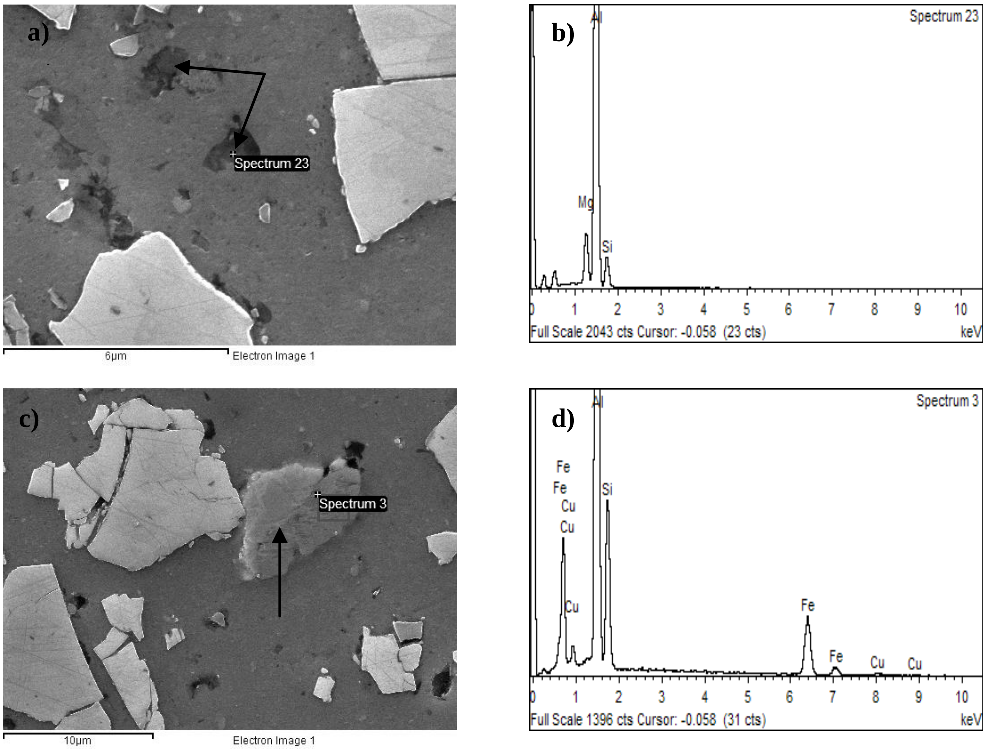

Fig. 2 Detail of particle morphology and corresponding EDX spectra; (a) particles contain Mg and Si(b) EDX spectrum of particle contains Mg and Si (c) particle contains Cu, Fe and Si (d) EDX spectrum of particle contain Cu, Fe and Si

The microstructure of extruded SiC/6061 composite was changed markedly due to after solution annealing and aging. It was found (**Fig. 3**) that fine second-phase particles containing Mg and Si was not present in 6061 Al matrix after heat treatment. Moreover, detailed comparison between microstructure of as-extruded (**Fig. 2**) and heat-treated (**Fig. 3**) composite indicates clearly that fine SiC particles decomposed. On the other hand, second-phase particles containing Cu, Fe a Si were also observed in composite matrix (**Fig. 3 and 4**) after heat treatment.

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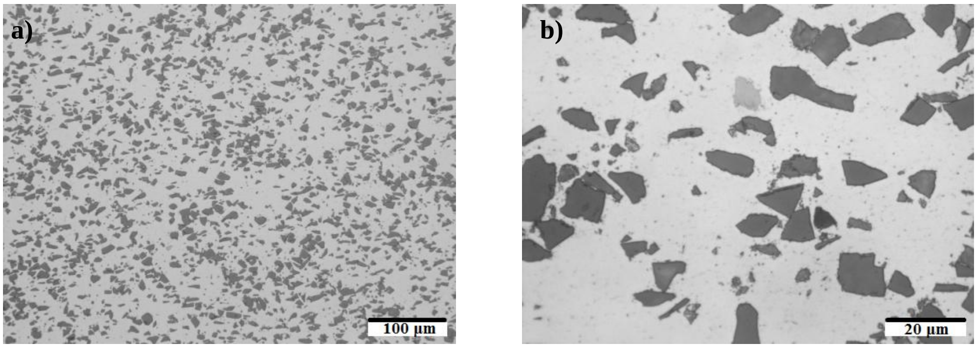

Fig. 3 Microstructure of SiC/6061 composite after heat treatment; (a) lower magnification (b) higher magnification

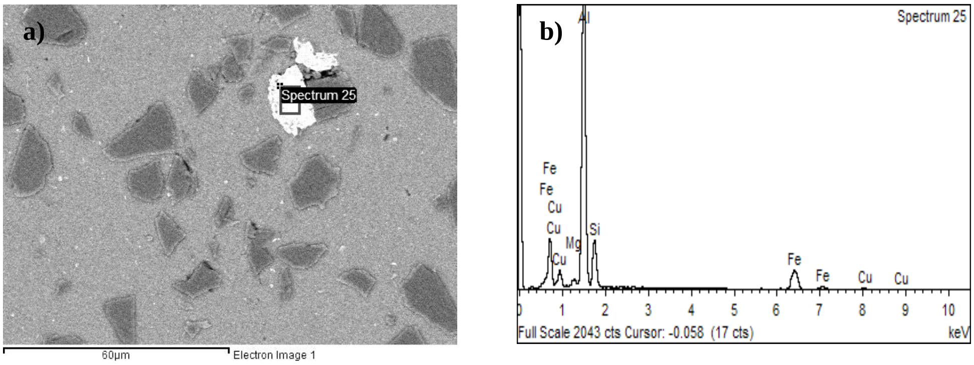

Fig. 4 Detail of particle morphology (a) and corresponding EDX spectra (b)

Mechanical properties

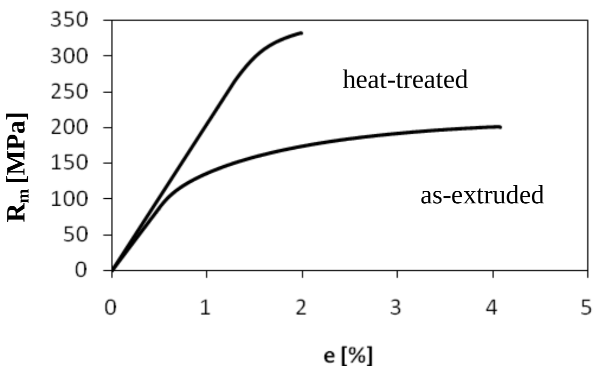

Fig. 5 Stress- strain curves obtained for the SiC/6061 composite in the as-extruded condition and after heat treatment

Fig. 5 shows the stress-strain curves of SiC/6061 composite analyse states obtained using by tensile test. 0.2% yield strength and ultimate tensile strength of composite in the as-extruded condition attained to about 130 MPa and 200 MPa, respectively. The application of heat treatment for extruded SiC/6061 composite leaded to a significant increases of tensile properties. Its 0.2% yield strength was increased of about 242% up to 320 MPa and the ultimate tensile strength of about 165% up to 330 MPa. On the other hand, the plasticity of composite was degreased by applied heat treatment. The value of ductility and reduction of area obtained for composite products decreased from 3% to 0.4% and from 7% to 3.2%, respectively.

Fracture morphology

Fig. 6 shows typical morphology of fracture surface observed for the as-extruded and heat treated composite. Their fracture surfaces consisted of numerous dimples with various sizes over the entire surface. The dimples were a result of the microvoids nucleation at interface between matrix and SiC-particles and second-phase particles and/or by SiC-particles irregular multiphase particles cracking and its coalescence. The dimple size is little bit different for as-extruded and heat treated composite. The average size of dimples which nucleated on SiC particles and fine second-phase particles during tensile test of the composite in the as-extruded condition was 7.7 μm and 1.8 μm, respectively. After tensile test of the heat treated state of composite, the dimples

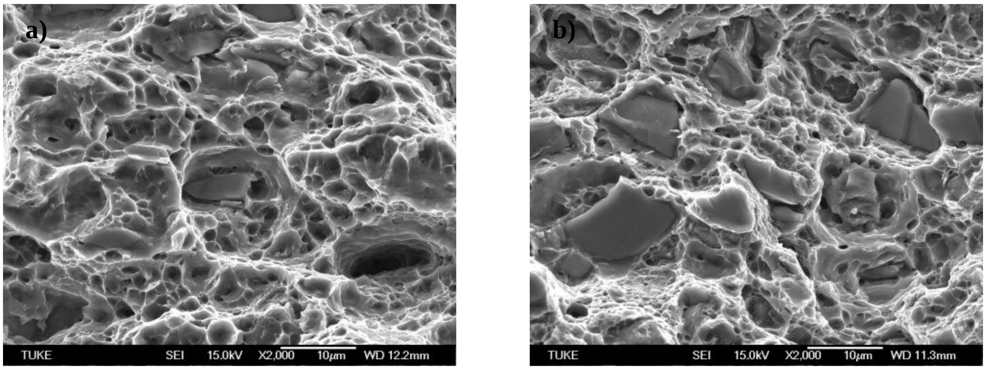

Fig. 6 SEM images of fracture surface obtained for the SiC/6061 composite; (a) in the as-extruded condition, (b) after heat treatment

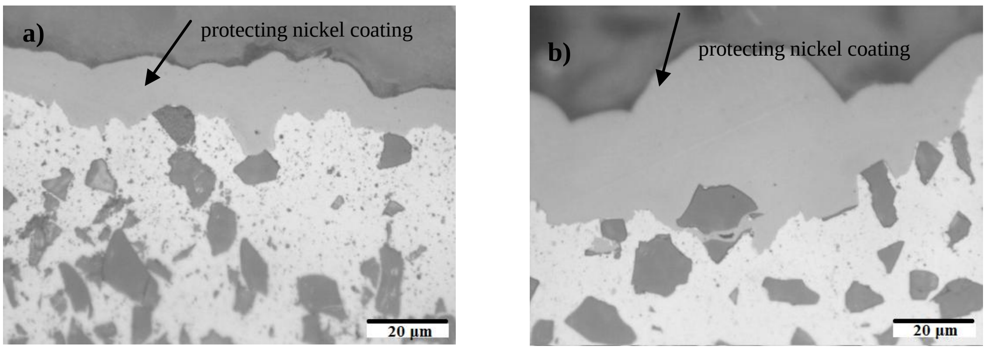

Fig. 7 Microstructure of the SiC/6061 composite near of fracture surface; (a) in the as-extruded condition, (b) afer heat treatment

which nucleated on SiC particles and fine second-phase particles have average size of 8 μm and 1.6 μm, respectively. It was proved using light microscopy (**Fig. 7**) that microvoids nucleated at

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SiC particles and second-phase particles or by cracking of SiC-particles that occurred more frequently for heat-treated state of composite. **Fig. 7b** shows detail of cracked SiC-particles on fracture surface of age-hardened composite.

4 Discussion

It was found that SiC particles were fairly homogenously distributed in the microstructure of the SiC/6061 composite in the as-extruded state. However, cracking and clumping of silicon carbide particles occurred. Decohesion in the SiC particles/matrix interface was not observed in the composite microstructure, which was clear evidence of strong bond between reinforced phase and matrix [18]. In addition, two types of second-phase particles were observed in the microstructure. Specifically, there were fine particles contained Mg and Si and particles contained Cu, Fe and Si of irregular shape. It can be assume, that the particles contain Mg and Si are common constituent phase Mg_2Si occurring in 6061 aluminium alloy [19]. It can be assume, that particles which contain Fe, Si and Cu were silicides of iron and copper. This type of phase is most commonly formed phase in aluminium alloys [20].

Heat treatment of the SiC/6061 composite in the as-extruded condition caused many changes in microstructure of composite. During solution annealing at 540 °C, the Mg_2Si phase completely dissolved into 6061 aluminium matrix solid solution [21]. It can be assume, that during artificial aging, the precipitation of nanosized β´´ phase particles was carried out [22]. An analysis by a high resolution transmission electron microscopy should be carried out to prove and evaluate formation this type of particles during applied aging treatment of composite.

Zhao [23] supposed, that near the interface of the SiC – matrix exist dislocation free band, where precipitates of Mg_2Si phase did not appear. Authors of work [24] claimed that as dislocation density increases, the precipitates nucleate and grow, than the GP zones transform to metastable phase β´´. It indicated that a high dislocation density facilitated precipitation. In addition, we were found that extrusion process caused the fragmentation of some SiC particles, which decomposed during solution annealing. The decomposition of SiC phase on the SiC/aluminium interfaces during annealing at 550°C was also observed by Liu et al. [25].The heat treatment did not affect the morphology and chemical composition of particles containing iron and copper, which were observed in aluminium matrix.

The mechanical properties of SiC/6061 composite in as-extruded condition were changed markedly by applied heat treatment. However with respect to the unreinforced aluminium alloy (0.2% YS= 276 MPa, UTS= 310 MPa, e= 12 % in T6 condition) [26], there were evident increases in the 0.2% yield strength and ultimate strength, while there was a general loss of ductility, both in the as-extruded and in heat treated state of composite. The heat treaded state of composite generally showed a remarkable increase in the 0.2% yield strength and ultimate tensile strength (about 242 % and 165 %, respectively). This behaviour was related to strengthening mechanism of precipitation of β´´- Mg_2Si phase particles in 6061 aluminum matrix, that occurred during aging treatment of AlMgSi alloys [27]. Strengthening effect produced by precipitation of β´´- Mg_2Si phase particles is accompanied by losses in ductility and impact resistance of this type of alloy [20]. Particle reinforced aluminium matrix composite were nearly always less tough than aluminium alloy matrix [28].

The heat treatment had the effect of increasing the dislocation density. It was a result of the mismatch between thermal expansion coefficients of the matrix and SiC particles. Interactions of SiC particle-dislocation increased, lead to a strengthening of the composites [29].

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Even though, ductility of the SiC/6061 composite in the as-extruded and heat treated condition was low, the dimple fracture mechanism was observed for both states of composite. Their fracture surfaces consisted of numerous dimples of various sizes. The SiC particles present in the as-extruded state of composite did not crack. The SiC particles were associated with deep, large dimples on the fracture surface and the finer scale dimples with fine second-phase particles present in the surrounding matrix [30]. Microvoids nucleated at interface between SiC particles and matrix and between second-phase particles and matrix. For heat-treated state of composite the deep and large dimples nucleated mainly by cracking of SiC-particles. During tensile deformation, as the strain increases, the larger SiC particles fracture first, then these smaller. The dimples are associated with each SiC particle.

5 Conclusions

The distribution of SiC particles in as-extruded SiC/6061 composite was quite homogenous, but they were still clumped. The extrusion process generated severe deformation stresses which cause the cracking of some SiC particles. In the 6061 aluminium alloy matrix of composite in the as-extruded condition Mg_2Si phase particles and Fe and Cu containing silicide particles was observed. Applied solution annealing of extruded composite caused the Mg_2Si phase particles dissolution into solid solution of 6061 aluminium matrix and small SiC particles decomposition.

The application of heat treatment for as-extruded composite caused the increase of 0.2% yield strength from 130 MPa to 320 MPa and ultimate tensile strength from 200 MPa to 330 MPa. The ductility degreased from 3% to 0.4% and reduction of area from 7% to 3.2% after heat treatment. The reason is the strengthening effect produced by precipitation of β´´- Mg_2Si phase particles that is accompanied by losses in ductility.

Samples of analysed SiC/6061 composite states were fractured without large macroscopic plastic deformation during tensile test. Their fracture surface consisted of dimples with various sizes. The dimples were a result of the microvoids nucleation at interface between matrix and SiC particles and second-phase particles. For heat-treated state of composite, the large dimples nucleated mainly by cracking of SiC-particles.

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