

Deep Cryogenic Treatment of Copper Chill Plates in Stir Casting of Al6061-Silicon Carbide Composites

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Abstract

Aluminum-Silicon Carbide Metal Matrix Composites (Al/SiC MMCs) represent advanced materials created through the integration of aluminum matrices with silicon carbide particle reinforcement. These composites demonstrate superior characteristics compared to conventional aluminum alloys, establishing their relevance across diverse engineering applications. This experimental investigation focuses on developing composites using aluminum as the base matrix while incorporating SiC particles (40-50µm particle size) as reinforcing agents. The reinforcement content was systematically varied from 3 to 12 weight percent in incremental steps of 3 weight percent. Composite fabrication utilized sand mold casting techniques incorporating specialized chill blocks, including Deep Cryogenic Treatment (DCT) processed copper and standard copper alternatives, with subsequent evaluation of resulting material characteristics. Experimental findings revealed that Al/SiC composites achieved maximum tensile strength when produced using DCT copper chill blocks, whereas specimens manufactured with conventional copper chills exhibited reduced strength values. Enhanced thermal conductivity properties of the chill plates directly correlate with improved strength characteristics. Additionally, increased composite hardness contributes to superior tensile strength through the development of refined grain structures during rapid solidification processes. Microstructural analysis conclusively demonstrated that specimens produced using DCT-copper chill plates exhibited significantly refined grain structures, while those manufactured with conventional copper chills displayed notably coarser grain formations. Comparative microstructural examination confirmed that DCT-copper chills produce substantially finer grain sizes compared to conventional copper chills, which generate coarser grain structures.

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INTRODUCTION

Metal matrix composites incorporating aluminum bases have established widespread industrial applications spanning aerospace, automotive, and structural engineering sectors [1]. Despite their extensive utilization, aluminum-based composites face several constraints in secondary forming processes that limit their application expansion. These limitations primarily stem from the anisotropic characteristics inherent in composite materials. Aluminum-alloy matrix composites (AMCs) reinforced with hard dispersion particles are gaining increased industrial significance due to their superior combination of physical, mechanical,

and tribological properties compared to base alloys [2]. Consequently, these composites find applications in numerous automotive and technical components where wear resistance, durability, and seizure prevention are critical considerations, while also providing weight reduction benefits.

Powder metallurgy processes present considerable disadvantages, including complex fabrication procedures and intensive material handling requirements, resulting in higher production costs compared to conventional casting methods [3]. Additionally, reduced interfacial contact between reinforcing particles and matrix materials may occur due to ceramic particle fracture during powder blending operations. Cryogenic treatment principles are founded on metallurgical concepts related to phase transformations and microstructural modifications occurring in metals subjected to extremely low temperatures [4]. At cryogenic conditions, atomic mobility within metal lattices decreases significantly, facilitating atomic structure rearrangement and phase stabilization. This process results in microstructure refinement, residual stress reduction, and enhanced mechanical properties [5].

The stir casting technique, also known as the vortex method, represents the most fundamental and widely adopted approach for composite fabrication. This method involves introducing pre-treated ceramic particles into molten alloy vortexes created by rotating impellers. Numerous aluminum manufacturers have refined and modified this procedure for large-scale AMC production. Microstructural inhomogeneities during melting and subsequent solidification can lead to particle agglomeration and sedimentation [6]. Inhomogeneity in reinforcement distribution within cast composites may also result from interactions between moving solid-liquid interfaces and suspended ceramic particles during solidification [7].

LITERATURE REVIEW

Previous research has demonstrated the effectiveness of stir casting methods for manufacturing MMCs using Aluminum 2024 matrices with beryl particle reinforcement, utilizing stirring speeds of 350 rpm for 8-minute durations. Investigations have shown uniform particle distribution throughout matrix materials with systematic variation of reinforcement percentages. Studies examining tribological properties of MMCs have incorporated aluminum alloys with alumina and graphite reinforcements. Research indicates that stir casting provides economical and efficient liquid processing technology for fabricating particle and discontinuous fiber-reinforced composites. Magnesium serves as an effective wetting agent to enhance interfacial bonding between matrix materials and hard reinforcement particles [8].

Performance evaluations of stir cast Al_2O_3 and SiC reinforced aluminum metal matrix composites have demonstrated improved physical and mechanical properties, including enhanced hardness and ultimate tensile strength increases of 23.68 percent [9]. These composite materials show potential for automotive applications as lightweight alternatives. Experimental observations indicate that aluminum composites reinforced with Al_2O_3 exhibit lower wear rates compared to SiC-reinforced compositions [10]. The majority of MMC research focuses on aluminum alloy matrix phases, with combinations of ductility, lightweight characteristics, corrosion resistance, environmental stability, and useful mechanical properties showing promise [11].

Aluminum 6061 represents a widely utilized aerospace and transportation alloy recognized for strength, corrosion resistance, and durability characteristics. This aluminum-silicon-magnesium alloy is considered among the most versatile aluminum alloys available for diverse applications [12]. Silicon carbide, as a ceramic material, has gained attention for various applications due to exceptional properties including high hardness, strength, and thermal stability. Recent developments have incorporated silicon carbide as reinforcement material in aluminum matrix composites to enhance mechanical properties [13]. Several studies have explored the properties and applications of natural fibers in polymer composites, highlighting their potential as sustainable and eco-friendly alternatives to synthetic materials.

Almeshaal et al. conducted a detailed physico-chemical characterization of *Grewia Monticola* Sond (GMS) fibers. Their study examined the morphological, chemical, and thermal properties of GMS fibers to evaluate their suitability as fillers in polymer composites. The findings contribute to a better understanding of plant-based fibers as viable reinforcements in biocomposite materials, emphasizing their structural and property attributes [14]. Padmanabhan et al. provided a comprehensive review on the integration of machine learning (ML) techniques in the study of natural fiber composites (NFCs). The authors discussed various ML methodologies employed in designing, optimizing, and characterizing natural fiber-reinforced composites. Their review highlighted both the opportunities and challenges of leveraging ML to accelerate materials research and enhance composite performance [15].

Palaniappan et al. presented an extensive overview of recent advancements in natural fiber composites, focusing particularly on the optimization of mechanical properties and processing technologies. The review emphasized the benefits of natural fiber composites compared to traditional synthetic counterparts, discussing sustainability, biodegradability, and reduced environmental impact as key advantages [16]. In another work, Palaniappan et al. explored the chemical characterization and performance enhancement of *Hibiscus Rosa-Sinensis* (HRS) plant fibers for composite reinforcement. Different chemical treatments such as Sodium Hydroxide, Potassium Permanganate, and Acetic Acid were applied to improve fiber purity, crystallinity, and thermal stability. Advanced analytical methods including X-ray diffraction (XRD), gravimetric analysis, and Soxhlet extraction were utilized for comprehensive compositional analysis [17]. Goutham et al. reviewed the mechanical and wear performance of natural fiber-reinforced composites. Their study underscored how the incorporation of natural fibers into polymer matrices yields composites that are sustainable, lightweight, and exhibit improved mechanical properties such as tensile strength, flexural strength, and impact resistance [18].

A review of a host of relevant literature on the composites leads to some important observations on the gap that prevails for developing the composite with increased strength to weight ratio, improved mechanical properties and reduced wear rate with the addition of SiC dispersion for the Al based alloy. The process of uniting different materials together opens up the opportunity to various researchers to develop new kind of materials that suits for several applications [19]. The research was conducted to fabricate the composite comprising of Al as the matrix and SiC particles as the reinforcement (size 40-50 μm). The reinforcement being supplemented varies starting from 3 to 12 wt. % in step-ladders of 3 wt. %. The resultant composite was cast in sand mould patterns comprising chill blocks (DCT Copper and regular copper) remained verified for their material properties [20].

1. To investigate the sand-portrayed Al6061-SiC composites via Deep-Cryo treatment copper chills.
2. To prepare the mold boxes with DCT chills and without DCT chills for to produce the Al-SiC composites.
3. To prepare sand sand-portrayed Al6061-SiC composites for different percentage of SiC by using stir casting process.
4. To understand the behaviour of mechanical and metallographic study as per the ASTM standards.

MATERIALS AND METHODOLOGY

Al6061 Alloy Matrix

Pure aluminum and certain aluminum alloys are characterized by extremely low strength and hardness values. Aluminum possesses a density of only 2.7 g/cm³, approximately one-third that of steel (7.83 g/cm³), copper (8.93 g/cm³), or brass (8.53 g/cm³) [16]. The material exhibits excellent corrosion resistance in most environments including atmospheric conditions, water systems (including saltwater), petrochemicals, and various chemical systems. Aluminum surfaces demonstrate high reflectivity properties, efficiently reflecting radiant energy, visible light, radiant heat, and electromagnetic waves. Type 6061 aluminum represents one of the most frequently utilized aluminum alloys, suitable for numerous general-purpose applications due to excellent weldability and formability characteristics [21-23]. This alloy proves particularly valuable for architectural, structural, and automotive applications due to high strength and corrosion resistance properties.

Table 1. Chemical composition of copper chill plate.

Elements	Cu	Zn	Sn	Pb	Fe	Si
%	96	3.5	0.03	0.04	0.18	0.28

Silicon Carbide Reinforcement

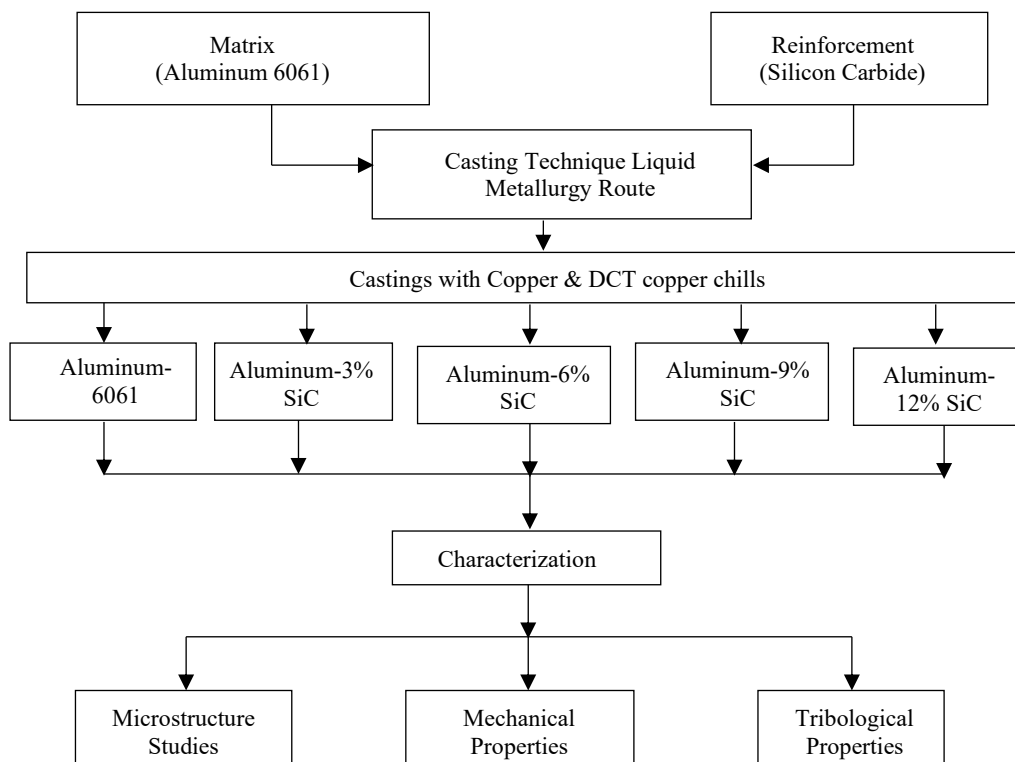
Silicon carbide (SiC) represents a ceramic material widely employed as reinforcement in Metal Matrix Composites as shown in Figure 1. These advanced materials consist of metal matrices reinforced with secondary phases, typically ceramics or fibers. SiC offers several advantageous properties making it a preferred choice for MMC reinforcement applications. When incorporated into MMCs, SiC particles or fibers contribute to improved tensile strength, compression strength, and wear resistance. The material exhibits excellent thermal stability, withstanding elevated temperatures without significant degradation. This property makes SiC-reinforced MMCs suitable for applications requiring thermal resistance, including aerospace components, automotive parts, and high-temperature machinery [24].

Despite high strength and hardness characteristics, SiC maintains relatively low density compared to metals, resulting in lightweight MMCs with high specific strength and stiffness [25].

This combination makes SiC-reinforced MMCs attractive for weight-critical applications in aerospace and automotive industries. SiC demonstrates chemical inertness and resistance to corrosion, oxidation, and chemical attack, even in harsh environments. This property enhances durability and longevity of SiC-reinforced MMCs, making them suitable for corrosive and aggressive operating conditions [26].

Copper Chill Plate Configuration

External chills serve the purpose of controlling solidification rates during casting processes. External chills need not consist of identical materials to casting components since fusion must be prevented. This investigation utilized copper chills with Deep Cryogenic Treatment (DCT) at -196°C and standard copper chill plates, selected based on their varying thermal conductivity properties.

**Figure 1.** Pattern of matrix, reinforcement, and variation of composite compositions.

Chemical composition analysis of copper chill materials was conducted at Geological and Metallurgical Laboratories in Bangalore. Deep Cryogenic Treatment was performed on copper chills using liquid nitrogen at Cryoteknics and Systems in Hosur, Bangalore. The treatment process lasted 48 hours with temperatures maintained at -196°C [27].

Stir Casting Process

Standard sand molds were prepared for casting by positioning chill plates on four sides with remaining surfaces utilizing green sand casting processes. Lower thermal conductivity and increased thickness of insulating sand create adiabatic boundary conditions on sand sides, while high conductivity chill plates permit heat extraction exclusively through plate surfaces. To prevent molten metal leakage from joints, edges were sealed using DYCOTE 140 ceramic paste [28]. Sprues and risers were incorporated on the cope side of mold boxes, with final cavity dimensions of $200\text{mm} \times 200\text{mm} \times 25\text{mm}$.

The experiment utilized commercially available Aluminum 6061 and silicon carbide particles (105 microns) as base metal and reinforcement materials, respectively. An electrical resistance furnace was employed for aluminum melting. Following matrix melting, a stirrer created fine vortexes ensuring proper mixing as depicted in Figure 2.

Degassing tablets composed of solid hexachloroethane (C_2Cl_6) were added to vortexes for impurity removal, with slag elimination from molten metal [30-32]. Preheated SiC particles were introduced into vortexes at 725°C , followed by mechanical stirring at 150 rpm for 15 minutes. K_2TiF_6 wetting agent enhanced SiC wettability during melt addition. Prior to pouring molten metal into molds, cover flux consisting of NaCl (45%), KCl (45%), and NaF (10%) was added to minimize atmospheric contamination [33].

Temperature Measurement and Data Acquisition

K-type chromel-alumel thermocouples with 0.3mm wire diameter enclosed in stainless steel sheaths with MgO insulation were utilized for temperature measurement. Final thermocouple diameter with insulation measured 1.5mm. Mineral insulated K-type thermocouples were inserted into mold cavity centers to measure time-temperature histories during pouring and subsequent solidification. Agilent 34972A Data Acquisition Instruments recorded time-temperature histories, configured with 16-channel relay multiplexers offering $6\frac{1}{2}$ digits of resolution and 0.004% accuracy [34-36].

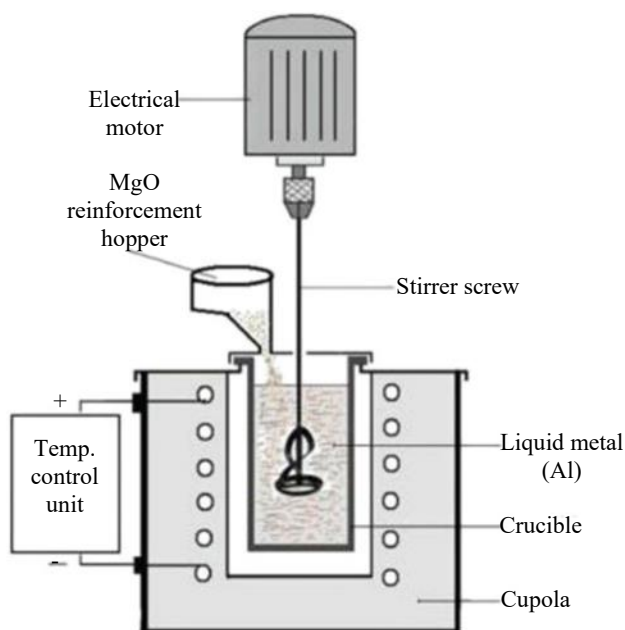


Figure 2. Stir-die casting process [29].

RESULTS AND DISCUSSION

This investigation focused on fabricating composites utilizing aluminum matrices with SiC particle reinforcement (40-50 μ m particle size). Reinforcement content varied from 3 to 12 weight percent in systematic 3 weight percent increments. Resulting composites were cast in sand mold patterns incorporating chill blocks (DCT Copper and regular copper) with subsequent material property verification [37].

Microstructural Analysis

Microstructural examination revealed that coarse grains developed in specimens cast with conventional copper chills, while fine grains were observed in specimens produced using DCT-copper chill plates shown in Figure 3 and Figure 4. Comparative microstructural analysis of copper chill plate sides indicated that DCT-copper chills generate significantly finer grain sizes whereas conventional copper chills produce coarser grain structures [38-40].

This phenomenon can be attributed to enhanced chilling effects induced during casting processes. The thermal conductivity of DCT-copper (401 W/m·K) significantly exceeds that of conventional copper (390 W/m·K), leading to higher cooling rates in proximate regions. Elevated cooling rates result in fine grain structures, while lower thermal conductivity of conventional copper produces slower cooling rates, generating coarse and medium grain structures [41].

Tensile Strength and Elongation Properties

Computerized Universal Testing Machine (UTM) equipment was utilized for conducting tensile strength tests on aluminum specimens and composites. Ultimate tensile strength (UTS) of discontinuously reinforced composites is influenced by several complex and interrelated factors including particle distribution and quantity within matrices, mechanical and physical properties of both matrix and reinforcing particles, and interfacial bonding characteristics as shown in Figure 5.

Various strengthening mechanisms have been proposed to explain improved strength in discontinuously reinforced metal matrix composites. Average values from five measurements were plotted to observe result variations. Results indicate that in Al-SiC composites, ultimate tensile strength increases monotonically with increased particulate content, attributed to increased bonding area at interfacial regions between matrix and reinforcement materials.

Research has consistently reported that ceramic particle additions to aluminum alloys improve strength, wear resistance, and hardness characteristics. Tensile strength test results demonstrate that Al-SiC composites produced through DCT-copper chill casting exhibit superior strength compared to pure aluminum cast with regular copper chills.



Figure 3. Schematic block of Al6061 alloys.



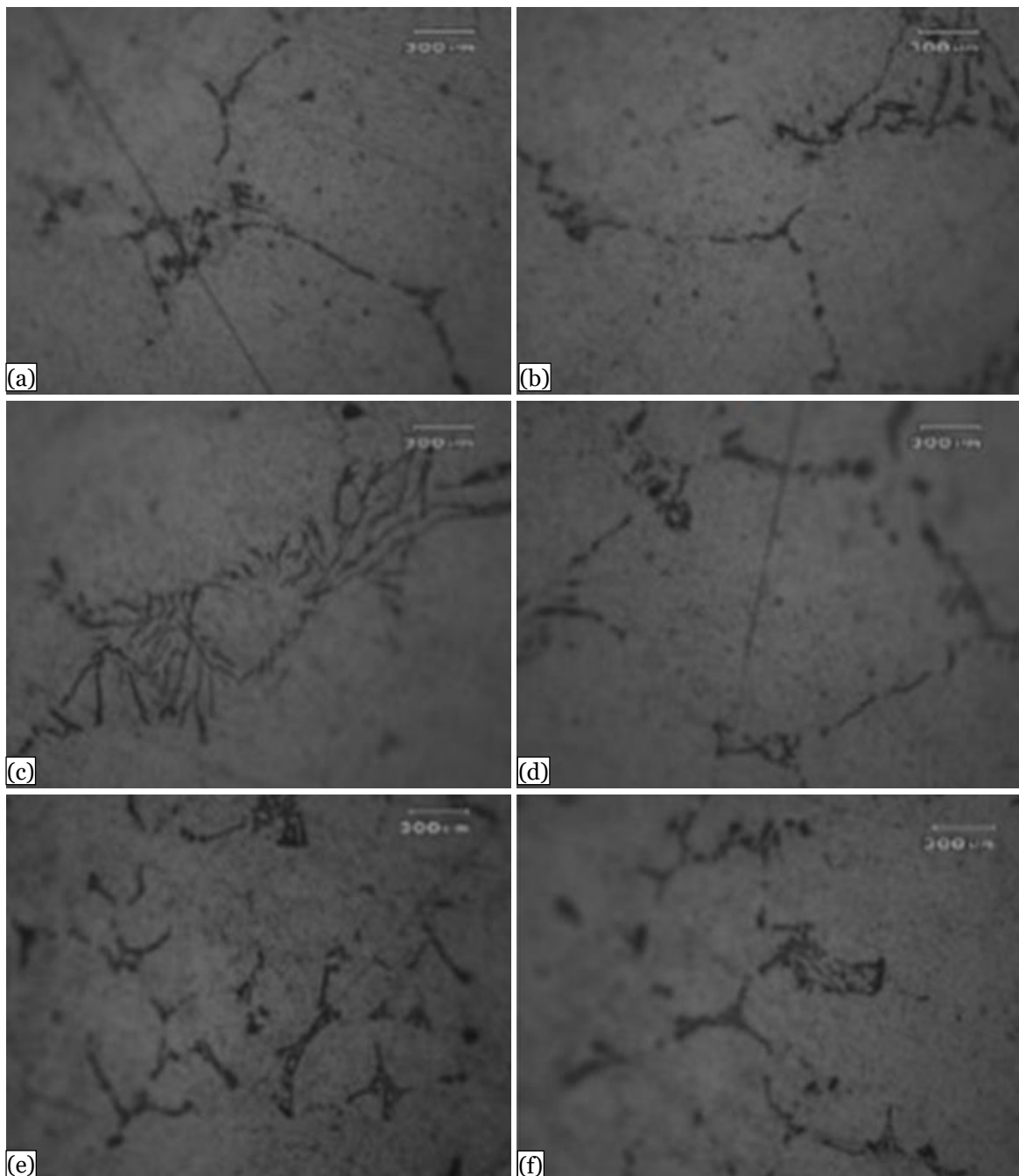
Figure 4. Silicon carbide particles of 40 μ m.

Analysis reveals that SiC particulate additions to matrix materials enhance matrix alloy strength by effectively resisting tensile stresses. Maximum tensile strength for Al-SiC composites was achieved in specimens cast with DCT copper chills, while minimum values occurred with conventional copper chills.

Hardness and Compressive Strength Analysis

Hardness studies indicated that Al-SiC composites produced through chill casting using DCT-chills exhibit higher hardness compared to specimens cast with regular copper chills.

Maximum hardness values were observed in composites prepared using DCT copper chill plates due to fine grain structures resulting from rapid freezing during melt solidification, while moderate hardness was observed in conventional copper-chilled composites.



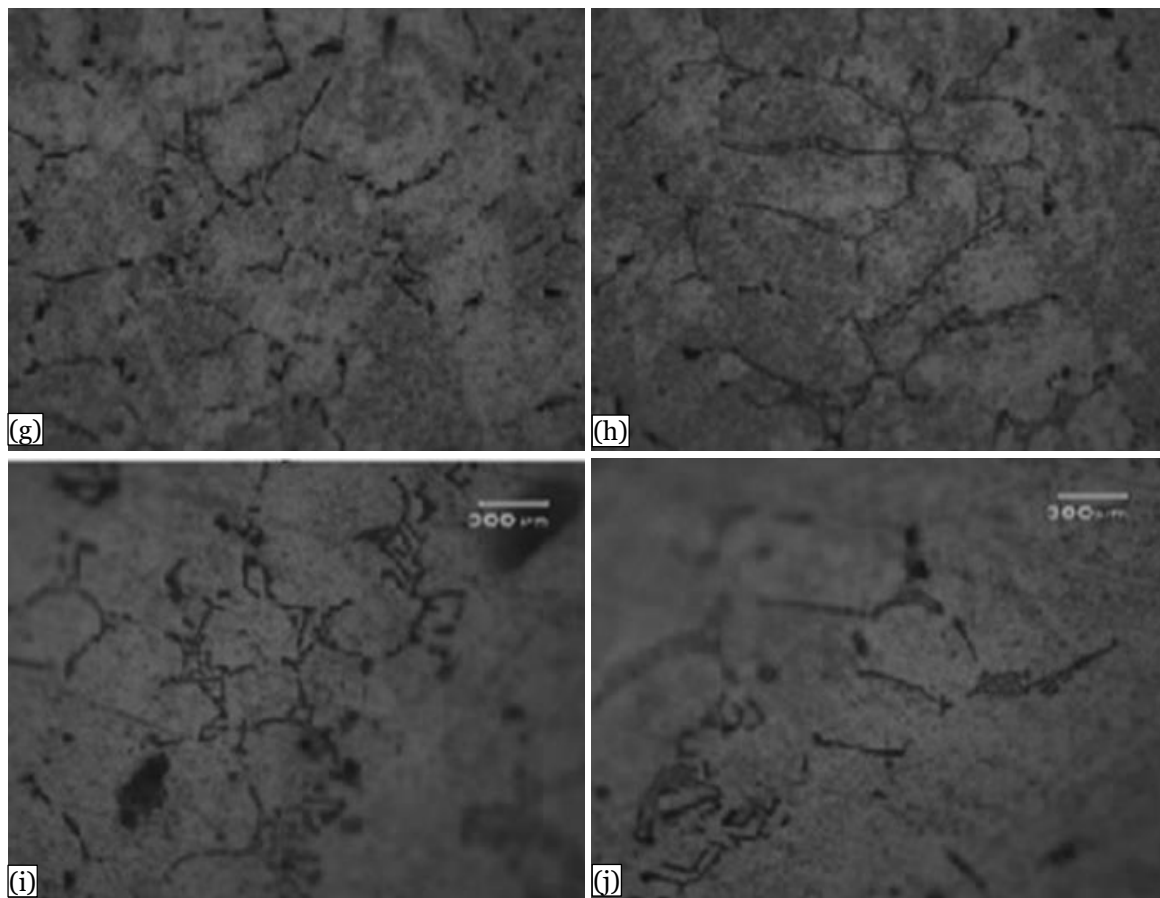


Figure 5. SEM images of (a-b) as cast, (c-d) Al+3%SiC, (e-f) Al+6SiC, (g-h) Al+9%SiC, and (i-j) Al+12%SiC.

The impact of SiC concentration percentage and chilling effects on composite material compressive strength demonstrates that compressive strength increases monotonically with reinforcement material increases. Enhanced hardness results from increased bonding areas at matrix-reinforcement interfacial regions and grain structure refinement. Hardness increases can also be attributed to SiC particle additions that impart strength to matrix alloys, thereby enhancing resistance to cracking or penetration.

CONCLUSIONS

Microstructural analysis conclusively demonstrated that specimens cast with DCT-copper chill plates exhibit small grain structures, while specimens cast with conventional copper chills display coarse grain formations. Comparative microstructural examination of copper chill sides confirmed that DCT-copper chills produce significantly finer grain sizes compared to conventional copper chills.

Al-SiC composites cast using DCT copper chilling demonstrated maximum tensile strength values, suggesting that optimal dispersion and bonding of SiC particles within aluminum matrices are achieved using DCT methods combined with copper chilling, resulting in enhanced mechanical characteristics. Al-SiC composites manufactured with DCT-chills in chill casting processes exhibit superior hardness compared to those produced with standard copper chills.

DCT-copper chill composites demonstrate maximum toughness due to fine grain structures resulting from rapid solidification, while conventional copper-chilled composites show moderate toughness characteristics. Enhanced hardness results from improved bonding at matrix-reinforcement interfaces and finer grain structure development, demonstrating the effectiveness of deep cryogenic treatment in improving composite material properties.

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