Fabrication of Aluminum Composites With Patterned Silicon Carbide Reinforcement Architecture by Semi-Solid Processing

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Abstract
Semi-solid powder processing is a promising technology, combining the advantages of semi-solid forming and powder metallurgy. In this study, spray deposition process combined with semi-solid powder processing was used to synthesize an aluminum alloy composite and to control its microstructure. Silicon carbide (SiC) reinforced aluminum alloy composites were fabricated with and without microstructure pattern. The influence of different composite microstructure on mechanical properties was analyzed by microstructure analysis, bend test and fracture analysis. Bend test results showed that patterned microstructure has the potential to significantly improve composite strength with minimal sacrifice of ductility.

Keywords
Aluminum, composite materials, manufacturing, silicon

Disciplines
Manufacturing | Metallurgy

Comments
FABRICATION OF ALUMINUM COMPOSITES WITH PATTERNED SILICON CARBIDE REINFORCEMENT ARCHITECTURE BY SEMI-SOLID PROCESSING

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ABSTRACT
Semi-solid powder processing is a promising technology, combining the advantages of semi-solid forming and powder metallurgy. In this study, spray deposition process combined with semi-solid powder processing was used to synthesize an aluminum alloy composite and to control its microstructure. Silicon carbide (SiC) reinforced aluminum alloy composites were fabricated with and without microstructure pattern. The influence of different composite microstructure on mechanical properties was analyzed by microstructure analysis, bend test and fracture analysis. Bend test results showed that patterned microstructure has the potential to significantly improve composite strength with minimal sacrifice of ductility.

KEYWORDS
Metal matrix composite, Spray deposition, Semi-solid processing, Microstructure

INTRODUCTION
In recent years, the demand for lightweight, high-strength materials has been increasing due to energy concerns. Metal matrix composites reinforced with high-strength fibers or particles have played an important role in aerospace and automotive industries [1]. Silicon carbide (SiC) reinforced with aluminum (Al) composites have been studied for their outstanding properties such as good wear resistance, excellent workability and high temperature strength [2]. Various fabrication methods, including powder sintering [3], infiltration casting [4], powder metallurgy [5], melt casting [6] and semi-solid powder processing [7, 8], have been investigated to incorporate silicon carbide into the Al matrix. Typical microstructures produced by these methods have simple configurations like homogeneous or graded SiC distributions in the matrix phase.

In this work, we investigated the use of spray deposition and semi-solid processing to create patterned SiC architecture in the Al matrix. The processing method involves integration of bottom-up (spray patterning) and top-down (semi-solid processing) approaches to create microstructure architectures while efficiently building large structural components.

In this study, spray deposition procedures combined with semi-solid powder processing (SPP) was employed to fabricate Al6061-SiC composites with architecture SiC particle distribution. A mask was used during the spray deposition process to produce patterned SiC particles distribution. Then semi-solid powder processing was used to consolidating Al sheets with well-distributed powder at temperatures involving medium liquid phase fractions with the help of pressure. The microstructures and mechanical properties of the composites were examined.

BACKGROUND ON SEMI-SOLID PROCESSING
Semi-solid processing exploits unique material behavior involving both solid and liquid phases. Semi-solid material behavior and their processing techniques were first investigated by Spencer et al. (Spencer et al. 1972) in 1970s [9]. The original technique involved bulk materials pretreated to breakdown the dendritic structures of alloys as illustrated in FIGURE 1. Various aspects of semi-solid forming have been studied involving microstructure refinement [10], material modeling [11], mechanical properties [12], etc. In general, semi-solid forming offers advantages of forging and casting, resulting in complex part geometries with excellent mechanical properties.
On the other hand, semi-solid powder processing (SPP) involves starting materials in the form of particles rather than bulk materials. SPP combines the benefits of the semi-solid forming and powder metallurgy [13, 14]. The composite properties can be modified through mixing desired particles or fibers. Variations of the SPP are illustrated in FIGURE 2, which involve processing steps typically used in powder metallurgy routes [15-19].

FIGURE 3: EXPERIMENTAL SETUP FOR SPRAY DEPOSITION; (a) OVERALL SETUP; (b) MASK LAYER FOR PATTERN DEPOSITION; (c) SUBSTRATE AND MASK ASSEMBLY ON HOT PLATE.

TABLE 1: CHEMICAL COMPOSITION OF AL1100 AND AL6061

<table>
<thead>
<tr>
<th>Element (wt.%)</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Ti</th>
<th>Zn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al6061</td>
<td>0.09</td>
<td>0.28</td>
<td>0.27</td>
<td>1.03</td>
<td>0.03</td>
<td>0.52</td>
<td>0.01</td>
<td>0.06</td>
<td>Bal.</td>
</tr>
<tr>
<td>Al1100</td>
<td>0.10</td>
<td>0.04</td>
<td>0.30</td>
<td>0.00</td>
<td>0.02</td>
<td>0.20</td>
<td>0.02</td>
<td>0.04</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Two types of deposition structures were fabricated: uniform distribution and patterned distribution. Uniform deposition was performed without the use of pattern, while a patterned deposition was created by inserting a mask layer on top of the substrate sheet (see FIGURE 3(b)). A magnet was used to secure the contact between the substrate and mask layer. Experimental settings used for spray deposition are summarized in TABLE 2.

TABLE 2: SETTING USED IN SPRAYING

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition of sprayed powder</td>
<td>Al6061 + 40 vol.% SiC, Al-50Si + 40 vol.% SiC, Al-50Si + 30 vol.% SiC, Al-50Si + 20 vol.% SiC</td>
</tr>
<tr>
<td>Particle size (μm)</td>
<td>Al6061: 13.8, SiC: 3, Al-50Si: 20</td>
</tr>
<tr>
<td>Solution</td>
<td>Ethanol</td>
</tr>
<tr>
<td>Al1100 sheet thickness (μm)</td>
<td>50</td>
</tr>
<tr>
<td>Nitrogen flow rate (sccm)</td>
<td>1700</td>
</tr>
<tr>
<td>Hot plate temperature (°C)</td>
<td>200</td>
</tr>
<tr>
<td>Spraying time (sec)</td>
<td>60</td>
</tr>
</tbody>
</table>
The experimental setup for the semi-solid process is shown in FIGURE 4. Twenty layers of Al1100 sheets were placed in the die as illustrated in FIGURE 4. The materials were heated to the target temperature in a furnace (Applied Test System Inc.). The load and movement of the upper ram were controlled and measured by the materials testing system (Test Resources Inc., 800LE). The aluminum sheets were pre-compacted with pressure of 100 MPa. The die set was heated to 630°C and held for 60 mins while 100 MPa of pressure was applied. The composite synthesis parameters are listed in TABLE 3.

![FIGURE 4: EXPERIMENTAL SETUP FOR CONSOLIDATION OF COMPOSITES USING MATERIAL TESTING SYSTEM](image)

**TABLE 3: SETTINGS USED IN COMPOSITE SYNTHESIS**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-compaction pressure (MPa)</td>
<td>50</td>
</tr>
<tr>
<td>Pressure at 630°C (MPa)</td>
<td>100</td>
</tr>
<tr>
<td>Pressure holding time (min)</td>
<td>10</td>
</tr>
<tr>
<td>Punch velocity (mm/s)</td>
<td>0.01</td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>630</td>
</tr>
<tr>
<td>Liquid fraction of Al6061 at 630°C</td>
<td>0.18</td>
</tr>
<tr>
<td>Liquid fraction of Al-Si at 630°C</td>
<td>0.43</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION
Spray Deposition

The Al1100 sheet without the mask layer during the spray deposition was fully covered by deposited particles as shown in FIGURE 6(a) and (b). Al6061 and SiC particles were homogeneously distributed on the Al1100 sheets. The distribution of particles on the substrate sheets sprayed with mask is presented in FIGURE 6(c) and (d). Due to the mask, the patterns formed by the particles of Al6061 and SiC were well organized on the Al1100 sheets. As shown in FIGURE 6(c), the pattern was clearly formed. Although a magnet was used to keep the contact between the substrate and mask, spray droplets were observed in the masked areas as shown in FIGURE 6(d). As the circular blanks were prepared by punching process, periphery of the Al sheets were slightly deformed preventing complete contact.

![FIGURE 6: SEM IMAGES OF SPRAY DEPOSITED STRUCTURES: (a) PARTICLES ON AL SHEET WITHOUT MASK, (b) MAGNIFIED IMAGE OF DEPOSITED STRUCTURE WITHOUT MASK, (c) PATTERNED DEPOSITION ON AL SHEET WITH MASK, AND (d) A SINGLE PATTERN ON THE ALUMINUM SHEET](image)
Microstructures
The SEM images of the planar and the cross sectional surfaces of the fabricated composites are shown in FIGURE 7. The microstructure images of the Al-(Al6061+SiC) composite confirm near full-density structure was obtained as shown in FIGURE 7 (a) and (b). No visible pores were found within the deposited Al-(Al6061+SiC) composite. Large Al6061 particles (as shown in FIGURE 6) may have resulted in the formation of non-uniform regions within the deposited layers as observed in FIGURE 7(a). Moreover, the cross sectional microstructure shows uniform thickness in the deposited composite.

![Planar surfaces](image1)

![Cross sectional surfaces](image2)

![Unconsolidated region](image3)

![Un-uniform deposited layer](image4)

![Single pattern](image5)

![Single pattern layer](image6)

![Pores](image7)

![Pores](image8)

FIGURE 7: SEM IMAGES OF CONSOLIDATED COMPOSITE: (a-b) AL-(AL6061+ 40VOL.%SiC) COMPOSITE, (c-d) AL-(AL-50Si+SiC) COMPOSITE, (e-f) AL-(AL6061+SiC) COMPOSITE WITH PATTERN, AND (g-h) AL-(AL6061+SiC) POWDER COMPOSITE.

On the other hand, numerous pores are observed in the Al-(Al-50Si+40vol. %SiC) composite as shown in FIGURE 7(c) and (d). Unconsolidated regions with in the deposited layer can be observed, and the thicknesses of the deposited layers were not uniform and distorted. A possible explanation is the exposure of the Al-50Si particles to high temperatures resulting in expulsion of the liquid phase by high pressure. Also, higher percentage of SiC within the deposited layer in Al-(Al-50Si+40vol. %SiC) composite went beyond percolation limit of SiC reinforcing phase. Microstructure images of a single pattern in planar and cross sectional views are shown in FIGURE 7(e) and (f), respectively. A very thin layer containing only several particles is observed. A complete circular planar view was difficult to obtain due to challenges in aligning the layers with the polisher. As shown in FIGURE 7(g) and (h), numerous small pores can be observed in the Al-(Al6061+SiC) powder composites as a result of using Al1100 powder instead of Al sheets.

The information on amount of powders in the overall composite and within the powder mixture is summarized in TABLE 4. The weight percentage of powder was calculated through recording the weight of each powder, the weights of Al1100 sheets before and after spraying, and the weight of final composite and bend sample. The weight percentages of powder and SiC in Al-(Al-50Si+40vol. %SiC) composite are larger than those in Al-(Al6061+SiC) composite. Due to the pattern, only small amount of powder and SiC was sprayed on Al-(Al6061+SiC) composite with pattern. For comparison, the Al-(Al6061+SiC) powder composite 1 was designed to have the same composition as Al-(Al6061+SiC) with pattern 1, and the Al-(Al6061+SiC) powder composite 2 has the same composition as the Al-(Al6061+SiC) with pattern 2.
TABLE 4: WEIGHT PERCENTAGES OF PARTICLE IN BEND SAMPLES

Bend Test

The stress-strain curves of the samples obtained from the bend test are shown in FIGURE 8. The flexural stress and strain can be calculated with the following equations:

\[ \sigma_f = \frac{3PL}{bd^2} \]  
(1)

\[ \varepsilon_f = \frac{6Dd}{L^2 f} \]  
(2)

where \( \sigma_f \) and \( \varepsilon_f \) is the flexural stress and flexural strain, \( P \) is the load applied, \( L \) is the span of the supporting pin, \( b \) is the width of bend sample tested, \( d \) is the depth of bend sample tested, and \( D \) is the maximum deflection at the center of the bend sample.

The flexural strengths of the Al1100, Al-(Al6061+SiC) with pattern 1, Al-(Al6061+SiC) with pattern 2, Al-(Al6061+SiC) powder composite 1, Al-(Al6061+SiC) powder composite 2, Al-(Al6061+SiC), Al-(Al50Si+40vol.%SiC), Al-(Al50Si+30vol.%SiC), and Al-(Al50Si+20vol.%SiC) are 75 MPa, 158 MPa, 171 MPa, 154 MPa, 160 MPa, 280 MPa, 340 MPa, 197 MPa and 186 MPa, respectively. The pure aluminum composite was made from 20 Al1100 sheets and was consolidated into a composite and polished.

![FIGURE 8: FLEXURAL STRESS-STRAIN CURVES OF AL1100, AL-(AL-50Si+40VOL.%SiC) COMPOSITE, AL-(AL6061+SiC) WITH PATTERN COMPOSITES, AL-(AL6061+SiC) POWDER COMPOSITES AND AL-(AL6061+SiC) COMPOSITE.](image)

The maximum flexural strain was 0.39. The flexural strength of the Al-(Al50Si+40vol.%SiC) bend sample was almost 4.5 times that of the pure aluminum composite. However, the flexural strain at the maximum flexural stress of the composite was about 0.07, which indicated a significant decrease in the ductility of the sample. When decreasing the volume percentage of SiC in the powder to 30%, as well as the weight of powder deposited on the Al1100 sheets, the flexural strength increased to 2.6 times that of pure aluminum bend sample, while the flexural strain at the maximum flexural stress was about 0.15. Similar result turned out if keep decreasing the volume percentage of SiC in the powder to 20%, and the weight of powder deposited onto the Al1100 sheets, the flexural strength was about 2.5 times and the flexural strain at that point was about 0.17. The three bend sample discussed above indicated that higher the weight percentage of SiC in the composite, the more significant increase in the flexural strength but decrease in ductility.

The volume percentage of SiC within the sprayed layer seemed to have a small influence on the overall flexural strength. The flexural strength of the Al-(Al6061+SiC) composite was about 3.7 times to the pure aluminum composite, but lower than that of the Al-50Si+40vol.%SiC composite due to lower SiC volume fraction. The flexural strength of Al6061-SiC composite with pattern 1 and 2 were 2.1 and 2.28 times higher than that of the pure aluminum composite, respectively. The flexural strength of the Al6061-SiC powder composite 1 and 2 were 2.05 and 2.13 times higher than pure aluminum composite. The strength enhancements to reinforcement amount material ratios for the patterned structures were 254 and 125 for the two patterned structures, and for the powder composites were 250 and 111. These were much higher than other composites which range between 15 and 35.

Though the increasing of flexural strengths between the Al-(Al6061+SiC) composite with pattern 1 and Al-(Al6061+SiC) powder composite 1, the Al-(Al6061+SiC) composite with pattern 2 and Al-(Al6061+SiC) powder composite 2 are within 10 MPa, the patterned composites have advantage in flexural strain over other composites. The maximum flexural strain of the Al-(Al6061+SiC) composite with pattern 1 was 0.2, while for the Al-(Al6061+SiC) powder composite 1 the maximum flexural strain is 0.158, and for Al-(Al6061+SiC) composite with pattern 2 was 0.163, while for the Al-(Al6061+SiC) powder composite 2 was 0.127. For all the other composites except pure aluminum composite, the maximum flexural strains were smaller than 0.1. Thus the patterned reinforcing.
microstructures were able to significantly enhance the strength without sacrificing the ductility.

The SEM images of the samples after the bend tests are shown in

FIGURE 9. Cracks were found in composites that had undergone a complete failure whereas patterned composite was near the tensile strength. The failure showed a crack penetration occurring at an angle from the outer surface. Also, small horizontal cracks were observed that penetrated into the SiC planar surface in the Al-(Al-50Si+40vol.%SiC) composite, Al-(Al-50Si+30vol.%SiC) composite and Al-(Al6061+SiC) composite, as shown in the FIGURE 9(a), (b), and (f). No visible cracks were observed in both the two patterned specimens near the flexural strength, both the two powder specimen near the flexural strength, and the Al-(Al6061+20vol.%SiC) composite, as shown in the FIGURE 9(c), (d), (e), (g) and (h).

FIGURE 9: SEM IMAGES OF FRACTURE IN BEND SAMPLES: (a) AL-(AL-50SI+40VOL.%SiC), (b) AL-(AL-50SI+30VOL.%SiC), (c) AL-(AL-50SI+20VOL.%SiC), (d) AL-(AL6061+SiC) WITH PATTERN 1, (e) AL-(AL6061+SiC) WITH PATTERN 2, (f) AL-(AL6061+SiC), (g) AL-(AL6061+SiC) POWDER 1, AND (h) AL-(AL6061+SiC) POWDER 2.

Fracture Surface Analysis

The fracture surfaces were analyzed from the bend samples of Al-(Al6061+SiC), Al-(Al6061+SiC) with patterns, Al-(Al6061+SiC) powder, Al-(Al-50Si+40vol.%SiC), Al-(Al-50Si+30vol.%SiC) and Al-(Al-50Si+20vol.%SiC) composite, which are shown in FIGURE 10. The fracture surface of the Al-(Al6061+SiC) and Al-(Al-50Si+40vol.%SiC) composite, displayed a clear separation between SiC particle containing layer and Al1100 layer as shown in FIGURE 10(a) and (b). A ductile fracture occurred in the Al1100 layers as evidenced by the dimples. For the fracture surface of Al-(Al-
50Si+40vol.%SiC), Al-(Al-50Si+30vol.%SiC) composite and Al-(Al-50Si+20vol.%SiC) composite. In particular, liquid squeeze out was observed in the latter two composites due to the high percentage of Si in the composite. The fracture surface of the Al-(Al6061+SiC) bend sample with pattern was quite different from other composites since the particle loading was much smaller compared with other composites.

CONCLUSIONS AND FUTURE WORK

A novel method of spray patterning combined with semi-solid processing was explored to investigate the potential of the method to create designed architectures in aluminium composite. Five kinds of composites, Al-(Al6061+SiC) composite, Al-(Al-50Si+40vol.%SiC) composite, Al-(Al-50Si+30vol.%SiC) composite, Al-(Al-50Si+20vol.%SiC) composite, and Al-(Al6061+SiC) composite with pattern were investigated. Bend tests were performed to study the mechanical behavior, microstructure and fracture. Controlling of the liquid phase within the SiC containing layer and the volume percentage of SiC in the powder are important as it may have led to porous structures within the Al-50Si+40vol.%SiC layer. While decreasing the volume percentage of SiC in the powder and the weight percentage of powder on the Al1100 sheets, the microstructures of Al-(Al-50Si+30vol.%SiC) composite and Al-(Al-50Si+20vol.%SiC) had fully densified structures. However, patterned composite showed a promising potential. With only 0.5 wt.% SiC loading, flexural strength was still 2.1 times that of the Al composite. Further analysis and testing are needed to fully explain the strengthening effect. Moreover, percolation threshold of reinforcing phase need to be studied. Finally, accurate loading of particles on the substrate material is required to precisely control the patterned microstructure.

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