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Development and Characterization of Semisolid-Formed Al-5%Cu-4%Mg/SiC Composites for Lightweight Structural Applications

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Abstract: Aluminum-based metal matrix composites (MMCs) are attractive for lightweight structures and components due to their low density and high specific strength. This study reports the synthesis of Al-5%Cu-4%Mg/SiC composites via an integrated route combining in-house alloy preparation, high-speed stir casting (5000 rpm), and semisolid compression forming at 640 °C under 150 tons. In contrast to prior works that relied on commercial alloys, pure aluminum ingot, pure copper wire, and Al-13%Mg master alloy were used to enable precise control over matrix–reinforcement interactions. Silicon carbide particles (50–200 µm) were incorporated at 5% and 20% volume fractions with argon-assisted dispersion, achieving uniform distribution and strong interfacial bonding. Semisolid forming refined the microstructure, producing fine, globular grains that enhanced mechanical performance. Standardized testing revealed significant improvements in hardness and tensile strength over as-cast counterparts. The results confirm the effectiveness of the proposed method for enhancing structural performance, highlighting its suitability for applications demanding lightweight and durable materials.

Keywords: Al-5%Cu-4%Mg; hardness; Metal matrix composites; semisolid forming; SiC reinforcement; tensile strength

1. Introduction

Metal matrix composites (MMCs) have attracted significant attention in various engineering fields due to their ability to combine the desirable properties of metals with those of reinforcing phases, resulting in superior mechanical, thermal, and wear characteristics compared to conventional alloys[1,2,3]. Among the available MMC systems, aluminum-based MMCs (Al-MMCs) are widely recognized for their favorable balance between strength, stiffness, and corrosion resistance, making them suitable for applications in automotive, aerospace, and other high-performance industries[4,5,6]. In addition, Al-MMCs can offer up to 253% higher thermal conductivity than steel and cast iron, which is advantageous for components requiring efficient heat dissipation[7].

The choice of reinforcement is crucial in determining the performance of MMCs. Silicon carbide (SiC) is one of the most extensively studied reinforcements for Al-MMCs due to its high hardness, high modulus, good thermal stability, and chemical compatibility with aluminum matrices[8,9,10]. These attributes enable significant improvements in wear resistance, strength, and thermal performance, particularly in applications where structural integrity must be maintained under thermal cycling and mechanical loading[11,12,13,14].

SiC offers a unique balance of properties compared to other reinforcements. Al_2O_3 provides low cost and chemical stability, but its lower thermal conductivity and higher thermal expansion mismatch with aluminum often cause interfacial stresses. TiC delivers excellent hardness, but it suffers from poor wettability and weak interfacial bonding unless costly surface treatments are applied. B_4C contributes low density and high hardness, but it is expensive, prone to particle fracture, and less chemically compatible with aluminum. SiC, in contrast, provides high

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hardness, good wettability (especially with Mg additions), and favorable thermal compatibility, which enhance interfacial bonding, heat dissipation, and process adaptability. These advantages make SiC particularly suitable for Al–Cu–Mg alloy systems and scalable processing routes such as stir casting and semisolid forming[15, 16)].

Recent advances in semisolid processing have significantly improved the microstructural control and performance of Al-MMCs. Hybrid approaches such as semisolid stirring combined with sequential squeeze casting have been shown to reduce reinforcement agglomeration, improve wettability, and enable controlled gradient microstructures in 7075 Al/SiCp composites[17, 18)]. Similarly, semisolid stir casting of Al 7075–Al_2O_3 at ~550 °C yielded uniform particle dispersion and peak tensile and hardness values at 10 wt.% reinforcement[19, 20)]. Powder-based semisolid processing highlights the importance of optimizing liquid fraction, with ~40% at 615 °C enhancing slurry flow, densification, and compressive strength, while higher liquid fractions led to segregation and porosity[21)]. Ultrasonic-assisted semisolid stirring (UASS) has further enabled effective dispersion of nano-sized SiC, supporting rheoforming and thixoforming of high-strength components with ultimate tensile strength (UTS) up to 550 MPa, albeit with reduced ductility[22)]. In rheoformed Al–Al_2O_3 nanoparticle composites, extended stirring times refined grains and achieved balanced mechanical performance (UTS ≈ 358 MPa, YS ≈ 245 MPa, elongation ≈ 5.6%)[23)].

Complementary hybrid methods, such as combining thermal spray with semisolid forming, have also demonstrated efficient densification and complex geometries in fiber-reinforced MMCs[24 25)]. These findings underscore the growing importance of semisolid and hybrid fabrication strategies in producing scalable, high-performance MMCs. Such hybrid and multifunctional processing strategies directly respond to current industrial demands for composites with a combination of high strength, thermal stability, and sustainability in production. Beyond semisolid processing, emerging techniques such as additive manufacturing (AM), spark plasma sintering (SPS), and friction stir processing (FSP) are transforming MMC fabrication. AM methods, including selective laser melting (SLM) and direct energy deposition, offer fine microstructural control and reduced porosity in Al-SiC systems[26)] showed that process parameters in laser AM significantly influence density and mechanical properties of Al–SiC composites. Abd Baghad and El Mabrouk[27)] reviewed AM of lightweight MMCs, emphasizing the role of powder preparation and reinforcement design. Similarly, FSP has proven effective for localized reinforcement and surface modification, enabling gradient composites with tailored hardness and wear resistance[28)]. Together, these advances illustrate the transition from conventional MMCs to hybrid and multifunctional systems, aligning with the latest research trends and ensuring relevance of this study to both academic development and industrial application.

The Al–5%Cu–4%Mg alloy system has been selected in this study as the matrix material because of its inherent high strength and good response to precipitation hardening [29, 30, 31).] The addition of copper enhances strength through precipitation of θ (Al_2Cu) phase, while magnesium contributes to solid-solution strengthening and promotes the formation of Mg_2Si when SiC is present[32, 33, 34)]. Previous studies have also reported that Mg improves the wettability of molten aluminum on ceramic particles, thereby enhancing interfacial bonding and overall composite performance[35, 36, 37)]. By optimizing the combination of alloy composition and SiC reinforcement, it is possible to achieve a tailored balance of strength, ductility, and thermal properties for demanding service environments.

In this context, the present work investigates the effects of SiC particle reinforcement and magnesium content on the microstructure and mechanical performance of semisolid-formed Al–5%Cu–4%Mg/SiC composites. The study aims to provide insight into the synergistic roles of matrix composition and reinforcement characteristics in improving the overall performance of Al-MMCs for structural and heat-dissipating applications.

This study introduces a novel processing route that combines in-house alloy synthesis, high-speed argon-assisted stir casting, and semisolid compression forming to produce a tailored Al-5%Cu-4%Mg/SiC composite, delivering refined microstructure, reduced defects, and enhanced mechanical performance for lightweight structural applications. By situating this study within the broader trajectory of hybrid and advanced processing strategies, it not only addresses the current gap in understanding Al–Cu–Mg/SiC composites but also connects to ongoing research trends in multifunctional and next-generation MMC development**.**

2. Experimental Method

The experimental material studied consisted of an Al-Cu-Mg alloy composite, with silicon carbide (SiC) particles as reinforcement, forming a metal matrix composite (MMC). The Al-Cu-Mg matrix was prepared by mixing pure aluminum, pure copper, and Al-13%Mg to obtain a parent alloy Al-5%Cu-4%Mg with the chemical composition shown in Table 1.

The next process was the addition of 50-200 μm silicon

Table 1: Chemical composition of Al-Cu-Mg alloy

Alloy material	**Weight %**			
	Al	**Cu**	**Mg**	**Others**
Al-Cu-Mg	Rest	5.05	4.12	0.46

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carbide particles into the parent alloy matrix with a target volume fraction of 15% and 20%. The mixture was stirred at a high speed of 5000 rpm for 30 seconds, while argon gas was continuously flowed into the molten Al-Cu-Mg/SiC composite to prevent oxidation and promote uniform particle dispersion. The molten Al-Cu-Mg/SiC composite is then poured into a 60 mm diameter open cylindrical mold and allowed to solidify. The final processing step was the formation of a semi-solid composite, by reheating the metal matrix composite (MMC) to a semi-solid temperature of 640°C and applying a pressure of 150 tons (39 MPa) for 3 seconds in the compression machine as in Figure 1.

The selection of 5 wt.% Cu and 4 wt.% Mg was aimed at optimizing both strengthening and interfacial characteristics. Cu promotes the formation of θ (Al_2Cu) precipitates, enhancing strength and creep resistance without excessive brittleness, while Mg provides solid-solution strengthening, refines precipitation through S′ (Al_2CuMg) and Mg_2Si phases, and significantly improves SiC wettability. This synergistic effect yields higher strength, improved ductility, and stable interfacial bonding under service conditions[38, 39, 40].

The next process was the addition of 50-200 μm silicon carbide particles into the parent alloy matrix with a target volume fraction of 15% and 20%. The mixture was stirred at a high speed of 5000 rpm for 30 seconds, while argon gas was continuously flowed into the molten Al-Cu-Mg/SiC composite to prevent oxidation and promote uniform particle dispersion. The molten composite was then cast into an open mold until solidified. The final processing step was the formation of a semi-solid composite, by reheating the metal matrix composite (MMC) to a semi-solid temperature of 640°C and applying a pressure of 150 tons (39 MPa) for 3 seconds in the compression machine as in Figure 1.

Microstructural characterization of the Al-Cu-Mg/SiC composite was carried out using an optical microscope and Field Emission-SEM (FE-SEM) brand Inspect F50. Metallographic samples, obtained from as-cast and thixoforming materials, were carefully prepared following standard procedures. These samples were etched in a Keller reagent solution consisting of 50 ml of distilled water, 50 ml of HNO3, 10 ml of HCl, and 10 ml of HF. Observations were made at magnifications ranging from 50 to 500x to examine the microstructure of the composites, including porosity and casting defects. The distribution of alloy constituents was further investigated using an energy dispersive spectrometer (EDS) system integrated with the SEM.

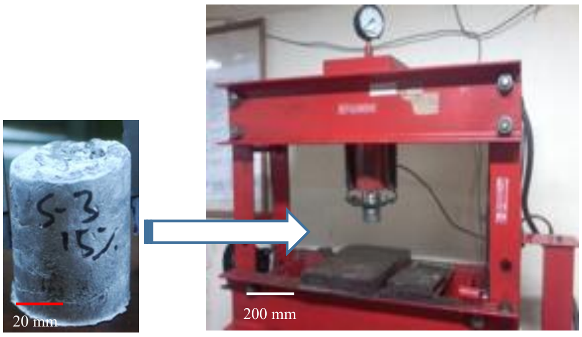


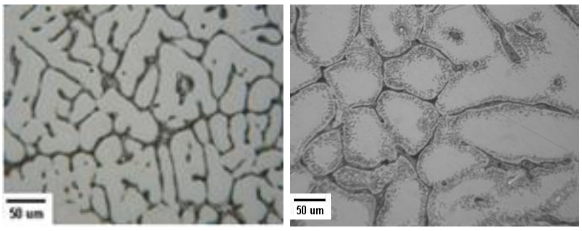
Fig. 1: As-cast Al-Cu-Mg/SiC composite prepared for pressing in a compression machine at 39 MPa for 3 seconds to produce a semi-solid composite.

Mechanical properties were examined through hardness and tensile tests. Hardness test was conducted based on ASTM E18-11 with Rockwell B using Frank Well brand tester while tensile properties were assessed using ASTM E8 standard on RMG 100-German testing equipment universal testing machine at a speed of 5 mm/s with a sample measuring length of 25 mm and a width of 6 mm. These evaluations provided insights into the impact of the semisolid forming process on the composite's performance and structural integrity.

3. Results and Discussions

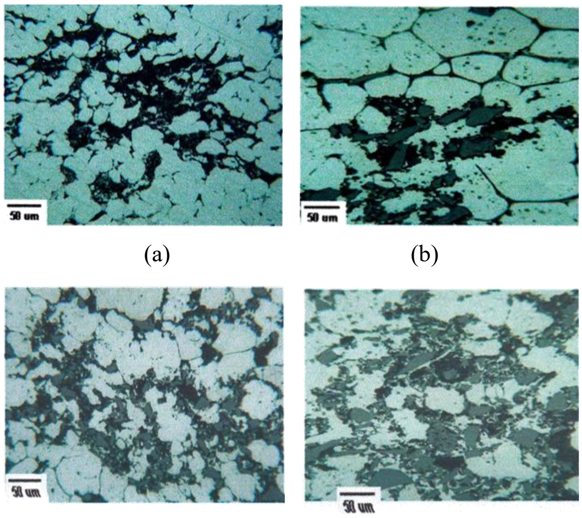
The mechanical properties of metal matrix composites (MMCs) are significantly influenced by the volume fraction of the reinforcement phase and the morphology of the matrix microstructure[41, 42]. The current research findings demonstrate that the microstructure of the material significantly influences the growth of initial cracks[43]. Figure 2 illustrates the changes in the microstructure of the Al-5%Cu-4%Mg matrix, comparing the as-cast condition with the condition after semisolid forming. As depicted in Figure 2(a), the as-cast MMC without SiC reinforcement exhibits a dendritic grain structure. In contrast, after the semi-solid semisolid forming process, the grain structure transforms into a globular form, as shown in Figure 2(b). The mechanism underlying the transformation from a dendritic to a globular structure has been explored in various studies on semi-solid processing. Fan’s research indicates that applying stress to a metal in a semi-solid state causes bending of the dendritic arms within the matrix. If the applied stress is sufficient, the dendritic arms may detach from the main dendrite and result in the formation of a new, globular structure[44]. Similarly, Adedayo reported that reheating a cast material and holding it isothermally in a semi-solid state can break the dendritic arms. The liquid phase of the metal then diffuses and coalesces with the solid phase, leading to the development of a globular microstructure[45, 46].

These findings underscore the significant impact of processing conditions on the microstructural evolution of MMCs, which in turn affects their mechanical performance. The transformation to a globular structure typically enhances the material's ductility and reduces its



(a) (b)

Fig. 2: Optical microscope images of the Al-5%Cu-4%Mg matrix without SiC reinforcement: (a) as-cast microstructure showing a dendritic grain morphology, and (b) microstructure after semi-solid processing, showing the transformation into a globular grain structure



(a) (b)

(c) (d)

Fig. 3: Optical micrographs of SiC-reinforced MMCs processed in the semi-solid state. All samples exhibit globular grain morphology, though the distribution of SiC particles remains somewhat uneven. The fraction of SiC reinforcement in the microstructure increases systematically with increasing particle: (a) 5 vol.%, (b) 10 vol.%, (c) 15 vol.%, and (d) 20 vol.%

brittleness, making it a desirable characteristic for many engineering applications.

Figure 3(a–d) displays the evolution of the microstructure of Al-5%Cu-4%Mg/SiC metal matrix composites fabricated via semisolid forming, with increasing SiC volume fractions from 5% to 20%. The micrographs clearly illustrate two key aspects: the distribution behavior of SiC particles and the response of the matrix microstructure to varying reinforcement content.

At 5 vol.% SiC (Figure 3a), the reinforcement particles are relatively sparsely distributed but show minimal clustering. The matrix exhibits a predominantly globular microstructure with moderate grain refinement, indicating effective semisolid stirring and partial melting behavior. However, the low particle density may result in limited load transfer efficiency, which could restrict improvements in strength.

In Figure 3b (10 vol.% SiC), the particle dispersion becomes more uniform, and the interparticle distance decreases, contributing to enhanced particle-matrix interfacial bonding. The grain morphology of the aluminum matrix continues to show a refined, near-spherical structure, which is favorable for mechanical isotropy and improved ductility.

The 15 vol.% SiC microstructure (Figure 3c) appears to be optimal, with a highly uniform dispersion of reinforcement particles and minimal signs of agglomeration. This suggests an ideal balance between particle content and matrix fluidity during semisolid processing. The homogeneous reinforcement distribution supports effective stress transfer across the matrix–particle interface, improving composite strength and toughness[47, 48].

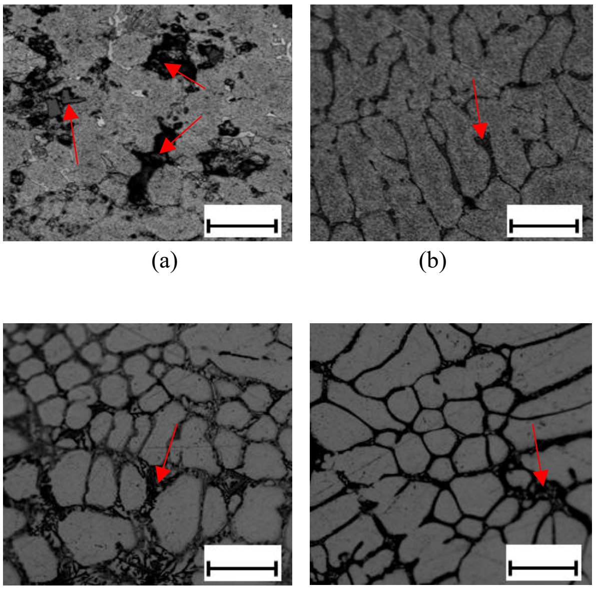
The matrix microstructure in this condition shows the most well-defined globular grains, a hallmark of successful semisolid processing under optimal shear and thermal conditions[49].

At the highest reinforcement level, 20 vol.% SiC (Figure 3d), significant particle agglomeration is evident, particularly at grain boundaries and inter dendritic regions. This clustering may originate from the increased viscosity of the slurry during forming, which inhibits uniform particle dispersion. Agglomerated SiC clusters are detrimental because they introduce stress concentrations and micro voids, which can serve as crack initiation sites under mechanical loading. Additionally, these regions are often associated with entrapped porosity, further compromising the material's structural integrity[50].

The microstructural analysis presented in Figure 3 highlights the critical relationship between SiC volume fraction and microstructural uniformity, with 15 vol.% identified as the most favorable condition for improved mechanical performance. Semisolid forming consistently promotes globular grain morphology in all samples, but its combined effect with optimal particle distribution is most pronounced at the intermediate reinforcement level.

Conversely, metallographic observations indicated a favorable wettability between the SiC particles and the aluminum matrix. This behavior can be ascribed to the addition of Mg during the initial alloying stage, which contributes to a lower contact angle. Magnesium plays a decisive role as a wetting agent by enhancing the driving force for wetting and reducing the interfacial tension between the matrix and the reinforcement. Increasing Mg content further decreases the contact angle, as magnesium is highly reactive and exhibits the lowest surface tension and contact angle compared with Al and SiC. Consequently, its presence is critical during the Al–SiC infiltration process. The aluminum matrix is inherently covered with a stable Al_2O_3 oxide film that hinders direct bonding with SiC. Magnesium mitigates this barrier by reacting with oxygen from aluminum, thereby facilitating stronger interfacial bonding between SiC and aluminum.

In Figure 4(a) and (b) show the microstructures of Al-

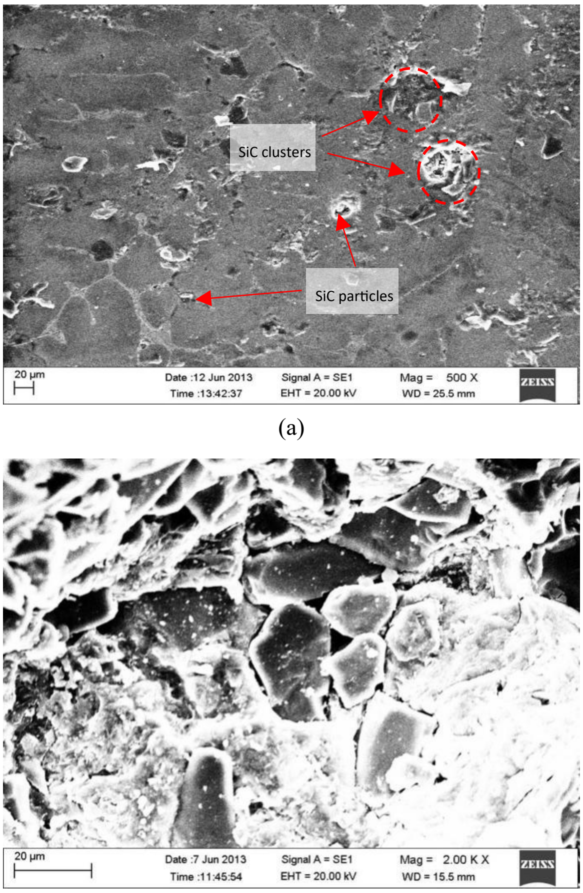

(a) (b)

(c) (d)

Fig. 4: Optical micrographs of MMCs containing different SiC reinforcement contens: (a) As-cast sample with 15 vol.% SiC, showing sparsely distributed particles with minimal clustering; (b) As-cast sample with 20 vol.% SiC, exhibiting improved particle dispersion and reduced interparticle spacing, while the aluminum matrix maintains a refined, near-spherical grain morphology; (c) Thixoformed sample with 15 vol.% SiC, displaying a uniform distribution of reinforcement particles with negligible agglomeration; (d) Thixoformed sample with 20 vol.% SiC, where significant particle clustering is observed, particularly along grain boundaries and interdendritic regions

5%Cu-4%Mg composites containing 15 and 20 vol.% SiC, respectively. Dark irregular regions observed throughout the matrix correspond to former SiC clusters, which appear as pores due to particle detachment during sample preparation. In contrast, the thixoformed composites in Figures 4(c) and (d) exhibit a globular rather than dendritic matrix, reflecting the phase transformation induced under semisolid conditions. The transition from dendritic to globular morphology is governed by heating and holding times, diffusion between liquid and solid phases, and applied deformation sufficient to separate dendrite arms. Residual dendritic features after thixoforming indicate incomplete transformation due to suboptimal processing conditions.

Figure 4(a) illustrates a porous region with a SiC content of 15%. This area exhibits a distinct contrast from its surroundings due to differences in depth, and the image clearly indicates poor SiC particle distribution within the aluminum alloy matrix. The dark regions correspond to localized clusters of SiC, revealing particle agglomeration and a generally low particle count in the surrounding matrix. Such agglomeration is likely driven by particle–particle interactions that promote clustering, as well as by incomplete stirring during processing, which hinders uniform dispersion. Figures 4(a) and 4(b) further demonstrate that only a small fraction of the SiC particles were incorporated into the melt, likely due to the high surface tension of liquid aluminum, which causes many SiC particles to remain at the surface rather than disperse into the bulk during stirring. In contrast, Figures 4(c) and 4(d) show that the subsequent thixoforming process improves particle distribution, resulting in a more uniform dispersion of SiC at the grain boundaries and within the matrix.



(a)

(b)

Fig. 5: (a) A scanning electron microscope (SEM) image of the microstructure of the Al-5%Cu-4%Mg composite with 5 vol.% SiC reinforcement, highlighting the presence of SiC clusters. (b) The accumulation of SiC particles within a specific area

Figure 5(a) presents a scanning electron micrograph (SEM) of the Al-5%Cu-4%Mg/SiC composite at 500× magnification, offering enhanced resolution to assess the microstructural characteristics beyond what is visible in optical micrographs. The image reveals two key microstructural features: the distribution of SiC particles along grain boundaries and the presence of agglomerated clusters in certain regions.

The SiC particles located at grain boundaries play a dual role. On one hand, they act as effective barriers to dislocation motion and can impede grain boundary sliding, thereby increasing the strength and thermal stability of the

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composite. On the other hand, when SiC particles form dense clusters instead of remaining uniformly dispersed, they can introduce stress concentration zones and micro voids, reducing the mechanical integrity of the material. Such inhomogeneities disrupt the load transfer mechanism, limiting the effectiveness of reinforcement and potentially promoting early crack initiation under mechanical loading. Figure 5(b) zooms into a specific region of the composite where a visible accumulation of SiC particles is detected. The particles in this area exhibit a distinct angular morphology with sharp boundaries, indicating minimal wetting or bonding with the surrounding aluminum matrix. This poor interfacial integration can result in weak particle–matrix adhesion, which under applied stress may lead to interfacial decohesion or particle pull-out, both of which are detrimental to strength and fatigue resistance.

To validate the nature of this region, Energy Dispersive Spectroscopy (EDS) was performed, and the results (as shown in Table 2) confirm a high concentration of silicon and carbon, characteristic of silicon carbide (SiC). The elemental mapping further supports the presence of a SiC-rich zone, affirming that the bright angular features seen in the SEM are indeed agglomerated SiC particles.

This localized SiC accumulation represents a microstructural defect, potentially acting as a crack initiation site under tensile loading. The combination of SEM and EDS analyses underscores the importance of uniform reinforcement distribution. While the presence of SiC improves the mechanical performance of the composite when properly dispersed, excessive or poorly distributed reinforcement can negate the benefits, reducing ductility, introducing porosity, and compromising strength. Figure 5 reinforces the notion that processing control during semisolid forming is essential not only for matrix grain refinement but also for achieving a homogenous dispersion of reinforcing particles. The micrographs and corresponding chemical analysis emphasize the critical balance between particle content and distribution, which governs the final mechanical performance and structural reliability of the metal matrix composite.

The EDS results presented in Table 2 reveal the elemental composition observed in the region shown in Figure 5(b). The table indicates a significant presence of silicon and carbon, suggesting a high concentration of SiC particles within the aluminum alloy matrix. This observation confirms the substantial presence of SiC particles in this area. The combination of Scanning Electron Microscopy (SEM) and EDS analyses effectively demonstrates the existence of SiC particles within the matrix and highlights regions of SiC accumulation. These SiC-rich zones are likely to become points of weakness in the Metal Matrix Composite (MMC) under external tensile loads, potentially leading to localized failure.

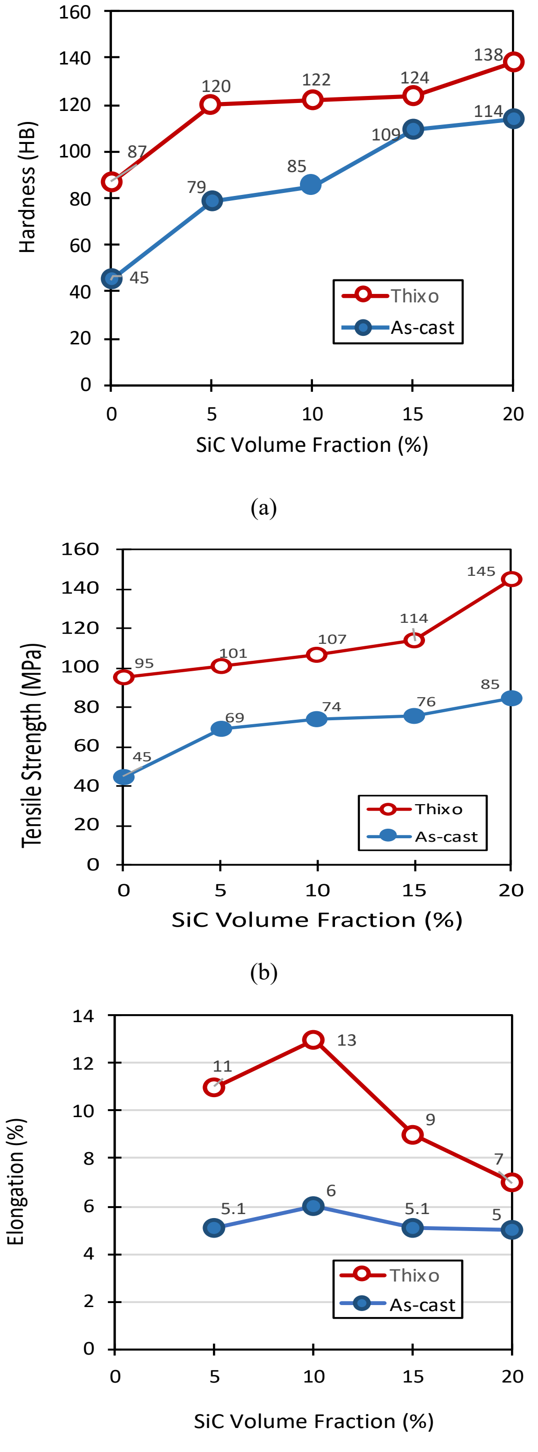
Table 2: EDS observation data within a specific area from Figure5(b)

Element	Unn. C [wt.%]	Norm. C [wt.%]	Atom. C [at.%]
Aluminium	47.70	39.70	39.75
Silicon	27.57	22.95	18.19
Magnesium	15.69	13.06	11.96
Carbon	16.86	14.03	26.00
Oxygen	8.63	7.18	9.99
Copper	2.80	2.33	0.82
Iron	0.88	0.73	0.29

In addition to the distribution of SiC particles, another critical factor influencing the mechanical properties of the composite is the formation of Al-Cu (θ-phase) and Al-Cu-Mg (S-phase, Al_2CuMg) precipitates. These strengthening phases play a significant role in enhancing the mechanical performance of aluminum alloys by impeding dislocation motion. However, their effectiveness depends strongly on their morphology, distribution, and location, which are governed by the applied heat treatment conditions. Ideally, these precipitates should form uniformly within the aluminum matrix grains, where they can most effectively hinder dislocation movement and contribute to strength and hardness. In contrast, precipitation along grain boundaries, often resulting from suboptimal heat treatment, may degrade mechanical properties by promoting intergranular fracture or localized stress concentrations. While the potential role of these precipitates was briefly mentioned in the Introduction, a more detailed analysis was not included in the Results and Discussion. Future studies should incorporate microstructural and compositional analyses (e.g., TEM or high-resolution SEM/EDS) to confirm the presence, type, and distribution of these precipitates and to fully understand their contribution to the observed mechanical behavior.

Figure 6(a) illustrates the hardness measurements of composites processed by semi solid forming, compared to as-cast samples, with SiC reinforcement levels of 15% and 20%. The thixoformed composite with 15% SiC exhibited a hardness of 124 HB, while the as-cast sample with the same SiC content had a hardness of 109 HB. This represents a 13% increase in hardness due to the semi solid forming process. Similarly, for the 20% SiC composites, semi solid forming resulted in a hardness of 138 HB, an increase of 16% from the as-cast sample's hardness of 114 HB. These results indicate that hardness is not only influenced by the SiC particle content but also significantly enhanced by the semi solid forming treatment.

Research by Rosso has demonstrated that semisolid forming aluminum castings transforms the dendritic microstructure into a more refined, globular form, which contributes to improved material properties, including increased hardness[51]. Vencl's studies corroborate this finding, noting that semisolid forming enhances mechanical properties such as wear resistance, which is indicative of increased hardness[52]. Additionally, semisolid



(a)

(b)

(c)

Fig. 6: Effect of semi-solid processing and SiC reinforcement content on the mechanical properties of Al–Cu–Mg/SiC composites: (a) hardness, (b) tensile strength, and (c) elongation

forming can eliminate porosity caused by trapped air, a factor that typically deteriorates material properties by acting as crack initiation sites. Thus, reducing or eliminating porosity through semisolid forming further enhances the material's hardness.

The hardness data from the experiments suggest that the composite hardness increases by 5% with the SiC reinforcement content rising from 15% to 20%. Furthermore, the semisolid forming process enhances hardness by 13% for the 15% SiC composite and by 16% for the 20% SiC composite, compared to their as-cast counterparts. This improvement in hardness is attributed to both the refinement of the microstructural features and the reduction of porosity achieved through semisolid forming. Figure 6(b) presents a graph of tensile strength versus SiC content for as-cast and thixoformed conditions. The semisolid forming process results in a notable increase in tensile strength compared to as-cast samples. This enhancement in tensile strength is linked to the transformation of the matrix grain structure from dendritic to globular. The graph also indicates that both hardness and tensile strength of MMCs generally improve with higher SiC reinforcement levels, though the changes are not always significant. The limited increase in tensile strength and hardness with higher SiC content may be attributed to the uneven distribution of reinforcement particles in the matrix, as evidenced by the microstructural analysis.

The elongation data depicted in Figure 6(c) reveal a marked enhancement in ductility following the semisolid forming process, particularly for aluminum composites containing a 5% to 10% volume fraction of SiC reinforcement. This significant improvement in ductility underscores the composite's excellent formability, indicating its suitability for a wide range of manufacturing applications that require high deformability. The optimized distribution of SiC particles within this specific range likely facilitates uniform plastic deformation, thereby contributing to the observed increase in elongation. However, a different trend emerges for composites with higher reinforcement levels, specifically those with 15% and 20% volume fractions of SiC. In these cases, the elongation values exhibit a noticeable decline, which can be primarily attributed to the agglomeration of SiC particles into larger clusters. These clusters act as sites of stress concentration, impeding the material's ability to deform plastically under load. The presence of such agglomerates disrupts the otherwise uniform microstructure, leading to a reduction in ductility. This phenomenon highlights the critical need for controlling the distribution of reinforcement particles to maintain the mechanical integrity of the composite, particularly in applications requiring both strength and ductility.

The semisolid forming process has been shown to significantly enhance the tensile strength of AI-5%Cu-4%Mg/SiC composites when compared to their pre-processed condition. Notably, in the absence of reinforcement particles, the tensile strength of the composite increases from 45 MPa to 95 MPa following semisolid forming. This substantial improvement is further amplified as the volume fraction of SiC particles increases from 5% to 20%. The observed increase in both hardness and tensile strength of the aluminum matrix composites can be largely attributed to the evolution of the microstructure induced by the semisolid forming process. Specifically, this process facilitates the transformation of the microstructure into a more globular and finer grain structure, which is crucial for enhancing the material's mechanical properties.

The improved ductility observed in the aluminum composite after semisolid forming, particularly with 5-10% SiC reinforcement, is another key benefit. The optimum distribution of reinforcing particles decreases stress concentrations and improves the material's ability to withstand plastic deformation. However, when the SiC content is increased to 15-20%, a decrease in ductility is observed. This reduction is primarily due to the formation of clusters at higher reinforcement levels, which create localized stress points that hinder uniform plastic deformation and promote early fracture.

While the semisolid forming process effectively enhances strength and ductility in aluminum composites with lower SiC content, care must be taken when increasing the reinforcement fraction to avoid detrimental effects on ductility. The findings emphasize the importance of microstructural control in optimizing the mechanical performance of these composites for various industrial applications.

Furthermore, the increase in composite strength with higher SiC content may also be influenced by the presence of magnesium (Mg) in the matrix. Magnesium plays a vital role in improving the wettability at the interface, potentially by promoting the formation of eutectic SiC phases. This interaction strengthens the composite by enhancing the overall cohesion and load transfer between the matrix and the reinforcement. As a result, the combination of microstructural refinement and effective interfacial bonding mechanisms contributes to the superior mechanical performance of semisolid-formed AI-5%Cu-4%Mg/SiC composites.

4. Conclusions

Semisolid forming, combined with controlled SiC reinforcement and magnesium-modified aluminum matrices, has been shown to markedly enhance the mechanical performance of Al-5%Cu-4%Mg/SiC composites. Microstructural refinement into fine, globular grains increased tensile strength from 45 MPa to 95 MPa, with additional improvements observed at higher SiC contents. Optimal strength–ductility balance was achieved at 5–10% SiC, while excessive reinforcement (15–20%) reduced ductility due to particle clustering. The role of magnesium in strengthening interfacial bonding highlights the influence of alloy chemistry on matrix–reinforcement interactions.

These findings provide a clear framework for the development of lightweight structural materials requiring high strength, durability, and formability. If microstructure and reinforcement distribution can be further optimized, the approach may offer broader applicability for the design of structural components intended for demanding service conditions. Future work should address fatigue performance under cyclic loading, evaluate process scalability for industrial production, and conduct component-level validation under service-representative environments to bridge the gap between laboratory results and engineering application.

The effect of SiC reinforcement particle addition on the improvement of mechanical properties of Al-Cu-Mg matrix after as-cast and semi-solid process compared to Al-Cu-Mg matrix without SiC particle is shown in Figure 6(a) for hardness and 6(b) for tensile strength. This improvement in mechanical properties indicates that SiC particle has functioned as reinforcement supported by magnesium, which improves the wetting properties of SiC particle in the matrix. The effect of SiC addition to the matrix is quite significant, both as-cast and post-semi-solid matrix material.

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References

1) K. Kirman, H. A. Suhartono, O. Ivano, and Y. Irawadi, “Enhancing Aluminum Alloys for High-Strength Electrical Conductor with Nanoparticle Reinforcement,” Evergreen, vol. 11, no. 3, pp. 2720–2727, 2024, doi: 10.5109/7236911.
2) K. C. Anil, Kumaraswamy, M. Reddy, and K. M. Mamatha, “Air Jet Erosion studies on Aluminum - Red Mud Composites using Taguchi Design,” Evergreen, vol. 10, no. 1, pp. 130–138, 2023, doi: 10.5109/6781059.
3) R. Kumar and K. N. Bairwa, “Optimizing Al6061-Based Hybrid Metal Matrix Composites: Unveiling Microstructural Transformations and Enhancing Mechanical Properties Through Ni and Cr Reinforcements,” Evergreen, vol. 10, no. 4, pp. 2161–2172, 2023, doi: 10.5109/7160891.
4) S. Sarker, M.S. Haque, M.S. Haque, M.S.A. Alvy, and M.M.H. Abir, “The Effects of Solution Heat Treatment on the Microstructure and Hardness of an Aluminum-4% Copper Alloy with Added Nickel and Tin”, Journal of Alloys and Metallurgical Systems, Vol. 4(15):100042, 2023, doi/ 10.1016/j.jalmes.2023.100042

5) R.X. Li, R.D. Li, Y.H. Zhao, L.Z. He, C.X. Li, H.R. Guan, and Z.Q. Hu, “Age-hardening behavior of cast Al–Si base alloy“, Mater. Lett. 58 (15), pp. 2096–2101, 2004, https://doi.org/10.1016/j.matlet.2003.12.027

6) A. Mohammadi, N.A. Enikeev, M.Yu Murashkin, M. Arita, and K. Edalati, “Developingage-hardenable Al-Zr alloy by ultra-severe plastic deformation: significance of supersaturation, segregation and precipitation on hardening and electrical conductivity“, Acta Materialia, Vol. 203, 2021. https://doi.org/10.1016/j.actamat.2020.116503

7) Hashim, J., Looney, L., & Hashmi, M. S. J. (1999). Metal matrix composites: Production by the stir casting method. Journal of Materials Processing Technology, 92–93, 1–7. https://doi.org/10.1016/S0924-0136(99)00118-1

8) K. Chen, L. Zhan, and W. Yu, “Rapidly modifying microstructure and mechanical properties of AA7150 Al alloy processed with electro pulsing treatment“, J. Mater.Sci. Technol, Vol. 95, pp.172–179, 2021. https://doi.org/10.1016/j.jmst.2021.03.060

9) M. Eddahbi, J.A. Jim´enez, and O.A. Ruano, “Microstructure and creep behaviour of an Osprey processed and extruded Al-Cu-Mg-Ti-Ag alloy“, J. Alloy. Compd. Vol. 433, issues 1–2, pp. 97–107, 2007. https://doi.org/10.1016/j.jallcom.2006.06.031

10) R.N. Lumley and I.J. Polmear, “The effect of long term creep exposure on the microstructure and properties of an underaged Al-Cu-Mg-Ag alloy“, Scr. Mater. Vol. 50, issues 9, pp. 1227–1231, 2004. https://doi.org/10.1016/j.scriptamat.2004.02.001

11) D.K. Koli, G. Agnihotri, and R. Purohit, “Properties and Characterization of Al-Al2O3 Composites Processed by Casting and Powder Metallurgy Routes (Review)”, International Journal of Latest Trends in Engineering and Technology, Vol.2, pp. 486-496, 2012

12) M. Rahimian and N. Parvin,“The Characteristics of Alumina Particle Reinforced Pure Al Matrix Composite”, Acta Physica Polonica A, Vol. 121, 108-110.

13) G. O. Shah and G. Arora, “Analyzing Thermal Conductivity of Composites through Different Theoretical Frameworks,” Evergreen, vol. 11, no. 3, pp. 1740–1752, 2024, doi: 10.5109/7236826.

14) Kainer, K. U. (Ed.). (2006). Metal matrix composites: Custom-made materials for automotive and aerospace engineering. Wiley-VCH. https://doi.org/10.1002/3527608117

15) Hasan, L.K.; Jiaad, S.M.; Salman, K.D.; Al-Maliki, W.A.K.; Alobaid, F.; Epple, B. Wear Characteristics of (Al/B4C and Al/TiC) Nanocomposites Synthesized via Powder Metallurgy Method. Appl. Sci. 2023, 13, 12939. https://doi.org/10.3390/app132312939

16) H. Mohamed Ibrahim Al-Zuhairi and S. A. Amin, “Manufacturing of hybrid aluminum MMCs reinforced with SiC and Al_2O_3: A review,” Rafidain J. Eng. Sci., vol. 3, no. 1, pp. 450–473, Mar. 2025, doi:10.61268/eqmby745

17) S. Karaman Genc and N. Urkmez Taskin, “New processing route for the production of functionally graded 7075 Al/SiCp composites via a combination of semisolid stirring and sequential squeeze casting,” Crystals, vol. 14, no. 4, p. 297, 2024. MDPI

18) Christy, J.V., Ramanathan, A., Arunachalam, Mourad, A.H.I., Krishnan, P.K., Piya, S. Al-Maharbi, M., “Processing, Properties, and Microstructure of Recycled Aluminum Alloy Composites Produced Through an Optimized Stir and Squeeze Casting Processes.” Journal of Manufacturing Processes, 59, 287-301(2020). https://doi.org/10.1016/j.jmapro.2020.09.067

19) M. M. Khaled, M. E. Moussa, M. I. Negm, and R. A. Al Kady, “A semisolid fabrication technique of Al 7075 metal matrix composites enhanced with alumina,” J. Al-Azhar Univ. Eng. Sect., vol. 19, no. 72, 2024. ResearchGate

20) Mohammad M. Khaled, M. E. MoussaMazen I. Ramy A. Al Kady, A SEMI-SOLID FABRICATION TECHNIQUE OF AL 7075 METAL MATRIX COMPOSITES ENHANCED WITH ALUMINA, Journal of Al-Azhar University Engineering Sector 19(72):131-146, July 2024 DOI: 10.21608/auej.2024.257021.1544

21) S. Aghajani, V. Pouyafar., R. Meshkabadi, “Mechanical characterization of high volume fraction Al7075-Al_2O_3 composite fabricated by semisolid powder processing,” Int. J. Adv. Manuf. Technol., 2023. SpringerLink

22) J. Jiang; Y. Wang, S. Luo, “Research on fabrication and semisolid processing of semisolid slurries of 7075 aluminum matrix composites reinforced with nano-sized SiC particles,” Sci. Netw.—details retrieved via Scientific.Net. scientific.net

23) J. Jiang, G. Xiao;, C. Che; Y. Wang, “Microstructure, mechanical properties and wear behavior of the rheoformed 2024 aluminum matrix composite component reinforced by Al_2O_3 nanoparticles,” Metals (MDPI), 2018. MDPI

24) M. Wenzelburger, M. Silber , R. Gadow , “Manufacturing of light metal matrix composites by combined thermal spray and semisolid forming process – summary of the current state of technology,” Scientific.Net, 2020. scientific.net

25) Alem, S.A.A., Sabzvand, M.H., Govahi, P. et al. Advancing the next generation of high-performance metal matrix composites through metal particle reinforcement. Adv Compos Hybrid Mater 8, 3

(2025). https://doi.org/10.1007/s42114-024-01057-4

26) Zhang, M., Ma, D., Wang, J., Dai, S., Xue, Y., & Zhu, L. (2025). Enhancing interfacial bonding in metal matrix composites: challenges, methods, and future prospects. Critical Reviews in Solid State and Materials Sciences, 1–54. https://doi.org/10.1080/10408436.2025.2542367

27) Abd Baghad, M., & El Mabrouk, K. (2023). Additive manufacturing of lightweight metal matrix composites: A review. Johnson Matthey Technology Review, 67(2), 133–150. https://doi.org/10.1595/205651323X16601431334489

28) Titus Thankachan, K. Soorya Prakash, V. Kavimani, Wenbin Zhou, The effect of friction stir processing on mechanical, wear and corrosion characteristics of Cu-AlN-BN surface composite, Heliyon, Volume 10, Issue 9, 2024, e30173, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2024.e30173.

29) B. Bhati, A. Rath, K. Bector, S. Ahmad, and R. M. Singari, “Recent Developments in the use of Composites for Knee Cap Prosthetics,” Evergreen, vol. 10, no. 2, pp. 1084–1093, 2023, doi: 10.5109/6793667.

30) M. Sekar, R. Thanigaivelan, V. Rangasami, and P. Elumalai, “Experimental investigation of MRR and ROC in aluminium metal matrix composites“, Materials Today: Proceedings 45, pp.1102–1106, 2021. DOI: 10.1016/j.matpr.2020.03.190

31) B. Stojanovic and L. Ivanovic, “Application of aluminium hybrid composites in automotive industry“, Tehnicki Vjesnik. Vol. 22, pp. 247-251, 2015. DOI: 10.17559/TV-20130905094303

32) N. Chawla and K.K. Chawla, “Metal-Matrix Composites in Ground Transportation”. Journal of Metals, Vol. 58, No. 11, pp. 67-70, 2006

33) W. H. Hunt and D. B. Miracle, “Automotive Applications of Metal-Matrix Composites”, in: Miracle, D. B.; Donaldson, S. L. (Ed.), ASM Handbook, Volume 21: Composites, ASM International, pp.1029-1032, 2001.

34) T. Donomoto, K. Funatani, N. Miura, and N. Miyake, “Ceramic Fiber Reinforced Piston for High Performance Diesel Engines”, SAE Technical Paper // 830252, 1983.

35) D. B. Miracle, “Metal matrix composites” – From science to technological significance, Composites Science and Technology. Vol. 65, 15-16, pp. 2526-2540, 2005.

36) M.A. Mehedi, “Aluminium matrix composites in automotive application”, International Journal for Industry, Research and Application. 7-8, pp. 55-58, 2011.

37) A. Daoud and M.T. El-khair, “Wear and friction behaviour of sand cast brake rotor made of A359-20 vol. % SiC particle composites sliding against automobile friction material”, Tribology International. Vol. 43, No. 3, pp. 544-553, 2010.

38) J. Chen, Z. Huang, and M. Wu, “Tailoring microstructure and properties of Al–Cu–Mg/SiC composites via semisolid processing,” Journal of Alloys and Compounds, vol. 950, p. 170934, 2024.

39) R. Sharma and P. Kumar, “Influence of Mg addition on wettability and bonding in Al-SiC composites,” Materials Characterization, vol. 200, p. 112883, 2023.

40) P. Zhang, L. Wang, and X. Liu, “Advances in aluminum matrix composites for lightweight applications: Processing and properties,” Journal of Materials Science & Technology, vol. 122, pp. 44–59, 2022.

41) J.D.R. Selvam, I. Dinaharan, and R.S.Rai, “Matrix and Reinforcement Materials for Metal Matrix Composites“, In book: Encyclopedia of materials: Composites, Publisher: Elsevier, 2020, DOI: 10.1016/B978-0-12-803581-8.11890-9

42) A. Zulfia, F. Robby, K. Kirman, and A. Sukarto. “Characteristic of Al-0.12Zr-0.15Ce reinforced by Al2O3np as composites conductor”, International Journal of Technology, Vol. 7(3), pp. 383-391, 2016. DOI : 10.14716/ijtech.v7i3.2866

43) A.V. Adedayo, “Development Process of Globular Microstructure”, Journal of Minerals and Materials Characterization and Engineering, vol. 10(7), pp. 651-659, 2011.

44) Y. Afandi and B. Adjiantoro, “Fabrication of MMCs Alloy A1-4.5%Cu-4%Mg/SiC(p) by Forging Process”, Proceeding of Quality in Research (QtR), pp. 1355-1361, 2011.

45) M.A. Gebril, M.Z. Omar, I.F. Mohamed, N.K. Othman, D.M. Elabar, F.I. Haider, S. Samat, and O.M. Irfan, “Effect of Semisolid and Heat Treatment Process on Microstructural Refinement of Al–7Si Alloy“, Materials, Vol. 16(3), 1086; 2023. https://doi.org/10.3390/ma16031086

46) P.N. Bindumadhavan, T.K. Chia, M. Chandrasekan, H.K. Wah, L.N. Lam, and O. Prabhakar, “Effect of Particle-Porosity on Tribological Behavior of Cast Aluminum alloy A356-SiCp Metal Matrix Composite”, Material Seience and Engineering A, Vol. 315, pp. 217- 226, 2001.

47) N.F.B.W. Anuar, M.Z. Omar, M.S. Salleh, W.F. Hakim, W. Zamri, and A.M. Ali, “Effect of Short Heat Treatments on the Microstructural Evolution and Hardness of Thixoformed Graphene Reinforced Aluminium Composites”, Sains Malaysiana 53(3): pp. 705-717, 2024. http://doi.org/10.17576/jsm-2024-5303-17

48) I. Ozedmir, S. Muecklich, H. Podlesak, and B. Wielage, B. (2011). Thixoforming of AA 20l7 Aluminum Alloy Composites. Journal of Materials

Processing Technology, vol. 211, 1260-1267, 2011, 10.1016/j.jmatprotec.2011.02.008

49) M. Rosso, “Thixoforming and Rheocasting Technologies, Improvement Going on”. Journal of achievement in Materials and Manufacturing Engineering, Vol. 54, pp. 110-119, 2012.
50) D. Liu and H.V. Atkinson, “Microstructural Evolution and Tensile Mechanical Properties of Thixoformed High Performance Aluminum Alloys”, Material Science and Engineering A, Vol. 361, pp.213-224, 2003.
51) A.Vencl, I. Bobic, and Z. Miskovic, “Effect of thixoforming and Heat Treatment on Tribological Properties of Hypoeutectoid Al-Si Alloy”, Wear, Vol. 264, pp.616-623, 2008.
52) H. Mayer, M. Papakyriacou, B. Zettl, and S.E. Stanzl-Tschegg, “Influence of Porosity on the fatigue limit of Die Cash Magnesium and Aluminum Alloys”, International Journal of Fatigue, Vol. 25, pp. 245-256, 2025.

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