Processing and Response of Aluminum-Lithium Alloy Composites Reinforced with Copper-Coated Silicon Carbide Particulates

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Lithium-containing aluminum alloys have shown promise for demanding aerospace applications because of their light weight, high strength, and good damage tolerance characteristics. Additions of ceramic reinforcements to an aluminum-lithium alloy can significantly enhance specific strength, and specific modulus while concurrently offering acceptable performance at elevated temperatures. The processing and fabrication of aluminum-lithium alloy-based composites are hampered by particulate agglomeration or clustering and the existence of poor interfacial relationships between the reinforcing phase and the matrix. The problem of distribution of the reinforcing phase in the metal matrix can be alleviated by mechanical alloying. This article presents the results of a study aimed at addressing and improving the interfacial relationship between the host matrix and the reinforcing phase. Copper-coated silicon carbide particulates are introduced as the particulate reinforcing phase, and the resultant composite mixture is processed by conventional milling followed by hot pressing and hot extrusion. The influence of extrusion ratio and extrusion temperature on microstructure and mechanical properties was established. Post extrusion processing by hot isostatic pressing was also examined. Results reveal the increase in elastic modulus of the aluminum-lithium alloy matrix reinforced with copper-coated SiC to be significantly more than the mechanically alloyed Al-Li/SiC counterpart. This suggests the possible contributions of interfacial strengthening on mechanical response in direct comparison with a uniform distribution of the reinforcing ceramic particulates.

Keywords	aluminum alloy, composite, fracture, microstructure, modulus, processing

1. Introduction

Sustained research efforts in areas spanning alloy design and innovative processing techniques have resulted from an increasing need for lightweight, high-performance materials as attractive and viable alternatives to traditional engineering alloys. In particular, much attention and emphasis has been given to the development and emergence of reinforced metallic matrices that can offer combinations of significant improvement in structural efficiency, reliability, and mechanical performance over monolithic counterparts. Increased interest in the use of continuous and discontinuously reinforced metal matrices for a spectrum of aerospace, ground transportation (automotive), and nonstructural applications to include leisure-related products such as sporting goods has gained significant importance as a direct result of the availability of relatively inexpensive reinforcements coupled with the concurrent development of a host of potentially viable processing routes that offer reproducible microstructures and properties (Ref 1-

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3). A large majority of commercially available metal-matrix composites (MMCs) are metastable matrices reinforced with high-modulus, high-strength and often brittle second phases, which can be either continuous in the form of fibers or discontinuous in the form of whiskers, platelets, and particulate reinforcements embedded in a metal matrix. Recently, incorporation of ceramic particulates into aluminum, titanium, and magnesium alloy metal matrices has offered notable improvements in strength, wear resistance, elastic modulus, efficiency, and reliability coupled with significant control of physical properties such as coefficient of thermal expansion, thereby affording the possibility of improved mechanical performance to the unreinforced matrix (Ref 4-17).

The possibility of producing newer generation materials to meet the stringent demands of aerospace, automotive, and commercial products required radical new approaches to material synthesis and preparation (Ref 1, 2, 18-23). Discontinuously reinforced metal matrices can be synthesized by ingot metallurgy (IM), powder metallurgy (PM), and mechanical alloying techniques (Ref 1-3, 20, 22). In classical IM processing, the reinforcement phase (i.e., fine ceramic particulates) is mixed with the molten metal, and the resulting mixture is subsequently cast. In PM processing, ceramic particulates are blended with the prealloyed metal powder. The resulting mixture is canned, vacuum degassed, and consolidated into a billet using hot pressing or hot isostatic pressing (HIP). The consolidated composites are either extruded or forged into desired shapes. Secondary processing is conveniently used to break up any pre-existing oxide in the alloyed powder. In the mechanical alloying (MA) approach, the pure metal powders and alloying

ingredients are mechanically alloyed using high-energy ball mills, while concurrently incorporating the reinforcement phase.

Of these three techniques, PM processing of discontinuously reinforced metal matrices (DRMMCs) is generally preferred because it offers a number of product advantages. Furthermore, examination of the process in the solid state minimizes deleterious reactions between the metal matrix and the reinforcing phase, while concurrently enhancing the range of potential matrix-reinforcement combinations. However, typical problems of discontinuously reinforced metal matrices include (a) clustering or agglomeration of the reinforcing particulates, (b) poor adhesion with the parent metal matrix, and (c) cracking, fracture, or decohesion of the brittle reinforcements under high-strain-rate deformation processing.

The available list of MMC markets is extensive (Ref 1, 2). Strong candidates for the matrices are aluminum, magnesium, and titanium, although copper, nickel-base superalloys, lead,
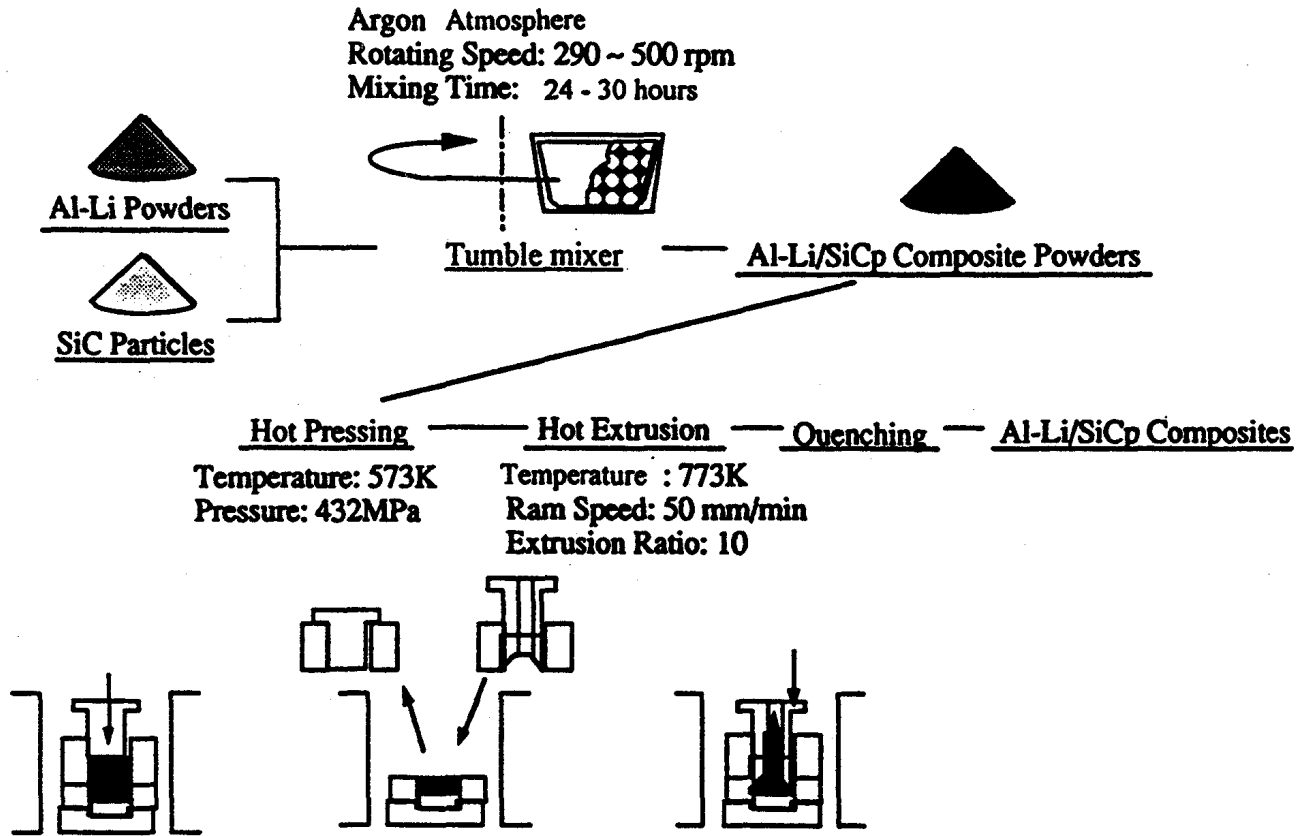

Fig. 1 Schematic of experimental production setup for Al-Li/SiC$_p$ metal-matrix composites used in this study
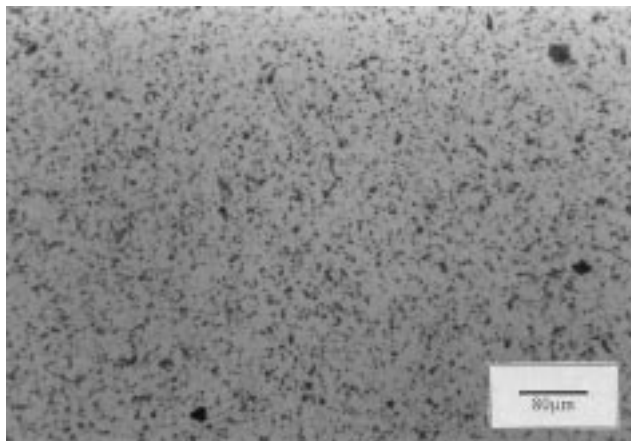

Fig. 2 Optical micrograph showing microstructure of the extruded Al-Li/SiC$_p$ composite in the transverse direction
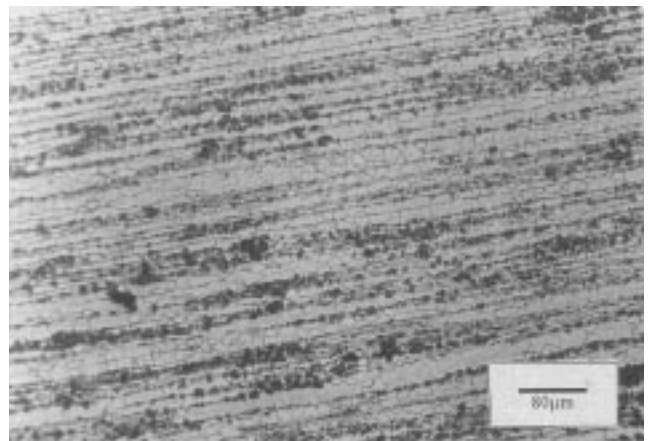

Fig. 3 Optical micrograph showing microstructure of the extruded Al-Li/SiC$_p$ composite in the longitudinal direction

and even tool steels have been developed and considered for specific applications (Ref 1, 2, 22, 23). Maintaining a near-uniform distribution of the reinforcing particulates in the metal matrix is a critical issue that exerts a profound influence on the final properties of the composite. An earlier study reported the use of mechanical milling to significantly enhance the distribution of submicron size (average 0.8 μm) silicon carbide particulates (SiC_p) in an aluminum-lithium alloy matrix (Ref 24). The resultant composite showed over 10% increase in elastic modulus, but with a resultant loss of ductility.

It is the objective of this article to present and discuss the use of copper-coated SiC particulates as reinforcements for an aluminum alloy matrix. The purpose is to establish the importance of interfacial relationship between the copper-coated reinforcing SiC particulate and the matrix on overall mechanical response. A lithium-containing aluminum alloy was chosen as the matrix material, because it has proven to offer advantages of low density (ρ), increased stiffness, improved specific strength (σ/ρ) and improved fatigue strength. SiC was selected as the reinforcing phase because of its low density, easy availability, and cost. However, problems related to interfacial compatibility with the aluminum alloy matrix have occurred. To this end, the SiC particulates were coated with copper to facilitate better adhesion to the alloy matrix.

2. Materials and Experimental Techniques

The aluminum-lithium alloy powders used in this study were provided by Sumitomo Light Metals (Japan). The powders were equivalent in composition to aluminum alloy 8091. The fine powders were produced by argon gas atomization in a small-scale atomizer. The powder particles ranged in size from less than 10 μm to greater than 200 μm. To enhance the possibility of homogeneous properties in the end product, only those powders less than 105 μm were used. Almost 60 vol% of the alloy powders were below 50 μm in size. The nominal chemical composition of the alloy is as follows:

		Element, wt%			
Li	Cu	Mg	Zr	Al	Density, g/cm³
2.5	2.0	1.0	0.15	bal	2.588

Copper-coated SiC particles were produced by a proprietary sol-gel-based process. The average size of the SiC particulates (SiC_p) was around 0.2 μm. The composition of the composite particles was approximately 10 wt% copper and the balance SiC. The experimental setup and process sequence used for the production of Al-Li/SiC_p composites is shown in Fig. 1.

Aluminum-lithium alloy and copper-coated SiC powders were mixed in a tumbling mixer for 24 to 30 h. Tumbling facilitates a homogeneous distribution of the copper-coated SiC_p, both at the macroscopic and microscopic levels, in the aluminum-lithium alloy powder. The homogeneous blend was then transferred into a metal die and hot pressed in an argon atmosphere to produce a fully dense billet. The billet was extruded at 773 K at extrusion ratios of 10:1 and 20:1. The extruded billet was quenched in cold water to prevent grain growth. The process conditions used in the production of the

Al-Li/SiC_p composites are summarized in Table 1. Some of the specimens underwent HIP treatment after extrusion. The Al-Li/SiC_p metal-matrix composites were HIPed without encapsulation. All of the specimens were solution heat treated at 500 °C to obtain the peak aged matrix condition (T6). Subsequently, the composites were artificially aged at 190 °C for 6 h.

Mechanical properties of the Al-Li/SiC_p composite specimens were obtained using a dynamic mechanical analyzer (DMA) (Perkin-Elmer series, Perkin-Elmer Corp., Norwalk, CT) and a universal testing machine (Instron, Model No. 4302). Each DMA specimen was initially subjected to a static stress of 2.26 MPa and subsequently superimposed with a sinusoidal stress of magnitude 2 MPa and at a frequency of 0 to 10 Hz. Tensile tests were performed in a room temperature (29 °C) laboratory air (relative humidity 60%) environment using a 10-kN load cell and a cross-head speed of 0.5 mm/min.

3. Results and Discussion

3.1 *Microstructure*

Optical micrographs illustrating the microstructure of the as-extruded Al-Li/SiC_p metal-matrix composite, in the longitudinal and transverse orientations, are shown in Fig. 2 and 3. In the transverse orientation, the copper-coated SiC particulates were dispersed uniformly throughout the alloy matrix. Agglomeration of particulates was rarely observed. In the longitudinal orientation, the copper-coated SiC_p were nonuniformly distributed throughout the alloy matrix, thus resulting in agglomeration, i.e., particle-rich and particle-depleted regions. The degree of agglomeration or clustering was found to be severe in those specimens extruded at a ratio of 10:1. Particle distribution was more homogeneous for the Al-Li/SiC_p metal-matrix composites extruded at a ratio of 20:1. Isolated pockets of SiC_p-rich clusters were observed (Fig. 4). The clusters ranged in size from 10 to 50 μm.

3.2 *Mechanical Properties*

The elastic modulus (E) of the extruded samples, obtained using three-point bend tests, is summarized as follows:

Sample No	Elastic modulus (E), GPa
A0	74.0
A1	80.5
A2	86.1
A3	91.2
A4	86.9
A5	92.6

Test results reveal that an increase in extrusion ratio from 10:1 to 20:1 results in improved elastic modulus of the composites. However, an increase in extrusion temperature from 500 °C to 510 °C was found to only marginally enhance the stiffness (modulus) of the composite samples. The post-extrusion HIP treatment further improved the elastic modulus by 6 to 8%. The moduli (E) of extruded plus heat treated specimens have been

reported to be lower than those of a 10 wt% SiC_p-reinforced aluminum-lithium alloy matrix produced by mechanical milling and hot extrusion (Ref 24). This can be attributed to the conjoint and mutually interactive influences of (a) a superior distribution of the SiC particulates in the metal matrix achieved by the mechanical milling process; and (b) an improvement at the interfaces of the hard, brittle, and elastically deforming reinforcing phase (ceramic) and the soft, ductile, and plastically deforming metal matrix through the presence of a plastically deforming copper layer. The enhanced modulus achieved by modifying the reinforcement-matrix interfaces out matched the detrimental effects arising from an agglomeration of the SiC particulates.

The observed improvement in the elastic modulus of the Al-Li/SiC_p composites after HIP (samples A1, A3, and A5) can be attributed to the conjoint influence of (a) a near-uniform distribution of the SiC particulates in the alloy matrix, and (b) the breakup of particulate SiC agglomerates in the samples. Furthermore, HIPing of the samples drastically reduces or eliminates microporosity around the reinforcing SiC phase. Also, the interfacial properties of the coated SiC particulate reinforcements and the Al-Li alloy matrix are significantly improved by solid solution strengthening of the aluminum alloy matrix by copper. Because aluminum alloy 8091 is amenable to age-hardening response, heat treatment is essential to achieve optimum properties. The presence of SiC particulates, up to 20 wt%, was found to have a negligible effect on the age-hardening response of aluminum alloy-based composites (Ref 20, 23, 25). However, elastic modulus decreased progressively with an increase in temperature (up to 400 °C), with an overall softening of the metal matrix at higher temperatures.

3.3 Fracture Behavior

Fracture of unreinforced aluminum alloys is associated with events of void nucleation and growth, with nucleation occurring at the coarse and intermediate size constituent particles and other inclusions present in the microstructure (Ref 26, 27). An essential requirement for the nucleation of voids is the development of a critical normal stress across the particle or the matrix-particle interfaces (Ref 28). In monolithic alloys, the nucleation of cavities and voids occurs by the concurrent and synergistic influences of (a) decohesion at the interfaces between the hard, brittle, and elastically deforming inclusion and the soft, ductile, and plastically deforming metal matrix; and (b) premature cracking and failure of the elastically deforming inclusion.

The Al-Li/SiC_p composites exhibited macroscopic and microscopic ductility. Microscopic examination of the fracture surface revealed features reminiscent of locally ductile mechanisms with extensive microplasticity.

Macroscopically, the fracture surfaces of the composite were essentially flat, but relatively rough when viewed on a microscopic scale (Fig. 5). The microscopic fracture surface revealed fractured SiC particulates surrounded by ductile regions described as tear ridges. The matrix of the composite was covered with fine microscopic voids of varying size and shape. The voids were intermingled with isolated pockets of dimples. The constraints in deformation caused by the hard, brittle, and elastically deforming SiC particulates in the adjoining soft, ductile,

and plastically deforming Al-Li alloy matrix aid in limiting or restricting flow stress of the composite and favor void initiation and growth. As a direct consequence of deformation constraints imposed by the SiC particulate reinforcements, higher applied stress is required to initiate plastic deformation in the alloy matrix. This translates into a higher elastic constant of the Al-Li/SiC_p-T6 composite. The limited growth of the fine microscopic voids in the matrix coupled with the lack of coales-

Table 1 Process conditions for Al-Li/Copper-coated SiC composites

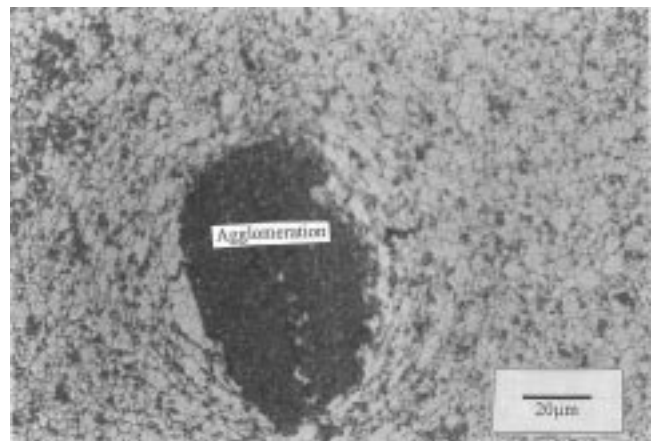| Sample No.	Extrusion ratio	Extrusion temperature, °C	Post-extrusion process
A0	10:1	500	As-extruded
A1	10:1	500	HIP and T6
A2	20:1	500	T6
A3	20:1	500	HIP and T6
A4	20:1	510	T6
A5	20:1	510	HIP and T6

Fig. 4 Micrograph showing an agglomeration of SiC in the extruded composite sample
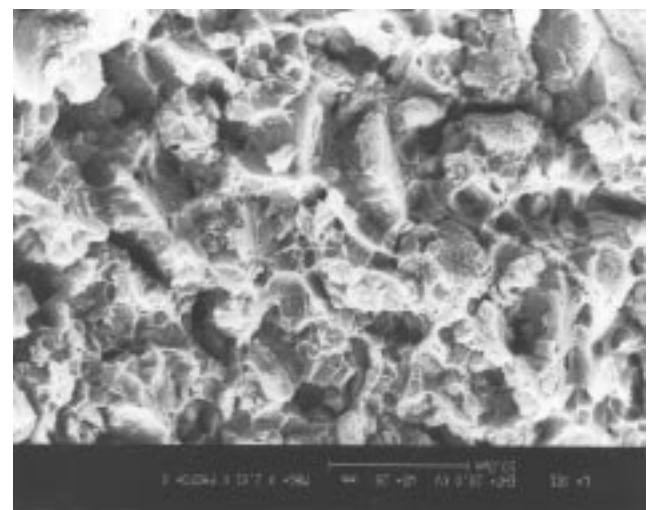

Fig. 5 Scanning electron micrograph of the HIPed Al-Li/SiC_p-T6 (sample A3) after three-point bend test

cence as a dominant fracture mode clearly suggest that the deformation properties of the aluminum-lithium alloy matrix are significantly altered by the presence of copper-coated SiC$_p$. Very few of the fine microscopic voids coalesce, and the halves of these voids are the shallow dimples on the fracture surface. The lack of formation of ductile dimples, as the dominant fracture mode, can be attributed to the constraints in plastic flow in the composite matrix caused by the presence of discontinuous copper-coated SiC reinforcements and not to the limited ductility of the aluminum-lithium alloy matrix. The constraints in plastic flow favor the formation of fine tear ridges between the reinforcing SiC particulates.

4. Conclusions

Results of a study on the processing of aluminum-lithium based metal matrix composites using copper-coated silicon carbide particulates as reinforcements provide the following key observations: Optical microstructure of the Al-Li/SiC$_p$-T6 composites revealed the particulate reinforcement phase to be stratified and distributed throughout the microstructure as fine, narrow bands of SiC and isolated regions containing an agglomeration or pockets of the reinforcing particulates (SiC$_p$). Mechanical properties obtained from the three-point bend test and the DMA revealed improved elastic modulus over the unreinforced counterpart. The HIPed test specimens revealed a notable increase in the elastic modulus of the composites reinforced with copper-coated SiC$_p$ compared to mechanically alloyed Al-Li/SiC$_p$ counterparts. A maximum elastic modulus of 92 GPa was obtained for a 10 wt% SiC-reinforced Al-Li alloy matrix. The improved elastic modulus and strength of the copper-coated SiC$_p$-reinforced aluminum-lithium alloy is ascribed to strengthening at the reinforcement-matrix interfaces through solid-solution strengthening of the aluminum alloy matrix by copper. The improved modulus over the mechanically milled counterpart suggests the importance of interfacial strengthening on mechanical response of the Al-Li/SiC$_p$ composite. Fracture of the test samples revealed macroscopic and microscopic features reminiscent of locally ductile failure. Fracture of the matrix between particulate clusters coupled with particle failure through cracking allows the microscopic cracks to grow and link.

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