New Processing Route for the Production of Functionally Graded 7075 Al/SiC$_p$ Composites via a Combination of Semisolid Stirring and Sequential Squeeze Casting

Serhan Karaman Genc and Nilhan Urkmez Taskin *

Abstract: Advanced processing techniques are required to produce functionally graded metal matrix composites due to the metallurgical conditions required during production. In this study, we developed a novel approach for this task by using a combination of two different methods to produce functionally graded 7075 Al/SiC$_p$ (5–20 wt.%) composites. The first process was direct semisolid stirring, which was used to prevent particle agglomeration, brittle reaction products, floating or settling of the reinforcements, and poor wettability. The second process was sequential squeeze casting, which enabled liquid diffusion between the two composite layers that were used to produce a functionally graded aluminum matrix composite. Thus, a method was developed to eliminate the problems encountered in the production of particle-reinforced metal matrix composite materials using liquid stirring methods and to produce composite materials with the desired functionally graded structure. The resulting functionally graded material was subjected to spectrometer analyses, density measurements, and metallographic examinations to determine the characteristics of its layers and interfacial zones, as well as to assess the formation of the graded structure. The results indicate the potential of using this new combined manufacturing method, which is efficient and controllable, to produce functionally graded metal matrix composites.

Keywords: metal matrix composites; functionally graded materials; semisolid stirring; squeeze casting; SiC; aluminum alloys

1. Introduction

Nature’s unique structures have been applied in high-tech materials; one example is in the advent of functionally graded metal matrix composites (FG-MMCS) [1]. This group of materials can be categorized as advanced materials in the engineering composites family [2]. FG-MMCS comprise two or more component phases with a continuous and gradually changing composition [3]. Engineers and scientists are increasingly interested in the study and fabrication of heterogeneous FG-MMCS for specific uses: by combining materials with different properties, their mechanical and physical properties such as strength, toughness, corrosion resistance, and thermal conductivity can be controlled, which vary across the material cross-section [4–7]. Ultimately, FG-MMCS are highly attractive materials for critical applications in various fields such as in the defense, aerospace, energy, nuclear energy, medical, biomaterials, automotive, and electronic smart structure fields [8–16]. Many processing techniques have been developed to produce FG-MMCS, such as laser metal deposition, vapor deposition, spark plasma sintering, centrifugal casting, squeeze casting, the solid free form method, and laser cladding [17,18]. The vapor deposition method, which is commonly used in FGM production, is primarily applied in surface coating processes. Owing to the high energy consumption of vapor deposition, which occurs due to the need for high temperatures and the associated costs of expensive
equipment, production methods using gas-phase deposition are disadvantageous in terms of overall cost. However, vapor deposition has advantages such as its effectiveness in achieving complex geometries and in obtaining a final product close to the desired shape [19]. During production, difficulties are encountered with liquid-phase methods such as liquid-phase precipitation, plasma spray, centrifugal casting, uncontrolled functional distribution, poor wettability between the reinforcement and matrix, heterogeneous reinforcement distribution, agglomeration, rejection of the reinforcement from the liquid metal, and the formation of undesirable reaction products [20].

With solid-phase methods, such as powder metallurgy, issues are encountered such as the time-consuming mixing, compression, and sintering processes; limited dimensions of the resulting product; and challenges with precision and control during the production stages. The measures implemented to overcome these problems often substantially increase processing costs. Despite efforts to address these issues, problems persist in the studies conducted using gas-, liquid-, and solid-phase methods; the available solutions are still not satisfactory [21,22].

The direct semisolid stirring method is promising for the production of FG-MMCs and is described in a patent held by Urkmez Taşkın and Taşkın [23]. With this method, the metal, which is kept in a semisolid state, is continuously stirred throughout the reinforcement-adding process. The viscosity of the composite mixture is relatively high, and the stirring process breaks down the naturally occurring dendrites, resulting in a semisolid microstructure surrounded by spherical solid particles dispersed in liquid. The spherical grain structure, which is termed spherical (nondendritic) and acquired via working at conditions close to the liquid phase, is essential for the semisolid process and the thixotropic state. The particle sizes obtained are also favorable due to working at conditions close to the liquid phase. Use of the combination of direct semisolid stirring with sequential squeeze casting for FGM production has not been reported in the literature. However, the method that closely resembles the proposed approach is the cast–decant–cast (CDC) approach, patented in 2008 and licensed by the ECK Company. The CDC method involves the merging of different metals and is particularly used in the production of functionally graded materials (FGMs) through semisolid casting. CDC is a more cost-effective, straightforward, and successful method compared with other techniques [23–25]. The use of the semisolid stirring process, which allows for the creation of a spherical grain structure with good mechanical properties, achieves desirable grain sizes and homogeneous mixtures. When followed by a compression process to reduce porosity, CDC provides new developments in FGM production methods. The semisolid stirring method overcomes the challenges encountered with both liquid- and solid-phase production methods. The reinforcement can be homogeneously mixed into the matrix, eliminating issues such as clumping, rejection of reinforcement from the mixture, and segregation. Furthermore, the reinforcement and matrix have relatively short contact times at lower temperatures, reducing the occurrence of undesirable interfacial reactions. Additionally, surface-modified reinforcement particles are effective in preventing these reactions. Surface modification of the reinforcement by coating or passive oxidation is one of the methods that prevents the formation of brittle phases between the liquid metal and the reinforcements. This technique is thought to have considerable potential for practical manufacturing in preventing undesirable interfacial reactions and increasing the wettability of the material (Shi, 2001) [26].

The aim in this study was to eliminate the problems encountered in the production of particle-reinforced metal matrix composite materials using liquid stirring methods. We wanted to develop a method for the production of composite materials with the desired functionally graded structure. This study explored the combined application of the direct semisolid stirring and sequential compression casting methods for the production of FGMs. The combined use of these methods is expected to enable the mass production of volumetrically larger products in FGM production, offering solutions to the previously mentioned problems and production-related issues.
The anticipated outcomes included the production of materials with higher strength, lower porosity, and controllable mechanical properties. Al7075 was selected as the matrix material in this study. SiCp-reinforced composites were created using different ratios of SiCp via the direct semisolid stirring method. Subsequently, a functionally graded product with dimensions of 110 × 110 × 50 mm was produced using the sequential squeeze casting method. One innovation provided by this study is the use of a new direct semisolid stirring method to create composite mixtures with different reinforcement ratios, in which the resulting composites are deposited using the sequential pressure casting method to obtain functionally graded aluminum composites. In addition, ensuring the bonding between composite layers via liquid diffusion and pressure application is a method that has not been applied for FGM production in the literature. The contributions of this study to the field include providing insights into the simultaneous use of these methods for obtaining functionally graded metal matrix composites on a mass scale.

2. Materials and Methods

2.1. Materials

AA7075 alloy was used as the matrix material for the production of a functionally graded 7075 Al/SiCp composite. In this alloy, copper serves as the primary alloying element, with additional alloying elements such as magnesium, chromium, and zinc. Owing to this composition, this alloy has the highest mechanical strength among all aluminum alloys. The AA7075 Al alloy were obtained from Guray Aluminum Pazarlama ve Sanayi Ticaret Limited Sirketi (Istanbul, Türkiye), and its specifications are provided in Tables 1–3.

Table 1. Physical properties of Al7075 alloy.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2.81 g/cm³</td>
</tr>
<tr>
<td>Elastic Modulus (273–373 K)</td>
<td>71–72 GPa</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>0.97</td>
</tr>
<tr>
<td>Linear Expansion Coefficient (293–373 K)</td>
<td>23 × 10⁻⁶ /K</td>
</tr>
<tr>
<td>Thermal Conductivity (373–673 K)</td>
<td>130 W/(m K)</td>
</tr>
<tr>
<td>Resistivity (293 K)</td>
<td>0.049 × 10⁻⁶ Ω m</td>
</tr>
</tbody>
</table>

Table 2. Chemical composition of AA7075 alloy.

<table>
<thead>
<tr>
<th>Element</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>-</td>
<td>0.4</td>
</tr>
<tr>
<td>Fe</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>Cu</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Mg</td>
<td>1.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Mn</td>
<td>2.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Cr</td>
<td>0.18</td>
<td>0.28</td>
</tr>
<tr>
<td>Zn</td>
<td>5.1</td>
<td>6.1</td>
</tr>
<tr>
<td>Ti</td>
<td>-</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 3. Mechanical properties of AA7075 alloy.

<table>
<thead>
<tr>
<th>Heat Treatment</th>
<th>Tensile Strength (Rm MPa)</th>
<th>Yield Strength (Rpo.2/MPa)</th>
<th>Elongation (%)</th>
<th>Hardness (Brinell)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>225</td>
<td>105</td>
<td>17</td>
<td>60</td>
</tr>
<tr>
<td>T6</td>
<td>530–570</td>
<td>460–505</td>
<td>10</td>
<td>150</td>
</tr>
</tbody>
</table>

Green SiC powders (GW Micro) had an average size of 12 µm (500 mesh) according to the supplier’s data sheets. This material, which is low in cost, readily available, and high in strength, is widely used in technical ceramics, semiconductor technology, and photovoltaic applications in processes such as bonding and polishing [21]. Some of the physical and mechanical properties of SiC powders are listed in Table 4, and their chemical compositions are described in Table 5.
Table 4. Physical and mechanical properties of SiC<sub>p</sub> reinforcements.

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Particle Type Size (μm)</th>
<th>Density (g/cm&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Tensile Strength (GPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>15–340</td>
<td>3.2</td>
<td>3</td>
<td>480</td>
</tr>
</tbody>
</table>

Table 5. Chemical composition of SiC<sub>p</sub> reinforcements.

<table>
<thead>
<tr>
<th>Products</th>
<th>Particle Size</th>
<th>SiC%</th>
<th>Free C %</th>
<th>Si %</th>
<th>SO&lt;sub&gt;2&lt;/sub&gt; %</th>
<th>Fe,O&lt;sub&gt;3&lt;/sub&gt; %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>F240–F800</td>
<td>99.5</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The summary of the squeeze casting conditions and designation for the production of FG-7075 Al/SiC<sub>p</sub> is given in Table 6.

Table 6. Summary of the squeeze casting conditions and designation.

<table>
<thead>
<tr>
<th>Condition</th>
<th>SiC Addition (wt%)</th>
<th>Application (5-Layer FDM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA7075</td>
<td></td>
<td>1st layer</td>
</tr>
<tr>
<td>AA7075 + 5% SiC</td>
<td>5</td>
<td>2nd layer</td>
</tr>
<tr>
<td>AA7075 + 10% SiC</td>
<td>10</td>
<td>3rd layer</td>
</tr>
<tr>
<td>AA7075 + 15% SiC</td>
<td>15</td>
<td>4th layer</td>
</tr>
<tr>
<td>AA7075 + 20% SiC</td>
<td>20</td>
<td>5th layer</td>
</tr>
</tbody>
</table>

SiC particles were oxidized in air in an electric furnace at atmospheric pressure. SiC particles were kept in the electric furnace at 1100 °C for 5 h, removed, and then allowed to cool under ambient conditions [23].

2.2. Preparation of FG-7075 Al/SiC<sub>p</sub>

The semisolid stirring and squeeze casting methods were combined for the production of FG-7075 Al/SiC<sub>p</sub>. The composite mixtures that formed the layers were prepared via direct semisolid stirring. The matrix alloy was used in small pieces to control the viscosity of the mixture and to ensure that the desired amount of matrix material was added during stirring of the product. The stirring was conducted under inert N<sub>2</sub> gas. For each layer, approximately 0.6 kg of alloy was heated to 635–655 °C. This temperature range is the semisolid state temperature for 7075 Al alloy, and the alloy was kept in this temperature range until the entire reinforcement was homogeneously distributed in the alloy. The process of maintaining metals in the semisolid state has been previously described in [23]. The homogenized composite slurry was poured into a mold (110 × 110 × 50 mm), heated to 340 °C after raising the temperature by 5–10 °C to facilitate pouring into the mold, and solidified by applying 100 bar pressure to the press. Thus, the first 7075 layer of the FG-7075 Al/SiC<sub>p</sub> structure, i.e., the unreinforced aluminum layer, was formed (Figure 1).

For the 2nd layer, the pre-oxidized ceramic particle reinforcement material was added at a total of 5% by weight to the matrix material that was prepared via heating to the semisolid temperature range. When the matrix material was at semisolid temperature, low-speed stirring and mashing processes were applied with a mixer and a masher possessing different end profiles to ensure that the reinforcement particles were dispersed in the matrix material [23]. Then, the composite slurry was poured onto the first layer in the mold and placed under the press table, and the upper mold was closed and pressed. Thus, the 2nd layer was formed, and a 2-layer FG-7075 Al/SiC<sub>p</sub> was obtained. This process was repeated with different reinforcement ratios (10%, 15%, and 20% SiC<sub>p</sub>) until the 3rd, 4th, and 5th layers were formed; a 5-layer FG-7075 Al/SiC<sub>p</sub> was successfully produced (Figures 1 and 2).
Figure 1. Steps followed for FG-7075 Al/SiC<sub>p</sub> production.

Figure 2. Cross-section of 5-layer FG-7075Al/SiC<sub>p</sub>.

2.3. Microstructural Characterization

To determine the microstructural properties of the obtained five-layer functionally graded material, a precision cutting device was used in the sample preparation process for the analyses. Test specimens were extracted for microstructure, spectrometer, and SEM–EDS analyses, as well as density measurements.

For each layer of the composite FGM, spectrometer analyses were performed using an optical emission spectrometer (METEK, Elmshorn, Germany) in 5 different zones (Figure 3).
The densities of the samples were determined first by using a Mettler Toledo precision balance (Mettler Toledo JE503C, Greifensee, Switzerland) with a sensitivity of 0.001 g to measure mass, and then by performing measurements according to the Archimedes principle.

FG-7075 Al/SiC_p was fabricated as a block; then, samples were sectioned for the microstructural analysis of different zones with a precision cutting device. Prior to metallographic preparation, the densities of the samples obtained from the different layers (Figure 4) of the cross-section were measured using the Archimedes principle. A Nikon Eclipse L150 metallurgical optical microscope was used to analyze the grain structure of the FG-7075 Al/SiC_p layers. The samples were prepared for metallography through successive grinding steps using various levels of SiC paper, and were then subsequently polished using 6 µm, 3 µm, and 1 µm diamond suspensions and then 0.02 µm colloidal silica, sequentially. Furthermore, SiC particles in the transition zone and matrix–SiC_p interfaces (Figure 5) were examined using a Cambridge S4-10 Stereoscan scanning electron microscope (Zeiss SEM, Oberkochen, Germany) at 20 keV. Energy-dispersive X-ray spectroscopy (Zeiss SEM, Oberkochen, Germany) was conducted using an integrated Ortec 6230 EDS system (Zeiss SEM, Oberkochen, Germany) to determine the elemental composition of the different layers of the FG-7075 Al/SiC_p samples.
SEM analysis was also performed to observe the globular structure formed as a result of the semisolid stirring process. The hardness measurements of the FG-7075 Al/SiC<sub>p</sub> composite layers were obtained by using a universal hardness tester with an indenter diameter of 2.5 mm. A load of 62.5 kgf was applied for 30 s at room temperature.

3. Results and Discussion

Effect of Direct Semisolid Stirring and Sequential Squeeze Casting

All layers on the cross-section of the 7075 Al/SiC<sub>p</sub> FGM block were produced via direct dispersion of oxidized SiC particles into a semisolid matrix. This method was used to obtain homogeneous mixtures without the problems caused by stirring, such as agglomeration, settling at the bottom of the mixture, and undesirable reaction products. In addition to the SEM and EDS analyses, spectrometer analyses and density measurements were conducted for different zones of each layer to verify the success of the method. The results of the spectrometry analysis showed the layers with different reinforcement ratios in the sample and the elemental distribution within these layers, as presented in Table 7.

Table 7. Spectrometry results for different layers.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Ti</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>0.061</td>
<td>0.025</td>
<td>0.516</td>
<td>0.0555</td>
<td>0.0287</td>
<td>1.57</td>
<td>0.257</td>
<td>4.00</td>
<td>93.4</td>
</tr>
<tr>
<td>2nd</td>
<td>2.420</td>
<td>0.639</td>
<td>1.210</td>
<td>0.0489</td>
<td>0.0817</td>
<td>2.69</td>
<td>0.159</td>
<td>4.57</td>
<td>88.1</td>
</tr>
<tr>
<td>3rd</td>
<td>6.420</td>
<td>0.831</td>
<td>1.450</td>
<td>0.0343</td>
<td>0.1670</td>
<td>2.80</td>
<td>0.241</td>
<td>4.79</td>
<td>83.1</td>
</tr>
<tr>
<td>4th</td>
<td>14.32</td>
<td>0.798</td>
<td>1.690</td>
<td>0.0360</td>
<td>0.0441</td>
<td>2.38</td>
<td>0.200</td>
<td>5.50</td>
<td>74.8</td>
</tr>
<tr>
<td>5th</td>
<td>20.84</td>
<td>1.030</td>
<td>1.600</td>
<td>0.0344</td>
<td>0.0253</td>
<td>2.01</td>
<td>0.190</td>
<td>4.94</td>
<td>68.7</td>
</tr>
</tbody>
</table>

According to the results of the spectrometer analysis performed on the FG-7075 Al/SiC<sub>p</sub> block section, the change in Si content in the composition of SiC<sub>p</sub> used as a reinforcing material proportionally increased with the increase in the reinforcement ratio. The contents of the other elements remained relatively constant with increasing reinforcement content in the cross-sectional direction. The increasing amounts of reinforcing SiC<sub>p</sub> particles from one layer to the next indicated that the FGM structure was formed as expected in terms of SiC<sub>p</sub> reinforcement ratios.

Density measurements were recorded for the samples of the functionally graded material layers and transition zones. Table 8 shows the measured densities, the theoretical densities, and the porosity values. The density measurements showed that the density increased with increasing reinforcement ratios, as expected. Additionally, the porosity increased with the increase in the reinforcement ratio due to issues with the semisolid stirring and casting processes, which were mainly caused by increased viscosity.
Table 8. Density and hardness measurements of FG-7075 Al/SiC\(_p\) layers and transition zones.

<table>
<thead>
<tr>
<th>SiC(_p)%</th>
<th>Measured Density (g/cm(^3))</th>
<th>Theoretical Density (g/cm(^3))</th>
<th>Porosity (%)</th>
<th>Brinell Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>2.787</td>
<td>2.81</td>
<td>1.06</td>
<td>108.8</td>
</tr>
<tr>
<td>0–5%</td>
<td>2.790</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5%</td>
<td>2.799</td>
<td>2.83</td>
<td>1.413</td>
<td>125.2</td>
</tr>
<tr>
<td>5–10%</td>
<td>2.805</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10%</td>
<td>2.812</td>
<td>2.85</td>
<td>1.403</td>
<td>127.8</td>
</tr>
<tr>
<td>10–15%</td>
<td>2.845</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15%</td>
<td>2.840</td>
<td>2.87</td>
<td>1.045</td>
<td>136.2</td>
</tr>
<tr>
<td>15–20%</td>
<td>2.831</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20%</td>
<td>2.848</td>
<td>2.89</td>
<td>1.73</td>
<td>115.4</td>
</tr>
</tbody>
</table>

Similar to this study, Prabhu (2017) used the centrifugal casting method to produce functionally graded composites from 7075 aluminum alloy reinforced with 6% and 9% SiC\(_p\), and they confirmed that increasing the reinforcement ratio led to an increase in the material’s density [27]. They found that porosity above 3% in 9% SiC\(_p\)-reinforced FGM. However, in this study, the porosity was less than 2% in all layers. In the FGM material obtained via the successive application of semisolid stirring and squeeze casting, the highest measured porosity was 1.73% in the zone with 20% SiC\(_p\) reinforcement, indicating that the applied method produces a less porous structure. Additionally, as shown in Table 8 and Figure 6, the density increased as the reinforcement ratio increased, in compliance with previously reported results in the literature [27–29]. Porosity increased with increasing reinforcement ratio in the FGM material, but this rate of increase and the functionally graded transition were more controllable than in centrifugal casting in terms of microstructure [27].

In Table 8, the change in Brinell hardness along the cross-section is compared with the porosity and density measurements. The table shows that a functionally graded structure formed along the section, where the hardness increased with the increase in the reinforcement ratio. The decrease in hardness in the 20% SiC\(_p\)-reinforced region could be explained by the increase in porosity in this region. The change in hardness along the cross-section is compatible with the results reported in the literature [27,30,31].

Figure 6. Density distribution along the cross-section of an FG-7075 Al/SiC\(_p\) sample.
The results of the combined scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) analyses of SiC-reinforced powders before and after oxidation are shown in Figure 7. The SEM image before oxidation shows that the powders were 12–15 µm in size and had sharp edges. After oxidation, the EDS results show the presence of oxygen elements on the surface of SiC particles.

Figure 7. SEM and EDS analyses of SiC particles.

Figure 8 shows that the SiC reinforcement particles were wetted with the Al 7075 matrix material. The EDS analysis did not reveal any voids or undesirable phases around the SiC grains.

Figure 8. SEM and EDS analyses of SiC reinforcement particles within the aluminum matrix.
The SEM images in Figure 9 at magnifications of ×1000, ×2500, and ×5000 show that the well-oxidized surface resulted in more successful wetting and bonding between the particles and matrix after oxidation was applied to the SiC particles.

**Figure 9.** SEM images at magnifications of ×1000, ×2500, and ×5000 from left to right.

In the SEM image in Figure 10a, the intermediate zone in the 0–5% SiC<sub>p</sub> layer and the interfaces between these layers is shown as a faint line. In the interface zone, some of the SiC was transferred to the unreinforced zone. Bonding via partial melting between the layers is indicated by the lack of a straight and distinct line shape in the interface zone and the transition of the reinforcement into the unreinforced layer.

**Figure 10.** SEM image of transition zones with (a) 0–5%, (b) 5–10%, (c) 10–15%, and (d) 15–20% SiC<sub>p</sub>. 
In the SEM image in Figure 10b, the intermediate zone between the 5–10% SiC<sub>p</sub> layers and the junctions of these layers is seen as an indistinct line. The zones where the line becomes less distinct are partial diffusion zones. The SEM image in Figure 10c shows the intermediate zone between the 10–15% SiC<sub>p</sub> layers and the junctions of these layers. In the interface zone, a transition zone formed where the SiC particles were homogeneously distributed, and no proportional difference was observed in this zone.

In the SEM image in Figure 10d, the intermediate zone between the 15–20% SiC<sub>p</sub> layers and the junctions of these layers is almost indistinct. A transition zone formed where the SiC particles were homogeneously distributed, and no proportional difference in the layer transition was observed. Successful bonding was achieved as the reinforcement content increased; small agglomerations were observed between the composite layers.

The SEM photographs at magnifications of 100×, 250×, 500×, and 1000× obtained from a sample taken from the 5% SiC<sub>p</sub> layer show that the separation surfaces between the grains had a globular structure (Figure 11). The globular structure of the grains that was expected from semisolid stirring was successfully achieved and maintained [28].

![SEM images](image1.png)

**Figure 11.** SEM images of 5% SiC<sub>p</sub> zone at magnifications of (a) 100×, (b) 250×, (c) 500×, and (d) 1000×, showing the formation of globular grains and the separation surfaces formed at the grain boundaries.

Light microscopy images of the zones with 0%, 5%, 10%, 15%, and 20% SiC<sub>p</sub> reinforcements and the junctions of these zones were captured at a magnification of 5×. The images in Figure 12a,c,d,g represent intermediate zones (junctions). Figure 12b,d,f,h displays the main zones of the layers.

In Figure 12a, the interface line between the zones with 0% and 5% SiC reinforcement has almost disappeared, and no substantial void or oxide layer can be observed, which is indicative of a strong bond. A partial diffusion zone was observed where the line was absent in the intermediate zone, and adhesion was observed where the line was present, as shown in Figure 12c. In the main zones, agglomeration was observed to some extent.
Figure 13 illustrates the functionally graded 7075Al/SiC\textsubscript{p} composite structure (FGM), which was achieved by combining the optical images taken at the same magnification from the intermediate and main zones.

![Figure 13](image)

To express the obtained FGM structure more clearly, ×500 magnified SEM images of the layers are arranged in order in Figure 13, where the reinforcement increased from the unreinforced Al layer to the 20% SiC\textsubscript{p}-reinforced layer. This figure shows that FGMs in

Figure 12. Light microscopy images of transition zones, (a) AA7075–5% SiC\textsubscript{p}, (c) 5–10% SiC\textsubscript{p}, (e) 10–15% SiC\textsubscript{p}, (g) 15–20% SiC\textsubscript{p}, and main zones, (b) 5% SiC\textsubscript{p}, (d) 10% SiC\textsubscript{p}, (f) 15% SiC\textsubscript{p}, and (h) 20% SiC\textsubscript{p}, in FG-7075 Al/SiC\textsubscript{p} composites.
layers containing the desired reinforcement ratios can be produced by the described method in a controllable manner.

Figure 13. FG-7075Al/SiC$_p$ composite structure.

4. Conclusions

A new processing route for metal matrix FGMs was developed by combining semisolid stirring and sequential squeeze casting. The major conclusions drawn from this study are as follows:

- By using a novel method—a combination of semisolid stirring and sequential squeeze casting—an FG-7075 Al/SiC$_p$ composite was successfully produced;
- Semisolid stirring prevented the movement of SiC$_p$ to the surface and its precipitation, and considerably reduced the agglomeration of SiC$_p$ particles during stirring;
- By applying sequential squeeze casting, the composite layers of desired reinforcement ratios were successfully bonded together by creating a transition zone;
- The SEM results showed that the Al matrix surrounded the SiC particles without gaps, and the desired interfacial bonding formed via the application of the combined method;
- The SEM results showed that the SiC$_p$ reinforcement dispersed into the matrix during semisolid stirring. Additionally, a globular grain structure formed, as expected, via semisolid stirring;
- The sequential squeeze casting method was effective in providing porosity values in the range of 1–1.7% throughout the entire cross-section;
- As the reinforcement ratio in the layers increased, the hardness in the different layers of the material tended to increase. This showed that the FGM structure was successfully created in the sample.

FGMs can be produced with different functions by changing and optimizing the casting temperature, pressure, number of layers, layer thickness, and the type and ratio of reinforcement material. For FGMs to be used in practice in the future and to open new areas and markets, studies on production processes need to be continued.

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