KAOLIN-REINFORCED ALUMINIUM METAL MATRIX COMPOSITES: A REVIEW OF PROCESSING AND INTERFACIAL BEHAVIOUR PROPERTIES

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ABSTRACT

Metal matrix composites have emerged as advanced engineering materials offering superior mechanical and thermal properties compared to conventional metals. Among various reinforcement options, kaolin clay presents a cost-effective and sustainable alternative to conventional ceramic reinforcements in aluminum matrix composites. This review examines the current state of research on kaolin-reinforced aluminum metal matrix composites, focusing on processing techniques, interfacial characteristics, and resulting material properties. The findings critically analyze liquid-state and solid-state processing methods, with particular emphasis on stir casting techniques and their process parameters. Interfacial bonding mechanisms between kaolin particles and aluminum matrix are discussed, highlighting the role of surface modification treatments in enhancing composite performance. The mechanical, thermal, and tribological properties of kaolin-reinforced aluminum composites are evaluated across various reinforcement contents and processing conditions. Optimization methodologies, particularly Taguchi design of experiments and grey relational analysis, are examined for their effectiveness in identifying optimal processing parameters. Despite promising results demonstrating improved wear resistance and hardness with kaolin addition, significant research gaps remain regarding particle size effects, modification temperature optimization, and multi-objective property enhancement. This review identifies critical areas requiring further investigation and provides insights into the potential industrial applications of kaolin-reinforced aluminum composites in automotive, aerospace, and structural engineering sectors.

Keywords: Kaolin, Aluminum matrix composites, Stir casting, Interfacial bonding, Mechanical properties, Optimization

1 INTRODUCTION

The development of advanced materials with tailored properties has become increasingly important in modern engineering applications where traditional materials fail to meet the demanding requirements of performance, weight reduction, and cost-effectiveness. Composite materials, fundamentally composed of two or more distinct phases working synergistically, have emerged as a solution to these challenges. The term “composite” originates from the Latin “componere,” meaning to put together, highlighting the strategic union of different materials to develop superior materials with properties surpassing those of individual constituents [1]. Metal matrix composites represent a particularly significant class of advanced materials, combining the ductility and toughness of metallic matrices with the high strength and stiffness of ceramic reinforcements [2]. Among various metal matrices, aluminium has attracted considerable attention due to its unique combination of low density, excellent corrosion resistance, good mechanical properties, and superior thermal conductivity. Aluminium-based composites offer significant advantages in applications requiring high strength-to-weight ratios, making them attractive for aerospace, automotive, and defense industries [2]. The selection of reinforcement material plays a crucial role in determining the final properties and cost-effectiveness of metal matrix composites. Traditional ceramic reinforcements such as silicon carbide, alumina, and boron carbide have been extensively studied and demonstrate excellent mechanical property enhancement. However, their high cost and processing challenges limit widespread industrial adoption. This economic constraint has driven researchers to explore alternative, cost-effective reinforcement materials that can deliver comparable performance while maintaining manufacturing feasibility. Kaolin, a naturally occurring aluminosilicate clay mineral with the formula $Al_2(Si_2O_5)(OH)_4$, has recently gained attention as a potential low-cost reinforcement for aluminium matrix composites. The material possesses several attractive characteristics including high surface area, fine particle size, thermal stability, and availability at significantly lower cost compared to conventional ceramic reinforcements. The crystal structure of kaolinite consists of two-dimensional layers with silica tetrahedral sheets bonded to alumina octahedral sheets, creating a structure that can potentially form strong interfacial bonds with aluminium matrices [3]. Figure 1 shows Kaolin-reinforced aluminium MMCs via stir casting.

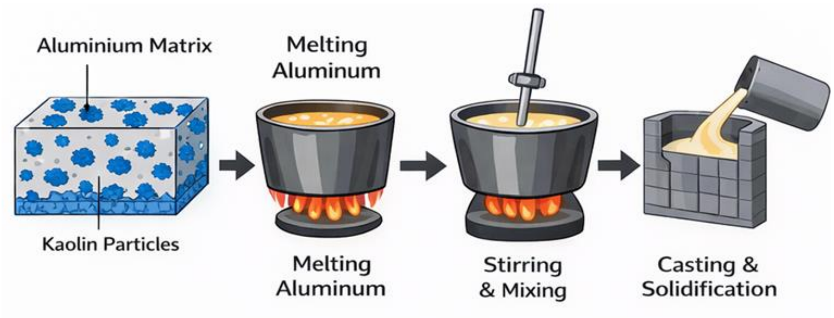

Figure 1. Kaolin-reinforced aluminium MMCs via stir casting

Despite the promising characteristics of kaolin, research on its application as a reinforcement in aluminium matrix composites remains limited compared to conventional reinforcements. The hydrophilic nature of kaolin presents challenges in achieving proper wetting with molten aluminium, potentially leading to poor interfacial bonding and reduced load transfer efficiency. Surface modification techniques have been proposed to address these challenges, though systematic investigations of modification parameters and their effects on composite properties are lacking [3]. Furthermore, the relationship between kaolin particle size, content, and processing parameters on the mechanical and microstructural properties of aluminium composites requires comprehensive evaluation. The processing method significantly influences the final properties of metal matrix composites by affecting reinforcement distribution, interfacial bonding quality, and microstructural characteristics. Liquid-state processing methods, particularly stir casting, offer advantages in terms of cost-effectiveness and scalability for industrial production. However, achieving uniform particle distribution and avoiding defects such as porosity, particle agglomeration, and interfacial reactions requires careful optimization of processing parameters including stirring temperature, stirring time, stirring speed, and reinforcement addition rate. Optimization of processing parameters for multi-response systems presents additional complexity, as improving one property may adversely affect others. Traditional single-objective optimization approaches are insufficient for composite materials where multiple conflicting properties must be simultaneously enhanced. Advanced optimization techniques such as Taguchi design of experiments combined with grey relational analysis provide systematic methodologies for identifying optimal processing conditions that balance multiple performance objectives [4]. This review critically examines the current state of research on kaolin-reinforced aluminium metal matrix composites, analyzing processing techniques, interfacial characteristics, mechanical properties, and optimization methodologies. The study identifies significant research gaps and proposes directions for future investigation to advance the understanding and industrial application of these materials.

2 METHODOLOGY

The literature search and its reporting followed the PRISMA 2020 guidelines and the PRISMA-S extension for systematic search reporting, ensuring transparency and reproducibility of the search strategy. A literature search was conducted across multiple academic databases, including Web of Science, Scopus, and Google Scholar, to identify relevant publications on kaolin-reinforced aluminium composites and related topics, with the search executed in March 2026. The search strategy employed a combination of keywords and Boolean operators to capture relevant studies. Primary search terms included "kaolin," "kaolinite," "aluminium matrix composite," "metal matrix composite," "reinforcement," "stir casting," "powder metallurgy," "interfacial bonding," and "mechanical properties," combined using AND/OR operators (e.g., "kaolin" OR "kaolinite" AND "aluminium matrix composite"). The temporal scope of the literature search primarily focused on publications from 2000 to 2025, though earlier seminal works were included where they provided foundational knowledge or established important concepts. Both peer-reviewed journal articles and conference proceedings were considered, with preference given to studies published in reputable journals with rigorous peer-review processes. The search was not restricted by geographical location or language, though English-language publications predominated in the final selection. Studies were included in this review if they met the following criteria: investigation of metal matrix composites with emphasis on aluminium-based systems; examination of kaolin, kaolinite, or clay minerals as reinforcement materials; analysis of processing techniques relevant to particulate-reinforced composites; evaluation of mechanical, thermal, or tribological properties; discussion of interfacial characteristics or bonding mechanisms; or presentation of optimization methodologies applicable to composite fabrication. Studies on polymer matrix composites reinforced with kaolin were included selectively, when they provided insights applicable to metal matrix systems, particularly regarding surface modification techniques or particle-matrix interaction mechanisms. The synthesized information was analyzed to identify consistent patterns, contradictory findings, and knowledge gaps in the literature. Comparative analysis was performed to evaluate the relative effectiveness of different processing methods, surface treatments, and reinforcement strategies. Trends in property evolution with changing processing parameters or reinforcement content were examined across multiple studies to establish general relationships [3, 4].

3 RESULTS AND DISCUSSION

3.1 Effect of Kaolin Content on Mechanical Properties

Research investigating the influence of kaolin content on mechanical properties of aluminium matrix composites has yielded varied results, reflecting the complex interplay between reinforcement volume fraction, particle distribution, and interfacial characteristics as reported by many studies [5, 6]. Several studies have reported improvements in hardness and wear resistance with increasing kaolin content up to an optimal threshold, beyond which properties deteriorate due to particle agglomeration and increased porosity. The work by Basma et al. [5] on PVC/kaolinite composites demonstrated that increasing kaolinite loading led to decreased tensile strength and elongation at break, while hardness increased. Although conducted on polymer matrices, these findings suggest that kaolin addition can enhance resistance to localized deformation while potentially compromising ductility. The observed decrease in impact strength at higher loadings was attributed to poor adhesion between kaolin and the matrix, highlighting the critical importance of interfacial bonding in determining composite properties. In metal matrix systems, the relationship between reinforcement content and mechanical properties depends strongly on processing conditions and particle characteristics. Studies on conventional ceramic reinforcements in aluminium matrices have shown that strength typically increases with reinforcement content up to approximately 10-15 weight percent, beyond which clustering effects and processing difficulties lead to property degradation [6]. The particle size of kaolin reinforcement plays a crucial role, with finer particles generally providing better distribution and higher surface area for load transfer, though they may also increase the difficulty of achieving uniform dispersion. Wear resistance has been consistently reported to improve with kaolin in addition composite systems. Sudeepan et al. [7] observed enhanced wear resistance in ABS composites containing calcined kaolinite at 5% filler content under specific processing conditions. This improvement can be attributed to the increased hardness of the composite and the presence of hard ceramic particles that resist abrasive wear. However, the magnitude of improvement depends on the quality of particle distribution and the strength of interfacial bonding.

3.2 Interfacial Characteristics and Bonding Mechanisms

The interface between kaolin particles and aluminium matrix represents a critical region that determines load transfer efficiency and overall composite performance (Figure 2). The layered crystal structure of kaolinite, consisting of silica tetrahedral sheets bonded to alumina octahedral sheets through strong ionic-covalent bonds, presents both opportunities and challenges for interfacial bonding. The weak van der Waals forces between adjacent kaolinite layers can be exploited through intercalation treatments to enhance surface reactivity. Wetting behavior between molten aluminium and kaolin particles is fundamentally influenced by surface energy considerations. The hydrophilic nature of untreated kaolin results in poor wetting by aluminium, potentially leading to weak interfacial bonding and ineffective load transfer. This wetting challenge can be addressed through surface modification treatments that reduce surface hydroxyl content or introduce coupling agents. Research by Zykova et al. [8] demonstrated that treated kaolinite forms, including intercalated and exfoliated varieties, led to enhanced mechanical and chemical properties compared to unmodified kaolinite in composite systems. The application of external forces during processing, particularly through vigorous stirring in liquid-state methods, can overcome poor wetting by disrupting oxide layers on particle surfaces and promoting particle spreading. The force balance on particles during melt stirring involves buoyancy, gravity, surface tension, hydrostatic pressure, and drag forces. Small particles require higher melt velocities for effective incorporation, especially when wetting is poor [9]. Achieving optimal stirring conditions that maximize particle incorporation while minimizing gas entrapment and oxide inclusion formation represents a key processing challenge.

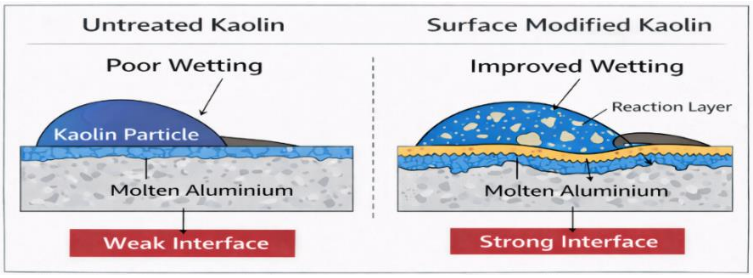

Figure 2. Schematic of interfacial bonding mechanism

Interfacial reactions between aluminium and kaolin at elevated temperatures can produce various phases depending on processing conditions. While limited reaction can enhance bonding through formation of transition zones, excessive reaction may lead to formation of brittle intermetallic compounds that degrade mechanical properties [10]. The formation of aluminium carbides, which can occur if carbon contamination is present or under reducing conditions, is particularly detrimental due to their brittleness and susceptibility to hydrolysis. Careful control of processing atmosphere and temperature-time exposure is therefore essential [11].

3.3 Processing Parameter Optimization

Systematic investigation of processing parameter effects has revealed complex relationships between individual parameters and composite properties. Studies employing Taguchi experimental designs have demonstrated that stirring temperature, stirring time, stirring speed, and reinforcement content all significantly influence the final properties, though their relative importance varies depending on the specific property being optimized. The study by Shanhin et al. [12] on Al-SiC composites provides insights applicable to kaolin-reinforced systems. Their investigation revealed that 2-minute stirring time was insufficient for effective bonding at the metal-ceramic interface, emphasizing the importance of adequate duration for particle-matrix interaction. Higher stirring temperatures improved particle incorporation but led to reduced mechanical properties due to increased shrinkage porosity and interfacial reaction products. This finding highlights the need to balance particle incorporation effectiveness against potential negative consequences of elevated temperatures. Stirring speed influences both the mechanical force available for particle incorporation and the propensity for gas entrapment. Excessive stirring speeds can create turbulence that entraps gas, leading to increased porosity. Conversely, insufficient stirring speeds may result in poor particle distribution and settling. The optimal stirring speed depends on melt viscosity, particle characteristics, and crucible geometry, requiring empirical determination for specific material systems [13]. The study by Chayong et al. [14] on thixoforming of 7075 aluminium alloy demonstrated that temperature control within narrow ranges (616-618°C) provided optimal results, with defects occurring at both lower and higher temperatures. Ram speed also affected defect formation, with moderate speeds generally superior. These findings emphasize the importance of precise parameter control in achieving high-quality composites. Some of these parameters are highlighted in Figure 3.

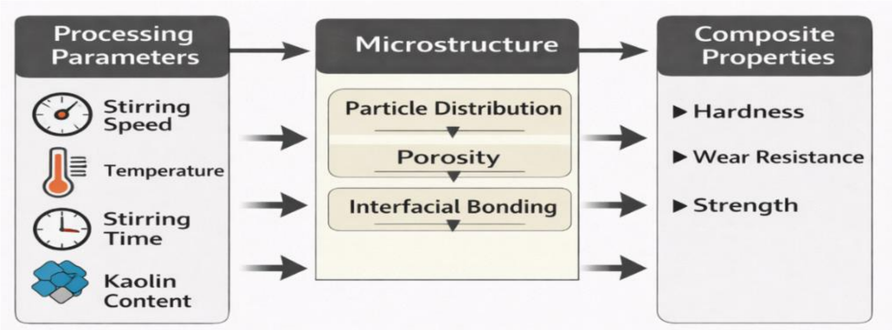

Figure 3. Processing Parameters → Microstructure → Properties

Multi-objective optimization studies employing grey relational analysis have successfully identified processing conditions that simultaneously enhance multiple properties. The approach converts multiple responses into a single optimization index, enabling identification of optimal parameter combinations that balance conflicting objectives. For instance, maximizing strength while minimizing porosity and maintaining acceptable ductility requires finding processing conditions that achieve proper particle distribution without excessive gas entrapment or interfacial degradation.

3.4 Comparison with Conventional Reinforcements

Kaolin-reinforced aluminium composites must be evaluated in context with composites using conventional ceramic reinforcements such as silicon carbide, alumina, and boron carbide to assess their relative performance and potential applications. Conventional reinforcements have been extensively studied and demonstrate well-established property enhancement profiles, providing benchmarks for comparison. Silicon carbide reinforced aluminium composites have shown remarkable improvements in strength, stiffness, and wear resistance. The work by Singh & Singh [6] demonstrated that increasing SiC content from 4% to 10% resulted in decreased wear rate but increased hardness, with optimal properties achieved at intermediate reinforcement levels. Similarly, Gopal et al. [15] observed that hardness and tensile strength increased with boron carbide (B_4C) content from 6% to 12%. These conventional reinforcements typically achieve higher absolute strength values compared to kaolin due to their superior mechanical properties and well-established processing techniques. However, kaolin offers significant advantages in terms of cost, availability, and environmental sustainability. The natural abundance of kaolin and its significantly lower cost compared to synthetic ceramic powders make it attractive for applications where moderate property enhancement is acceptable and cost considerations are paramount. Additionally, kaolin's lower density compared to many conventional reinforcements contributes to overall composite weight reduction. The investigation by Krishna & Sandeep [16] demonstrated that substituting stainless steel with SiC-reinforced aluminium in hydraulic actuators decreased weight by 65.73% while reducing fabrication costs by 44.95%. Similar weight and cost advantages could potentially be realized with kaolin reinforcement, though the magnitude of mechanical property improvement may be lower. This trade-off between cost and performance must be evaluated for specific application requirements. Research by Khalil et al. [17] on titanium carbide nanofiber reinforcement achieved compressive and yield strengths of 415 MPa and 350 MPa respectively at 5 wt% content, demonstrating the high performance achievable with advanced reinforcements. While kaolin-reinforced composites may not reach such strength levels, they may be suitable for applications requiring moderate strength enhancement combined with improved wear resistance and thermal properties at lower cost.

3.5 Microstructural Evolution and Defect Formation

The microstructure of kaolin-reinforced aluminium composites is characterized by the distribution of ceramic particles within the metallic matrix, the nature of the particle-matrix interface, and the presence of various defects. Achieving uniform particle distribution represents a primary challenge in composite processing, as non-uniform distribution leads to localized property variations and potential failure initiation sites [18]. Several defect types commonly occur in liquid-state processed composites, including gas porosity, shrinkage porosity, particle clustering, and interfacial voids. Gas porosity arises from entrapment of gases during stirring or from gas evolution during solidification. Shrinkage porosity forms due to volumetric contraction during solidification, particularly in regions with high local reinforcement content that restrict feeding of liquid metal [19]. Particle clustering occurs when particles agglomerate due to insufficient dispersion forces or attractive interactions between particles. Interfacial voids can form when wetting is inadequate, leaving gaps between particles and matrix [20]. The work by Eslamian et al. [21] on centrifugal atomization of Al/SiC composites found that the void volume fraction in composites prepared using their method was low, indicating suitability for high-quality production. This finding suggests that processing method selection significantly influences defect formation and that careful process design can minimize porosity. In stir casting processes, controlling stirring parameters, melt cleanliness, and solidification conditions is essential for defect minimization. Particle size distribution influences microstructural uniformity and mechanical behavior. Fine particles provide larger interfacial area for load transfer but are more difficult to disperse uniformly and may agglomerate more readily. Coarse particles are easier to disperse but provide less interfacial area. Optimal particle size distributions may involve bimodal or multimodal distributions that combine the advantages of different size ranges. The study by Oladele and Akinpelu [22] demonstrated that the rheo-process considerably enhanced reinforcement dispersion compared to conventional compo-casting, leading to notable improvements in both ultimate tensile strength and tensile elongation. This finding illustrates the importance of processing method selection in achieving superior microstructures. Advanced processing techniques that apply high shear forces during the semi-solid state can break up particle clusters and improve distribution uniformity.

3.6 Thermal and Tribological Properties

Beyond mechanical properties, thermal and tribological characteristics of kaolin-reinforced aluminium composites are important for many applications. Thermal conductivity, thermal expansion coefficient, and wear resistance determine suitability for thermal management applications, engine components, and sliding contact applications. The addition of ceramic reinforcements generally reduces thermal conductivity of aluminium due to increased phonon scattering at particle-matrix interfaces. However, this reduction must be balanced against other property improvements. Basma et al. [5] found that thermal conductivity and effectivity increased with kaolin loading in PVC composites, though the mechanisms in metallic matrices may differ. The thermal stability of kaolin enables its use in elevated temperature applications without degradation, maintaining structural integrity where polymer-based composites would fail. Wear resistance improvements with kaolin addition have been documented in several studies. The presence of hard ceramic particles provides resistance to abrasive wear mechanisms, while increased hardness reduces plastic deformation during sliding contact. Shanmughasundaram [23] demonstrated that heat treatment significantly improved wear resistance of AA7075/SiC composites, with T6 aging for 6 hours providing optimal results. Similar heat treatment approaches could potentially enhance kaolin-reinforced composites through precipitation strengthening of the matrix while maintaining reinforcement integrity. The tribological behavior depends on factors including reinforcement content, particle size, testing conditions, and counter face material. Under sliding wear conditions, kaolin particles can act as solid lubricants if they are exposed at the surface, potentially reducing friction and wear. However, if particles are pulled out of the matrix due to weak interfacial bonding, they may act as abrasive third bodies, increasing wear. Achieving strong interfacial bonding is therefore critical for optimal tribological performance.

3.7 Research Gaps and Future Trends

Despite progress in understanding kaolin-reinforced aluminium composites, significant research gaps remain that require systematic investigation. The effect of kaolin particle size on mechanical properties under varying processing conditions has not been comprehensively studied.

While general trends suggest finer particles provide better properties, the optimal particle size likely depends on processing method, reinforcement content, and desired property profile. Systematic investigation across a range of particle sizes using consistent processing conditions would provide valuable insights. The influence of surface modification temperature on interfacial bonding strength and subsequent mechanical properties requires detailed examination. While thermal treatment of kaolin is known to alter surface characteristics, the optimal modification temperature for aluminum matrix composites has not been established. Investigation spanning a range of temperatures from 400°C to 800°C, with detailed characterization of interfacial bonding mechanisms and mechanical property evolution, would address this gap. Multi-objective optimization addressing the inherent trade-offs between strength, ductility, density, and cost has received limited attention. Most studies optimize single properties or use simplified approaches that may not capture the complex interactions between multiple objectives. Application of advanced multi-objective optimization algorithms that can explore the Pareto frontier of achievable property combinations would enable better-informed material design decisions. The long-term stability of kaolin-reinforced composites under service conditions requires investigation. Environmental exposure, thermal cycling, and sustained loading may affect interfacial bonding and lead to property degradation over time. Understanding these aging mechanisms is essential for predicting service life and establishing appropriate design allowable for engineering applications. Scale-up from laboratory to industrial production presents practical challenges that have not been adequately addressed. Most studies involve small batch sizes where process control is relatively straightforward. Maintaining consistent quality in larger production volumes requires understanding of scaling relationships and development of appropriate quality control procedures. Investigation of industrial-scale processing methods, including continuous casting approaches, would facilitate commercial adoption.

4. CONCLUSIONS

This review has examined kaolin-reinforced aluminum metal matrix composites, covering processing techniques, interfacial characteristics, mechanical properties, and optimization methodologies. Kaolin offers a low-cost, sustainable alternative to conventional ceramic reinforcements, though its hydrophilic nature and layered aluminosilicate structure make wetting and interfacial bonding with molten aluminum a key challenge. Stir casting remains the preferred fabrication route, with hardness and wear resistance improving at intermediate reinforcement contents before agglomeration and porosity become limiting. Optimization approaches such as Taguchi design and grey relational analysis have proven effective for identifying optimal processing conditions and addressing multi-objective property trade-offs. Notable gaps remain around particle size distribution, optimal surface modification, and industrial scale-up, and addressing these will be essential to developing reliable process-structure-property relationships. With continued research, kaolin-reinforced aluminum composites hold strong potential for cost-sensitive automotive, aerospace, and structural applications.

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