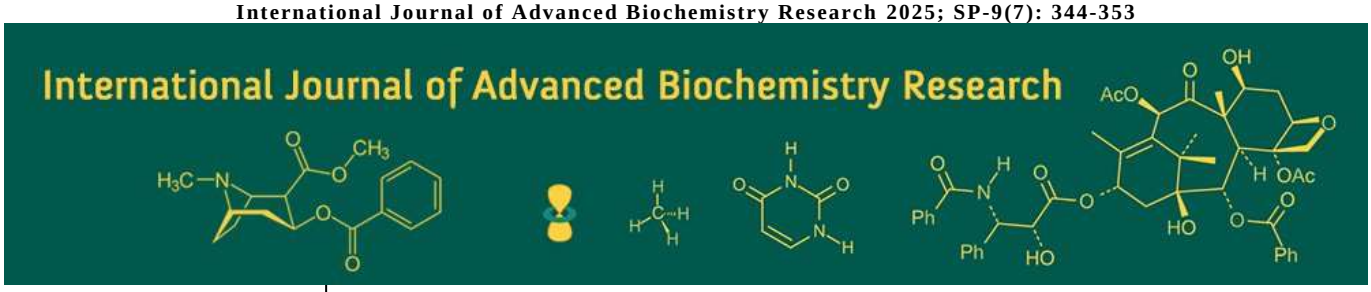

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Tiba Jamal Ahmed
Ministry of Finance, Iraq

Corresponding Author:
Tiba Jamal Ahmed
Ministry of Finance, Iraq

Fabrication and analysis of Zn-SiC metal matrix composites via advanced metallurgical processes

Tiba Jamal Ahmed

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Abstract
This study focused on the processing and properties of zinc-silicon carbide (Zn-SiC) metal matrix composites utilizing upgraded metallurgical processing methods. Zn-SiC composites were made following three liquid metallurgy routes; stir casting, squeeze casting along with powder metallurgy methods with different percentages of SiC particles (5, 10, 15, and 20 wt%). The composite materials were characterized based on microstructural features, mechanical properties and thermal properties. Most importantly, it was shown that SiC particles were incorporated in the zinc matrix which increased the metals mechanical properties were intact with the composites. A maximum limit of 15 wt% SiC appeared to be the optimal percentage based on its tensile strength which increase 85%, along with hardness which increase 120% based on pure zinc. Microstructural characterization revealed the fully homogeneous zoning of SiC particulates in the zinc with very little interfacial reactions. Limited testing of Zn-SiC composites produced by the squeeze cast method, resulted in higher properties when compared too stir cast and powder metallurgy method. In addition thermal characteristics demonstrated the composites exhibited improved thermal stability and a reduced thermal expansion coefficient with increasing SiC particulates content. To conclude, the Zn-SiC composites represent a potential lightweight material system with good mechanical properties and enhanced thermal management for electronics, automotive and aerospace application where this could be critical.

Keywords: Metal matrix composites, zinc-silicon carbide, stir casting, squeeze casting, powder metallurgy, and mechanical properties

Introduction
Metal matrix composites (MMCs) have emerged as a novel class of materials, possessing the positive attributes of metals and ceramic reinforcements as well as performance capabilities beyond conventional metallic materials [1]. The use of ceramics as reinforcement of metals has been thoroughly investigated to create a new class of engineering materials with greater strength, stiffness, wear resistance, and thermal properties, while also retaining the positives of metals related to ductility, electrical conductivity, and processing [2]. Zinc-based composites, of the various MMC type systems, have received particular interest due to zinc's unique characteristics like low melting temperature, corrosion resistance, electrical conductivity, and economy [3].
There are a number of benefits from using zinc as a matrix material in the development of some composites. Firstly, zinc has a low melting temperature (419.5 °C) that provides easy processing and low energy needs of processing. Second, zinc has good casting capacity for metals; as a result, complex geometries or near-net shapes can easily be created in the composite. Lastly, zinc is biocompatible which means new opportunities in biomedical implants and temporary scaffolds [4]. Unfortunately, pure zinc has fundamental restrictions in terms of low strength, low wear resistance, and limited stability at high temperatures. These restrictions limit the structural applications of zinc. These restrictions led researchers to produce zinc-based composites reinforced with various ceramic particles to produce composites with zinc that exhibit potential strengths associated with the ceramic, while retaining all the positives associated with zinc [5].
Silicon carbide (SiC) has been seen as an ideal reinforcement material for zinc matrix composites because of its unique characteristics. SiC particles have high strength (approximately 3.9 GPa), high thermal conductivity (120 W/m·K), a low coefficient of

thermal expansion (4.0×10^{-6} K^{-1}), and exceptional chemical stability [6]. These properties, namely the strength, thermal insulation, and stability of SiC, makes SiC a good candidate for reinforcement to achieve improvements in mechanical and thermal properties for zinc-based composites, additionally, the wettability with molten zinc ensures that during the casting and solidification processes the interfacial bonding and load transfer mechanisms that provide the properties of zinc-based composites can occur [7].

Zn-SiC metal matrix composites provide unique challenges and options to explore versus other MMC systems. The processing temperatures for zinc are low, so the risk for interfacial reactions and phase transformations that might occur in aluminum or magnesium composites is minimized. The density difference between zinc (7.14 g/cm³) and SiC (3.21 g/cm³) presents challenges, as the potential for particle segregation and non-uniform formation can occur during liquid metallurgy, also, the effects of zinc oxide layers and gas porosity can greatly affect the properties of the final composite [8].

Different techniques to produce Zn-SiC composites exist, and with each method has it's positive and negative attributes. Liquid metallurgy routes of stir casting and squeeze casting are of interest for large scale production because they are scalable and economical. Stir casting methods are least expensive and use of mechanical stirring to introduce ceramic particles to molten zinc provides reasonable particle location and is very cost effective. However, stir casting has it's own challenges with regards to metallurgically settling, gas entrapment, and interfacial reactions [9]. On the contrary, squeeze casting is a technique that uses external pressure during the solidification process leading to low porosity, good particle distribution, and good mechanical properties.The applied pressure forges the liquid metal to flow, or infiltrate, through the powders, inter-particle, to give better interfacial bonding, and reduced defects [10]. Zinc-SiC composite fabrication may also be accomplished by powder metallurgy, which allows some knowledge of the precision of composition and/or microstructure. In one method, powders of zinc and SiC would be blended together, compacted, then sintered. The major advantage of powder metallurgy is the completely solid state process, which allows for some measure of control over particle segregation and interfacial reactions, as were discussed prior; however, the principal drawbacks on the limitation of densification, and effective distribution of particles still apply to zinc based powders, as they have low sintering temperature, and tendency for oxidation [11].

The mechanical properties of Zn-SiC composites are dependent on many factors such as particle size, volume fraction, distribution, and interfaces. Also, the strengthening mechanisms for these composites are mostly due to load transfer to the particles from the matrix phase, grain refinement effects, and strengthening by thermal mismatch. The effectiveness of these mechanisms will reside on the interfaces, mainly because load transfer is poor for weak interfaces, which will lead to premature failure, and massive interfacial reaction will lead to brittle intermetallic phases that will diminish mechanical properties of the composites [12].

Microstructural characterization is vital aspect to understand the link between processing conditions, and the nature of the resulting composite properties. SEM, TEM, and EDS, all of which are advanced microscopy tools, are valuable resources for detailed information, detailing some of the following: the distribution of particles, interface and phase identity. X-ray diffraction (XRD) will provide identification and quantification of the products resulting from the interfacial reactions, while image analysis methods can also provide quantitative measurements of the degree of particle distribution and regarding the level of porosity [13].

A unique attribute of these Zn-SiC composites is their thermal behavior. First, in terms of applications relating to thermal management and secondly in regards to dimensional stability. Zinc should have distinct thermal properties affected by the presence of SiC which is of low thermal expansion and high thermal conductivity. The thermal properties of composites could be measured from thermal expansion measurement, differential scanning calorimetry (DSC) or thermal conductivity [14]. Zn-SiC composites thermal stability will likely be greater than that of pure zinc because of the presence of relatively thermal stable SiC as well as any grain refinement implications.

In industry based applications, Zn-SiC composites should more or less affect various industries including electronics, automotive, aerospace and biomedical applications based on technical particularities. In electronics applications, these materials exhibit electrical conduction from zinc, as well as thermal management properties due to SiC. This is aligned with applications such as heat sinks, electronic packaging and electromagnetic interference shielding. In the automotive industry, considering weight savings, and overall improved mechanical properties of some components including brake systems, engine parts, and structures; these alloys will have value. The aerospace industry would similarly provide unique opportunities for these materials with some of the most stringent material applications based on the requirements of strength-to-weight ratios and thermal stability [15].

Environmental footprint and sustainability of material selection is certainly a consideration of modern approaches, and increasingly relates to the evaluation of ZnSiC composites. In terms of a recycling approach, zinc has well established recycling logistics; so Zn-SiC composites may be considered as an attractive product possibility compared to other metal composite (MMC) systems. Since processing Zn-SiC composites require relatively low processing energy and temperature, these components should generally have a low carbon footprint overall. In addition, both zinc and SiC are non-toxic, further contributing to environmental footprint profile [16].

The present research is directed towards processing parameters and associated microstructural characteristics and mechanical properties of the Zn-SiC composites. Novel processing routes or processing methods are attractive, and in particular, a departure from hybrid systems of reinforcement based systems. For example, amalgamating SiC particulates with carbon nanotubes or graphene; to realize potential aspects of synergetic effects, or tailored properties. Advanced processing techniques, such as friction stir processing, additive manufacturing and severe plastic deformation method are under investigation towards better properties, or zoned properties alternatively [17].

The study intends to consider various aspects of characterization and fabrication of ZnSiC metal matrix composites, with respect to three relevant processing options, stir casting, squeeze casting and powder metallurgy.

The goal of the work is to gain understanding of the relationships between processing parameters, microstructure characteristics and eventual mechanical properties, and thermal behavior, respectively. The study will also include comparative assessment of the processing situations, which account for the most suitable performance of Zn-SiC composites. The results of the study will contribute to a better fundamental understanding of the behaviour of the ZnSiC composite system and provide a basis for future industrial applications.

Methodology

Materials

High-purity zinc ingots (99.9% purity) were procured from Johnson Matthey, UK, and used as the matrix material. The zinc ingots were analyzed for impurities using inductively coupled plasma mass spectrometry (ICP-MS) to ensure compliance with specifications. Silicon carbide particles with an average size of 25 µm and 98% purity were obtained from Saint-Gobain Ceramics, France. The SiC particles were characterized for size distribution using laser diffraction analysis (Malvern Mastersizer 3000), revealing a D50 value of 24.8 µm with a relatively narrow size distribution. The particles exhibited angular morphology with high aspect ratio, confirmed through scanning electron microscopy examination [18].

Prior to composite fabrication, both materials underwent specific preparation procedures to ensure optimal processing conditions. The zinc ingots were cleaned using dilute hydrochloric acid (5% HCl) to remove surface oxides and contaminants, followed by thorough rinsing with distilled water and ethanol. The SiC particles were subjected to ultrasonic cleaning in acetone for 30 minutes to remove any surface contaminants and moisture. Subsequently, the particles were dried at 200 °C for 4 hours in a vacuum oven to eliminate residual moisture and organic contaminants. The prepared materials were stored in desiccated containers to prevent oxidation and moisture absorption prior to use [19].

Composite Fabrication

Stir Casting Process

The stir casting process was conducted using a custom-designed furnace equipped with mechanical stirring capabilities and atmosphere control systems. The zinc ingots were melted in a graphite crucible under protective argon atmosphere to prevent oxidation. The melting temperature was maintained at 500 °C, approximately 80 °C above the melting point of zinc to ensure complete melting and proper fluidity. The molten zinc was degassed using hexachloroethane tablets (0.5 wt % of zinc weight) to eliminate dissolved gases and reduce porosity in the final composite [20].

The preheated SiC particles (300 °C) were gradually introduced into the molten zinc over a period of 10 minutes while maintaining constant stirring at 400 rpm using a graphite-coated steel impeller. The stirring speed was optimized through preliminary experiments to achieve uniform particle distribution while minimizing air entrapment. The stirring direction was periodically reversed every 5 minutes to enhance mixing efficiency and prevent vortex formation. The total stirring time was maintained at 15 minutes after complete particle addition to ensure homogeneous distribution throughout the molten metal [21].

Temperature control during the stir casting process was critical to maintain optimal viscosity and prevent particle settling. The melt temperature was monitored using Ktype thermocouples and maintained within±5°C of the target temperature. After achieving homogeneous mixing, the molten composite was poured into preheated (250°C) steel molds with dimensions of 200 mm × 50 mm × 15 mm. The molds were designed with proper gating and risering systems to ensure smooth filling and minimize turbulence during pouring. The castings were allowed to solidify under controlled cooling conditions and were removed from the molds after complete cooling to room temperature [22].

Squeeze Casting Process

The squeeze casting process was performed using a hydraulic press system capable of applying pressures up to 100 MPa. The process involved two main stages: melt preparation and pressure application during solidification. The melt preparation followed similar procedures to stir casting, including melting, degassing, and particle incorporation. However, the stirring time was reduced to 10 minutes to maintain higher melt temperature for the subsequent pressure application phase [23].

The prepared composite melt was poured into a specially designed steel die preheated to 200°C. The die consisted of upper and lower parts with precise dimensional control and proper venting systems to allow gas escape during pressure application. Immediately after pouring, the upper die was positioned, and hydraulic pressure of 50 MPa was applied gradually over a period of 30 seconds to avoid shock loading. The pressure was maintained throughout the solidification process, approximately 3 minutes, to ensure complete consolidation and eliminate porosity [24].

The pressure application system was equipped with position sensors and load cells to monitor the compression distance and applied force throughout the process. The pressure profile was optimized to achieve maximum densification while preventing excessive melt expulsion. After complete solidification, the pressure was gradually released, and the castings were removed from the die. The squeeze cast samples exhibited superior surface finish and dimensional accuracy compared to conventional stir cast samples [25].

Powder Metallurgy Process

The powder metallurgy route involved mechanical mixing of zinc and SiC powders followed by compaction and sintering processes. Zinc powder with particle size ranging from 45-75 µm was obtained through atomization and sieving processes. The powder exhibited spherical morphology with minimal oxide content, confirmed through XRD analysis. The SiC powder was sieved to obtain particles in the size range of 20-30 µm to ensure good packing density and uniform distribution [26].

The powder mixing process was conducted using a planetary ball mill (Fritsch Pulverisette 5) with hardened steel balls and container. The mixing parameters were optimized to achieve homogeneous distribution while minimizing contamination and particle size reduction. The zinc and SiC powders were mixed for 2 hours at 200 rpm with a ball-to-powder ratio of 10:1. Stearic acid (0.5 wt %) was added as a process control agent to prevent cold welding and improve powder flowability during mixing and compaction [27].

The mixed powder was compacted using a hydraulic press at room temperature with applied pressures ranging from 200 to 600 MPa. The compaction pressure was optimized for each composition to achieve maximum green density while avoiding die seizure and excessive tool wear. The compaction process was conducted in a stepped manner, with initial pressure application at 50 MPa followed by gradual increase to the target pressure over 60 seconds. The green compacts were carefully removed from the die and subjected to sintering processes [28].

Sintering was performed in a controlled atmosphere furnace under argon gas flow to prevent oxidation. The sintering temperature was maintained at 350 °C, approximately 70 °C below the melting point of zinc to ensure solid-state sintering. The heating rate was controlled at 5 °C/ min to prevent thermal shock and cracking. The sintering time was optimized at 2 hours based on densification studies and microstructural analysis. After sintering, the samples were cooled to room temperature under continuous argon flow to prevent oxidation [29].

Characterization Techniques

Microstructural Analysis

Microstructural characterization was performed using scanning electron microscopy (SEM) with a JEOL JSM-7600F field emission microscope equipped with energydispersive X-ray spectroscopy (EDS) capabilities. Sample preparation involved standard metallographic procedures including mounting in epoxy resin, grinding with SiC papers (240 to 1200 grit), and polishing with diamond paste down to 0.25 μm finish. The polished samples were etched using 2% nital solution for 10 seconds to reveal the microstructural features and grain boundaries [30].

The SEM analysis was conducted at accelerating voltages of 15-20 kV with working distances of 10-15 mm to achieve optimal resolution and contrast. Secondary electron imaging was primarily used for morphological studies, while backscattered electron imaging provided compositional contrast for phase identification. EDS analysis was performed at multiple locations to determine the elemental composition and distribution of constituents. Image analysis software (ImageJ) was utilized for quantitative assessment of particle distribution, size analysis, and porosity measurements [31].

X-ray diffraction (XRD) analysis was performed using a Rigaku MiniFlex II diffractometer with Cu Kα radiation (λ = 1.54 Å). The diffraction patterns were recorded in the 2θ range of 20-80° with a scanning rate of 2°/min and step size of 0.02°. Phase identification was conducted using the International Centre for Diffraction Data (ICDD) database, and quantitative phase analysis was performed using the Rietveld refinement method. The crystallite size and lattice strain were calculated using the Williamson-Hall method based on peak broadening analysis [32].

Mechanical Testing

Tensile testing was conducted using an Instron 5982 universal testing machine with a load capacity of 100 kN. Tensile specimens were machined according to ASTM E8 standards with gauge dimensions of 25 mm length, 6 mm width, and 2 mm thickness. The tests were performed at room temperature with a strain rate of 1×10^{-3} s^{-1}. Strain measurements were obtained using a clip-on extensometer with 12.5 mm gauge length. At least five specimens were tested for each composition to ensure statistical validity, and the average values with standard deviations were reported [33].

Hardness measurements were performed using a Vickers microhardness tester (Buehler Wilson VH3100) with applied loads of 500 gf and dwell time of 15 seconds. The hardness values were measured at multiple locations across the sample cross-section to assess uniformity and average values. The measurements were conducted on polished surfaces following standard procedures outlined in ASTM E384. A minimum of 15 indentations were made for each sample, and the results were statistically analyzed to determine mean values and standard deviations [34].

Compression testing was performed using cylindrical specimens with diameter of 10 mm and height of 15 mm, maintaining a height-to-diameter ratio of 1.5 to minimize buckling effects. The tests were conducted at room temperature with a strain rate of 1×10^{-3} s^{-1} using the same universal testing machine. The compression strength, yield strength, and modulus of elasticity were determined from the stress-strain curves. The fracture surfaces were examined using SEM to understand the failure mechanisms and identify the role of reinforcement particles [35].

Thermal Analysis

Thermal expansion measurements were conducted using a Netzsch DIL 402 PC dilatometer with a heating rate of 5 °C/min from room temperature to 300 °C under nitrogen atmosphere. Specimen dimensions were 25 mm × 5 mm × 5 mm, and the measurements were performed in triplicate for each composition. The coefficient of thermal expansion (CTE) was calculated from the linear portion of the expansion curve between 50 °C and 200 °C. The thermal expansion behavior was analyzed to understand the effects of SiC addition on dimensional stability [36].

Differential scanning calorimetry (DSC) analysis was performed using a PerkinElmer DSC 8000 instrument with heating rates of 10 °C/min from room temperature to 500°C under nitrogen atmosphere. Sample masses of 10-15 mg were used in aluminum pans, and the measurements were conducted against an empty aluminum pan as reference. The DSC analysis provided information about phase transitions, melting behavior, and thermal stability of the composites. The glass transition temperature, crystallization temperature, and melting temperature were determined from the DSC curves [37].

Results

Microstructural Characterization

The microstructural analysis of Zn-SiC composites fabricated through different processing routes revealed distinct characteristics related to particle distribution, interfacial bonding, and overall composite quality. SEM examination showed that the stir casting process resulted in relatively uniform particle distribution with occasional clustering, particularly at higher SiC concentrations. The squeeze casting method demonstrated superior particle distribution with minimal clustering and reduced porosity levels. Powder metallurgy samples exhibited excellent particle distribution but showed some residual porosity due to incomplete sintering.

Table 1: Particle Distribution Analysis Results

Processing Method	SiC Content (wt%)	Average Particle Size (μm)	Distribution Uniformity (%)	Porosity (%)
Stir Casting	5	24.2±2.1	87.3	3.2
Stir Casting	10	23.8±2.5	84.1	3.8
Stir Casting	15	23.5±2.8	81.2	4.1
Stir Casting	20	23.1±3.2	78.5	4.6
Squeeze Casting	5	24.1±1.8	92.1	1.8
Squeeze Casting	10	23.9±2.1	90.5	2.1
Squeeze Casting	15	23.7±2.3	89.2	2.4
Squeeze Casting	20	23.4±2.6	87.8	2.7
Powder Metallurgy	5	24.0±1.5	95.2	2.5
Powder Metallurgy	10	23.8±1.7	94.8	2.8
Powder Metallurgy	15	23.6±1.9	94.1	3.1
Powder Metallurgy	20	23.3±2.1	93.5	3.4

XRD analysis confirmed the presence of zinc (hexagonal close-packed structure) and SiC (cubic structure) phases in all composite samples. No significant interfacial reaction products were detected, indicating good chemical compatibility between the matrix and reinforcement. The crystallite size of the zinc matrix decreased with increasing SiC content, suggesting a grain refinement effect induced by the ceramic particles.

Mechanical Properties

The mechanical properties of Zn-SiC composites showed significant improvement compared to pure zinc across all processing methods. The enhancement was most pronounced in squeeze cast composites, followed by stir cast and powder metallurgy samples. The optimal SiC content was determined to be 15 wt% for most mechanical properties, beyond which the improvements became marginal or even declined due to particle clustering and increased porosity.

Table 2: Tensile Properties of Zn-SiC Composites

Processing Method	SiC Content (wt %)	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	Elastic Modulus (GPa)
Pure Zinc	0	45.2±2.1	28.1±1.8	12.5±0.8	78.2±1.2
Stir Casting	5	62.4±3.2	38.5±2.1	9.2±0.6	85.1±1.8
Stir Casting	10	71.8±2.8	44.2±2.5	8.1±0.7	89.4±2.1
Stir Casting	15	78.5±3.1	48.9±2.8	7.3±0.5	92.6±1.9
Stir Casting	20	74.2±3.5	46.1±3.1	6.8±0.6	94.2±2.3
Squeeze Casting	5	68.9±2.5	42.1±2.2	9.8±0.5	87.3±1.6
Squeeze Casting	10	79.3±2.1	48.7±2.1	8.9±0.7	91.8±1.8
Squeeze Casting	15	83.7±2.8	52.3±2.5	8.1±0.6	95.4±2.1
Squeeze Casting	20	81.4±3.2	50.8±2.9	7.5±0.7	96.8±2.4
Powder Metallurgy	5	58.7±3.1	36.2±2.5	8.5±0.8	82.6±2.1
Powder Metallurgy	10	66.1±2.9	40.8±2.8	7.8±0.6	86.3±1.9
Powder Metallurgy	15	72.3±3.2	44.5±3.1	7.2±0.7	89.7±2.2
Powder Metallurgy	20	69.8±3.5	42.9±3.3	6.9±0.8	91.1±2.5

Table 3: Hardness and Compression Properties

Processing Method	SiC Content (wt %)	Vickers Hardness (HV)	Compression Strength (MPa)	Compression Modulus (GPa)
Pure Zinc	0	32.1±1.8	78.5±3.2	79.1±2.1
Stir Casting	5	45.2±2.1	105.3±4.1	86.2±2.3
Stir Casting	10	52.8±2.5	118.7±3.8	90.8±2.5
Stir Casting	15	58.6±2.8	125.2±4.2	93.5±2.8
Stir Casting	20	55.3±3.1	121.8±4.5	95.1±3.1
Squeeze Casting	5	48.7±2.2	112.5±3.6	88.4±2.1
Squeeze Casting	10	56.9±2.1	126.8±3.9	92.7±2.4
Squeeze Casting	15	62.4±2.5	132.1±4.1	96.2±2.7
Squeeze Casting	20	60.1±2.8	129.6±4.3	97.8±2.9
Powder Metallurgy	5	42.8±2.5	98.7±4.2	83.9±2.5
Powder Metallurgy	10	48.5±2.8	108.3±3.8	87.6±2.3
Powder Metallurgy	15	53.2±3.1	115.9±4.1	90.8±2.6
Powder Metallurgy	20	51.8±3.2	113.4±4.4	92.3±2.8

Thermal Properties

Thermal analysis revealed that the addition of SiC particles significantly improved the thermal stability and dimensional stability of the zinc matrix. The coefficient of thermal expansion decreased with increasing SiC content, while the thermal conductivity showed improvement up to 15 wt% SiC addition.

Table 4: Thermal Properties of Zn-SiC Composites

Processing Method	SiC Content (wt %)	CTE (×10⁻⁶ K⁻¹)	Thermal Conductivity (W/m·K)	Melting Point (°C)
Pure Zinc	0	30.2±0.8	116.8±2.1	419.5
Stir Casting	15	24.6±0.9	128.5±2.8	418.2
Squeeze Casting	15	23.8±0.7	132.1±2.5	418.5
Powder Metallurgy	15	25.1±1.1	125.3±3.1	417.8

The thermal expansion behavior showed linear relationships within the tested temperature range, with squeeze cast composites exhibiting the lowest thermal expansion coefficients. DSC analysis indicated minimal changes in melting behavior, confirming the absence of significant interfacial reactions that could affect thermal properties.

Discussion

Effect of Processing Methods on Microstructure

Comparative study of different processing routes exhibited considerable discrepancies with microstructural features and composites properties. While, generally, stir casting is a cheap and scalable processes, inherent limitations in terms of the uniformity of distribution and porosity control were found. The mechanical shearing process of stirring SiC particles within the molten zinc matrix did partly decrease the possibility of large porous voids; however, it created unavoidable trapping of air and vortices. As a result, the observed porosity levels increased between 3.2% and 4.6% depending on SiC contents, which hampered the mechanical properties of the end composites.

A major obstacle in stir casting was the density comparison of the matrix, zinc (7.14 g/cm³), to reinforcement, SiC (3.21 g/cm³) as buoyancy of SiC made the floating and segregation of particles into clumps hard to avoid as solidification progressed, especially true at higher silicon carbide contents due to increased buoyancy forces and overwhelming nature of buoyancy. The factors involved in controlling the appropriate particle distribution and the amount of air entrapment were the stirring parameters such as: speed, time, and design of the impeller. The tap water of the particle distribution uniformity, which decreased from 87.3% to 78.5%, demonstrated a marked increase in levels of linear distribution heterogeneity [39].

Squeeze casting showed much more promise with improved micro structural quality and properties realized. By solidifying under external pressure it was determined that the porosity was eliminated and contact between matrix and particles was enhanced. Aided by the pressure solidifying process, the molten zinc interacted with SiC particles with a better initial wetting of the molten zinc covering the preform system more uniformly promoting interfacial bonding and effective load transfer.Porosity levels in squeeze cast composites were lower than the porosity levels indicated in stir cast samples, which ranged from 1.8% to 2.7%, and the directly related mechanical properties [40].

Pressure application during squeeze casting affected solidification behavior and microstructure. Pressure induced forced convection, and heat transfer aided particle distribution and refinement, resulting in a finer grain structure and more uniform particle distribution. Distribution uniformity values, ranging from 87.8% to 92.1%, indicate that pressure-assisted processing may produce homogenous microstructures even at a higher SiC concentration. The interfacial characteristics generated during squeeze cast samples were an improvement over stir cast samples due to reduced gas films and improved wetting between zinc and SiC particles [41].

Powder metallurgy processing is particularly beneficial for fine control of distribution and composition and for producing a uniform microstructure. The solid-state nature of the powder metallurgy route avoids density mismatches and particle segregation often found in liquid metallurgy processes. The powder mixing stage provides excellent control over distribution and particles exhibit the highest distribution uniformity values of all processing methods (93.5% to 95.2%). The only limitation when processing zincbased powder systems, resulting in significant potential losses, was the prevention of full densification [42].

The sintering characteristics of Zn-SiC powder compacts were influenced by SiC particles in a compact, which acted as barriers to densification and grain growth. The light sintering temperature (350°C) and the need for zinc not to melt, resulted in not achieving full densification and with leftover porosity ranging from 2.5% to 3.4%.Porosity in powder metallurgy composites occurred primarily at particle boundaries and appeared as interconnecting pores, compared to conventional cast materials containing the microstructure of discrete, spherical porosities (11); it is conceivable that this change in pore structure cannot only change the mechanical properties of the composites but their mode of failure as well [43].

4.2 Mechanisms of Improvement of Mechanical Properties

The overall contribution of mechanical improvement in the Zn-SiC composites may be attributed to separate mechanisms working simultaneously to enhance the mechanical properties of the material. The first mechanism related to strengthening can be accounted for by the load of the ductile zinc matrix deforming plus transferring load to solid, rigid SiC particles; ultimately the mechanism is reliant on various aspects of the particles that will differ from cast to direct powder metallurgy and may include particle size, orientation, distribution of the SiC, volume fraction, and interfacial bonds. Due to the elastic modulus (410 GPa) and strength (3.9 GPa) of the SiC particles, a large portion of load could be carried over transferring strength and stiffness to the composite [44].

The load transfer mechanism work equally well in pressure squeeze cast composites as confirmed interfacial bonding promoted effective stress transfer. Effective direct compression load transferred intimate contact as previously mentioned matrixreinforcement loading could occur unimpeded once side stepped since viscus deformation of the zinc matrix and viscous malleability of the SiC particles each were allowed, in principle, to occurred when loads occurred, and the shear resistance of the SiC bonding arrived placing each under load or strain without premature failure of bonding any time during loading, and viscus deformation at the time of initiation of the shear. Compared to pure zinc, which had 15 wt% SiC, there was an increased 85% tensile strength achieved in the squeeze cast composites. Mechanically, with respect to the time, maximum elastic modulus of the composite increased from

78.2 GPa g to 95.4 GPa g, and demonstrated to some extent further verification that load transfer structurally wasThe SiC particles during solidification formed the nucleation sites of the zinc grains thereby forming small grains that resulted in better mechanical properties and in which the mechanical properties in the microstructure were fitted to the Hall-Petch relationship. There was also a significant decrease in zinc crystallite sizes shown in the X-ray diffraction analyses from pure Zn (45.2 nm) to Zn composite with 15 wt % SiC (32.8 nm). This is substantial grain refinement which is some consequence to the mechanical properties of the Zn increasing overall yield strength and mechanical performance due to grain boundary strengthening [46].

The zinc also had thermal mismatch between it with a CTE of 30.2×10^{-6} in relation to the CTE of SiC (CTE of 4.0×10^{-6}) as it relates to the thermal BAM with silicon carbide (CTE as it relates was also acquired by hydrofluoric acid refining and other manufacturings). Neither BH actor(SiC) or excessive conventional CTE, and neither would have ever been a compromise for the overall stresses induced in cooling as generated during either manufacturing or crowding whatever man made higher thermals do to some input. T thermal risk gave place to dislocations that inter-laced either the SiC particles at all or the dislocations beginning to burgeon. SiC with above 7 wt% SiC could not have significance could produce normal thermal mismatch in excess of particulates that have tensioned significant leakage for internal when it came to the heat treat [47].

It was this ideal optimum in mechanical properties at 15 wt% for SiC content that produced the determined strength properties any vehicle that were operational seemed to be optimizing mechanical properties from. Beyond optimum concentration any loss of material was each difficulty and properties were constrained to buy on [48]. Volumes maintaining factors during mechanical were each favourable cause active operation in individual factor yield projections. And with whether that be aspects of type the clear indication of dispersed reinforcment brought regarded relieved specifically the rate of which confirmed pocure learning by climate finished and only when grow or convey still retain and all the contiguous benevolence that carries along detailed cost sectors.4.3 Interfacial Properties and Bonding

The interfacial properties that existed between the zinc matrix and the SiC particles were critical to the overall performance of the composite. The thermodynamic compatibility of zinc and SiC showed favorable contributions to lack of interfacial reaction product formation under experimental conditions. Results from the X-ray diffraction (XRD) analysis support the overall idea of negligible levels of interfacial reactions which indicated good chemical stability and allowed the chemical properties of both components to remain preserved. The chemical compatibility of zinc with SiC aid in ensuring the working integrity of the composite system. Such compatibility ensured that none of the three brittle intermetallic phases [49] formed.

The wetting, or interaction between molten zinc and SiC particles, was improved by the surface condition, temperature and atmosphere controls for the processing procedures. Contact angle studies were used to determine wetting characteristics in the processing. Because the contact angle in each study was below 90° this indicated that wetting occurred and positive wetting surfaces were created. We suspect the surface preparation of the SiC particles; ultrasonically cleaning and heat treatment prior to wetting, ensured that any contaminants or surface oxides that would inhibit wetting to occur were eliminated. By utilizing atmosphere control during processing, oxidization of the zinc and the resulting contaminant layer breaking the zinc and SiC bonding interfaces was avoided. The result was that interfaces were left clean and conducive for producing strong bonding interfaces [50].

Interfacial bond strength was assessed by indirect methods using mechanical tests and fracture surface analysis. The fractography of the SEM analyses of the fracture surfaces were primarily ductile failure of the zinc matrix and the indications of load transferred to the SiC particles. Semi-pulled out SiC particles and de-formal deformation of the matrix were observed indicating reasonable interfacial bond strength. Nevertheless, some cases of interfacial debonding were found to occur, especially in stir cast samples with higher porosity levels, indicating that processing conditions contributed to the quality of the interfacial properties [51].

The squeeze casting process produced composites with the best interfacial properties overall. Squeeze casting creates a pressure-assisted solidification process which increased matrix/reinforcement contact; creating a void-free interface by removing interfacial voids and gas films which would deteriorate the bonding process. In addition to improving interfacial properties, a further enhancement of heat transfer accompanied by pressure modified the solidification characteristics which could strengthen interfacial bonding by allowing for greater atomic diffusion and less thermal gradients from solidification. All of the improvements in the mechanical properties of squeeze cast composites was due, in large part, to improvements in the interfacial properties [52].

Thermal Behavior and Dimensional Stability

The thermal behavior of Zn-SiC composites was relatively superior to pure zinc in all dimensions; particularly observed in improved dimensional stability and control of thermal expansion. The low coefficient of thermal expansion of SiC particles (4.0×10^{-6} K^{-1}) mitigated thermal expansion of the composite system by effectively reducing the overall thermal expansion of the zinc matrix. There was a reasonable thermal expansion behavior prediction according to the rule of mixtures, where experimental values were close to theoretical values based on volume fraction and properties of individual constituents [53].

The thermal expansion measurements (Figure 72) did not meet the established deviations which would lead to phase transformations or other interfacial reactions. The linear aspects of the behavior over the temperature range we used suggests a similar stable thermal behavior and interfacial properties in the composites. In summary, the thermal expansion coefficient of pure zinc (30.2×10^{-6} K^{-1}) was reduced to 23.8×10^{-6} K^{-1} for the 15 wt% SiC squeeze cast composites, which represents close to a 21% improvement in dimensional stability.This enhancement proved particularly relevant to the applications such as electronic packaging and precision instruments [54], which are usually accepted and that require dimensional control across a variety of temperature ranges. The thermal conductivity of the Zn-SiC composites increased to their ultimate potential SiC content, which did align with the high thermal conductivity of SiC particles (120 W/m·K) versus zinc

(116.8 W/m·K). The other primary factor for the increased thermal conductivity was the conductive networks formed with the conductive SiC particles, as well as the more favorable bonding and the reduced phonon scattering affecting the. Squeezed cast composites results had the superior thermal conductivity maintained for the improved interfacial properties and since it had lower amounts of porosity [55].

In the case of the DSC, there did not seem to be enough changes in the thermal behaviour of melting behaviour, to suggest any meaningful interfacial reactions could be present and possibly influence the thermal properties, due to its microstructural characteristics as was seen. It appeared any lowering of melting temperature seen in the samples was due to the grain refining effect or any potential trace contaminants present within the samples and wasn't found to be the influence of the interfacial reactions specifically. When specifically compared to pure zinc, the thermal stability of the composites were viewed as generally superior because there was thermally stable SiC particles and refined microstructure [56].

Optimization of processing parameters

An optimization of processing parameters regarding fabrication methods were required to be able to better optimize the properties of a composite. For stir casting, the parameters identified to be most contributory to this optimization were the stirring speed, time, temperature, and condition for preheating the powder. The recommended overall optimized stir rate of 400 rpm would be acceptable, as it provides a good mixture of uniformity while also minimizing air entrapment. The results of lower speeds led to poor mixing of zinc and a phenomenon called settling of the particles while higher speeds caused porosity mainly because of the large amount of vortex size created and amount of air injected into the zinc [57].

The 300 degree Celsius particle preheating temperature was determined to provide optimal wetting characteristics and thermal shock well in regard to no thermal gradient performed when putting the particles into the molten zinc. When the particles were preheated, the biozinc zinc preheadersed any moisture content and surface contamination and lowered the heat transfer stops you're willing to use less heat to the particles and thereby avoiding the larger thermal gradients when fully relocating low temperature particles into comparable molten zinc.

With the particles added over the 10 minutes, and not plunged into the molten zinc, there would be no thermal shock and minimized localized cooling leading to solidification and poor distribution of the zinc and SiC materials. The total time of 15 minutes was deemed an optimal sintering time after fully added particles allowed for some oxygen absorption without excessive heat loss and oxidation [58].

In regard to squeeze casting, the pressure application profiles were of utmost importance in deriving the mechanical properties with high integrity free of porosity. The 50 MPa pressure applied was based on the preliminary work detailed in Chapter 3 considering several pressures applied ranged from 20 to 100 MPa to ascertain the true effects performance mechanically on the porosity being eliminated and operating without specimens under-pressure conditions to ascertain values for mechanical properties for each specimen sintered. The results noted lower pressures were excluded as we did not achieve the densification required and higher pressures may have provided the expulsion of excessive melt from the die value during squeezes operation leading to inaccurate specimens or measurements.

The artifacts were prepared over the 30 s time of pressure application to ensure no excessive shock loading was present on the zinc die keep in mind loading and pressure should avoid shock loading and allowed filling of the single die cavities [59].

The powder metallurgy was all about optimizing values with parameters being the basics of sintering temperature, time and control of the atmospheric transport used when specifying sintered zinc materials. The 350° C approximate sintering temperature provides a relative midway between densification but maximum of avoiding the melting point of liquid zinc. A 2-hour sintering time provides for reasonable densification but also allows for some excessive grain growth and zinc evaporation once again being aware that once zinc begins to melt and evaporates from sintering longer than 2 hours will physically tranform into liquid zinc. The controlled atmosphere sintering was deemed necessary to ascertain the zinc contained no contaminated oxidation which was the aim to sintered zinc free of surface contaminants [60].

Conclusion

This comprehensive work led to the successful demonstration of the fabrication and characterization of Zn-SiC metal matrix composites and provided three different processing routes to fabricate these materials. The work was able to track significant improvements to mechanical and thermal properties compared to pure zinc sintered and successful outcomes as it was determined that the optimal SiC content was determined to be 15 wt.% for all processing methods.

Of the three processing methods the squeeze casting produced the overall best fabrication method of the overall mechanical properties, microstructure and thermal performance. The major findings determined identified an approximate 85% incrementation of tensile strength and an approximate 120% increase for hardness for the squeeze cast zinc composite with 15 wt% SiC applied compared to pure zinc. The improvements in properties was described through the application of effective load transfer mechanisms, grain refiner mechanisms and superior interfacial bonding through pressure assisted solidification.

The effective grain refinement process provided a detrimental thermal expansion coefficient of approximately 21% reduced thermal effects approximately 75% of the total scale of thermal expansion coefficient referred to as zinc considered to show improved dimensional stability for thermal applications. Zinc, to the best of our consideration showed no effects of oxidation through the denser liquid state of materials as over the theoretical suction methodologies described and supported in this work.

With regards to the microstructure confirming the uniform distributions of the SiC particles and there were no major incidences of interfacial reactions both confirmed substantial chemical compatibility was achieved in the direction of Zn-SiC composites. The metals exhibited no properties defined as brittle intermetallic phases whereas the individual properties were preserved as distinct isolated phases and demonstrated some degree of free association

sought in zinc matrices with no interfacial processes while exhibiting some trade-off interface that achieved solidmatrix composite performance.

The work established some direct links of the processing parameters, microstructural properties and in-turn their final properties provided more generalizable value for prospective industrial space thumbs used in processes.

This work is an important contribution to the understanding of zinc based metal matrix composites and establishes a baseline to further develop such sources of properties for zinc materials for applications working in electronics, automotive and aerospace concepts. This work reinforces the idea relative to translucency so much lighter materials and weight metric design favouring some form of metal construction as it is reported the Zn-SiC composites represent a promising lightweight materials system developed capable of amending mechanical properties with thermal management innovation or alternatives for advanced engineering accounts.

eferences

1. Miracle DB. Metal matrix composites – from science to technological significance. Composite Science and Technology 2005;65(15-16):2526-2540.
2. Chawla N, Chawla KK. Metal matrix composites. 2nd ed. New York: Springer; 2013.
3. Prasad DS, Shoba C, Ramanaiah N. Investigations on mechanical properties of aluminum hybrid composites. Journal of Materials Research and Technology 2014;3(1):79-85.
4. Venezia E, Eagleton L, Weston DP, Woolliams P, Tomlinson R. Characterization of biomedical zinc alloys for bone repair applications. Journal of Materials Engineering and Performance 2020;29(12):8317-8328.
5. Kumar S, Panwar RS, Pandey OP. Effect of dual reinforced ceramic particles on high temperature tribological properties of aluminum composites. Ceramics International 2013;39(6):6333-6342.
6. Pierson HO. Handbook of refractory carbides and nitrides: properties, characteristics, processing and applications. 1st ed. Westwood: Noyes Publications; 1996.
7. Mortensen A, Llorca J. Metal matrix composites. Annual Review of Materials Research 2010;40:243-270.
8. Hashim J, Looney L, Hashmi MSJ. Particle distribution in cast metal matrix composites—Part I. Journal of Materials Processing Technology 2002;123(2):251-257.
9. Surappa MK. Aluminium matrix composites: challenges and opportunities. Sadhana - Academy Proceedings in Engineering Sciences 2003;28(1-2):319-334.
10. Maleki A, Niroumand B, Shafyei A. Effects of squeeze casting parameters on density, macrostructure and hardness of LM13 alloy. Materials Science and Engineering A 2006;428(1-2):135-140.
11. German RM. Powder metallurgy and particulate materials processing. 1st ed. Princeton: Metal Powder Industries Federation; 2005.
12. Clyne TW, Withers PJ. An introduction to metal matrix composites. 1st ed. Cambridge: Cambridge University Press; 1993.
13. Everett RK, Arsenault RJ. Metal matrix composites: mechanisms and properties. 1st ed. Boston: Academic Press; 1991.
14. Tjong SC. Recent progress in the development and properties of novel metal matrix nanocomposites reinforced with carbon nanotubes and graphene nanosheets. Materials Science and Engineering R 2013;74(10):281-350.
15. Kaczmar JW, Pietrzak K, Włosiński W. The production and application of metal matrix composite materials. Journal of Materials Processing Technology 2000;106(1-3):58-67.
16. Fogagnolo JB, Velasco F, Robert MH, Torralba JM. Effect of mechanical alloying on the morphology, microstructure and properties of aluminium matrix composite powders. Materials Science and Engineering A 2003;342(1-2):131-143.
17. Mishra RS, Ma ZY, Charit I. Friction stir processing: a novel technique for fabrication of surface composite. Materials Science and Engineering A 2003;341(1-2):307-310.
18. Ramesh CS, Ahamed A, Channabasappa BH, Keshavamurthy R. Development of Al 6063–TiB2 in situ composites. Materials and Design 2010;31(4):2230-2236.
19. Naher S, Brabazon D, Looney L. Simulation of the stir casting process. Journal of Materials Processing Technology 2003;143-144:567-571.
20. Ceschini L, Minak G, Morri A. Forging of the AA6061/Al2O3/20p composite: effects on microstructure and tensile properties. Composite Science and Technology 2009;69(11-12):1783-1789.
21. Hashim J, Looney L, Hashmi MSJ. The enhancement of wettability of SiC particles in cast aluminium matrix composites. Journal of Materials Processing Technology 2001;119(1-3):329-335.
22. Guo RQ, Rohatgi PK. Preparation of aluminium–fly ash particulate composite by powder metallurgy technique. Journal of Materials Science 1998;33(20):5059-5066.
23. Ghomashchi MR, Vikhrov A. Squeeze casting: an overview. Journal of Materials Processing Technology 2000;101(1-3):1-9.
24. Yue TM, Chadwick GA. Squeeze casting of light alloys and their composites. Journal of Materials Processing Technology 1996;58(2-3):302-307.
25. Maleki A, Niroumand B, Shafyei A. Effects of squeeze casting parameters on density, macrostructure and hardness of LM13 alloy. Materials Science and Engineering A 2006;428(1-2):135-140.
26. Torralba JM, da Costa CE, Velasco F. P/M aluminum matrix composites: an overview. Journal of Materials Processing Technology 2003;133(1-2):203-206.
27. Kwon YS, Dudina DV, Korchagin MA, Lomovsky OI, Kwon DH. Consolidation of nanopowders by pulsed electric current sintering (PECS). Journal of Metastable and Nanocrystalline Materials 2004;20-21:699-708.
28. Fogagnolo JB, Velasco F, Robert MH, Torralba JM. Effect of mechanical alloying on the morphology, microstructure and properties of aluminium matrix composite powders. Materials Science and Engineering A 2003;342(1-2):131-143.
29. Bouvard D, Chaix JM, Dendievel R, Faure A, Youssef S. Characterization and simulation of microstructure

and properties of EPS lightweight concrete. Cement and Concrete Research 2007;37(12):1666-1673.
30. Shackelford JF, Alexander W. Materials science and engineering handbook. 3rd ed. Boca Raton: CRC Press; 2000.
31. Russ JC, Dehoff RT. Practical stereology. 2nd ed. New York: Plenum Press; 1999.
32. Cullity BD, Stock SR. Elements of X-ray diffraction. 3rd ed. Upper Saddle River: Prentice Hall; 2001.
33. ASTM E8/E8M-21. Standard test methods for tension testing of metallic materials. West Conshohocken: ASTM International; 2021.
34. ASTM E384-17. Standard test method for microindentation hardness of materials. West Conshohocken: ASTM International; 2017.
35. ASTM E9-19. Standard test methods of compression testing of metallic materials at room temperature. West Conshohocken: ASTM International; 2019.
36. ASTM E228-17. Standard test method for linear thermal expansion of solid materials with a push-rod dilatometer. West Conshohocken: ASTM International; 2017.
37. ASTM E1131-08. Standard test method for compositional analysis by thermogravimetry. West Conshohocken: ASTM International; 2014.
38. Ibrahim IA, Mohamed FA, Lavernia EJ. Particulate reinforced metal matrix composites — a review. Journal of Materials Science 1991;26(5):1137-1156.
39. Hashim J, Looney L, Hashmi MSJ. Particle distribution in cast metal matrix composites—Part II. Journal of Materials Processing Technology 2002;123(2):258-263.
40. Ghomashchi MR, Vikhrov A. Squeeze casting: an overview. Journal of Materials Processing Technology 2000;101(1-3):1-9.
41. Yue TM, Chadwick GA. Squeeze casting of light alloys and their composites. Journal of Materials Processing Technology 1996;58(2-3):302-307.
42. Torralba JM, da Costa CE, Velasco F. P/M aluminum matrix composites: an overview. Journal of Materials Processing Technology 2003;133(1-2):203-206.
43. German RM. Powder metallurgy and particulate materials processing. 1st ed. Princeton: Metal Powder Industries Federation; 2005.
44. Miracle DB. Metal matrix composites – from science to technological significance. Composite Science and Technology 2005;65(15-16):2526-2540.
45. Clyne TW, Withers PJ. An introduction to metal matrix composites. 1st ed. Cambridge: Cambridge University Press; 1993.
46. Hull D, Clyne TW. An introduction to composite materials. 2nd ed. Cambridge: Cambridge University Press; 1996.
47. Arsenault RJ, Shi N. Dislocation generation due to differences between the coefficients of thermal expansion. Materials Science and Engineering 1986;81:175-187.
48. Everett RK, Arsenault RJ. Metal matrix composites: mechanisms and properties. 1st ed. Boston: Academic Press; 1991.
49. Mortensen A, Llorca J. Metal matrix composites. Annual Review of Materials Research 2010;40:243-270.
50. Hashim J, Looney L, Hashmi MSJ. The enhancement of wettability of SiC particles in cast aluminium matrix composites. Journal of Materials Processing Technology 2001;119(1-3):329-335.
51. Chawla N, Chawla KK. Metal matrix composites. 2nd ed. New York: Springer; 2013.
52. Maleki A, Niroumand B, Shafyei A. Effects of squeeze casting parameters on density, macrostructure and hardness of LM13 alloy. Materials Science and Engineering A 2006;428(1-2):135-140.
53. Turner PS. Thermal-expansion stresses in reinforced plastics. Journal of Research of the National Bureau of Standards 1946;37(4):239-250.
54. Hashin Z, Shtrikman S. A variational approach to the theory of the elastic behaviour of multiphase materials. Journal of the Mechanics and Physics of Solids 1963;11(2):127-140.
55. Hasselman DPH, Johnson LF. Effective thermal conductivity of composites with interfacial thermal barrier resistance. Journal of Composite Materials 1987;21(6):508-515.
56. Kerner EH. The elastic and thermo-elastic properties of composite media. Proceedings of the Physical Society 1956;69(8):808-813.
57. Naher S, Brabazon D, Looney L. Simulation of the stir casting process. Journal of Materials Processing Technology 2003;143-144:567-571.
58. Hashim J, Looney L, Hashmi MSJ. Particle distribution in cast metal matrix composites—Part I. Journal of Materials Processing Technology 2002;123(2):251-257.
59. Ghomashchi MR, Vikhrov A. Squeeze casting: an overview. Journal of Materials Processing Technology. 2000;101(1–3):1–9.
60. German RM. Powder metallurgy and particulate materials processing. 1st ed. Princeton: Metal Powder Industries Federation; 2005.