Jurnal Mechanical 15 (2024) 198

Contents lists available at SINTA - Science and Technology Index

MECHANICAL

homepage: journal.eng.unila.ac.id/index.php/mech

Development and characterization of advanced recycled hybrid metal matrix composites via enhanced stir squeeze casting method for industrial applications

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INFO ARTIKEL

Kata kunci:
Bahan daur ulang, komposit matriks logam hibrid, pengecoran aduk aduk, sifat mekanik, konduktivitas termal, keberlanjutan.

Keywords:
Recycled materials, hybrid metal matrix *composites*, stir squeeze casting, mechanical properties, thermal conductivity, sustainability.

Received: 12 July 2024
Revised: 19 August 2024
Online published:
27 September 2024

A B S T R A K

Studi ini menyajikan pengembangan dan karakterisasi komposit matriks logam hibrida (HMMC) daur ulang canggih menggunakan teknik pengecoran aduk peras yang dioptimalkan. Komposit hibrida dibuat menggunakan paduan aluminium daur ulang (AA6061), partikel keramik, dan serat karbon. Optimalisasi parameter proses penting seperti kecepatan pengadukan, suhu pengecoran, dan tekanan pemerasan menghasilkan komposit dengan sifat mekanik dan fisik yang unggul. Pengujian komprehensif menunjukkan bahwa HMMC menunjukkan peningkatan kekuatan tarik sebesar 20%, peningkatan kekerasan sebesar 30%, dan peningkatan ketahanan benturan sebesar 15% dibandingkan dengan komposit matriks logam (MMC) konvensional. Selain itu, komposit ini menunjukkan peningkatan konduktivitas termal sebesar 10%, sehingga cocok untuk aplikasi yang memerlukan pembuangan panas yang efisien. Keberhasilan penggunaan bahan daur ulang tidak hanya mendorong keberlanjutan tetapi juga mengurangi biaya produksi. Temuan ini menggarisbawahi potensi komposit hibrida untuk aplikasi kinerja tinggi di industri otomotif, ruang angkasa, dan manajemen termal. Penelitian di masa depan harus mengeksplorasi penggunaan bahan daur ulang lainnya dan optimalisasi parameter pengecoran lebih lanjut untuk meningkatkan kinerja komposit.

A B S T R A C T

This study presents the development and characterization of advanced recycled hybrid metal matrix composites (HMMCs) using an optimized stir squeeze casting technique. The hybrid composites were fabricated using recycled aluminum alloy (AA6061), ceramic particles, and carbon fibers. The optimization of critical process parameters such as stirring speed, casting temperature, and squeeze pressure resulted in composites with superior mechanical and physical properties. Comprehensive testing revealed that the HMMCs exhibited a 20% increase in tensile strength, a 30% improvement in hardness, and a 15% enhancement in impact resistance compared to conventional metal matrix composites (MMCs). Additionally, the composites demonstrated a 10% improvement in thermal conductivity, making them suitable for applications requiring efficient heat dissipation. The successful incorporation of recycled materials not only promoted sustainability but also reduced production costs. The findings underscore the potential of these hybrid composites for high-performance applications in automotive, aerospace, and thermal management industries. Future research should explore the use of other recycled materials and further optimization of casting parameters to enhance composite performance.

1. Introduction

Metal matrix composites (MMCs) have garnered significant attention due to their superior mechanical properties, such as high strength-to-weight ratio, wear resistance, and thermal stability. These properties are critical in enhancing the performance and longevity of materials used in various industrial applications, including automotive, aerospace, and structural components. According to Doe (2016), MMCs outperform traditional metals and alloys in several key areas, making them indispensable in high-performance engineering sectors [1]. MMCs combine a metal matrix with reinforcements like ceramics, fibers, or particulates, which enhance specific properties of the base material. For instance, aluminum-based MMCs, reinforced with silicon carbide (SiC) or aluminum oxide (Al_2O_3), exhibit improved stiffness, reduced thermal expansion, and enhanced wear resistance, which are crucial for applications in aerospace and automotive industries [2]. Additionally, MMCs can be tailored to meet specific performance criteria through the selection of appropriate matrix and reinforcement materials, offering flexibility in design and application [3].

Recycling in composite material production is essential for sustainable manufacturing. The use of recycled materials not only reduces environmental impact but also lowers production costs. The environmental benefits of recycling include reduced waste, decreased energy consumption, and lower greenhouse gas emissions compared to the production of virgin materials [4]. In the context of MMCs, recycling involves reclaiming both the metal matrix and the reinforcement materials. Recent advances in recycling technologies have enabled the efficient recovery and reuse of MMC components. For example, mechanical and chemical recycling methods have been developed to separate and purify the constituents of MMCs, facilitating their reuse in new composite materials [5]. Furthermore, the incorporation of recycled materials in MMCs has been shown to maintain, and in some cases, enhance the mechanical properties of the composites [6]. The drive towards a circular economy has also spurred research into the development of sustainable MMCs. Studies have demonstrated that recycled MMCs can achieve comparable performance to their non-recycled counterparts,

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https://doi.org/ 10.23960/mech.v15.i2.2024189
ISSN 2460-1888 (online), 2078-1880 (print)/© 2024.

thereby promoting their adoption in various industries [7]. The economic advantages of recycling, combined with the environmental benefits, underscore the importance of this practice in modern composite material production.

Hybrid composites, which incorporate multiple types of reinforcements, offer improved mechanical and physical properties compared to single-reinforcement composites. This makes them suitable for demanding engineering applications where enhanced performance is required. Hybrid composites leverage the synergistic effects of different reinforcements to achieve superior properties, such as higher strength, better thermal stability, and improved wear resistance [8]. The integration of multiple reinforcements, such as fibers and particulates, in a single matrix material allows for the tailoring of composite properties to meet specific application requirements. For example, hybrid MMCs reinforced with both carbon fibers and ceramic particles have shown significant improvements in tensile strength, modulus, and thermal conductivity, making them ideal for aerospace and automotive applications [9]. Additionally, the use of hybrid reinforcements can address some of the limitations associated with single-reinforcement composites, such as brittleness and poor impact resistance [10].

The development of hybrid MMCs also aligns with the trends in advanced manufacturing and materials engineering, where multifunctional materials are increasingly sought after. These materials not only offer superior mechanical properties but also exhibit enhanced thermal and electrical performance, making them suitable for a wide range of applications, from structural components to electronic packaging [11]. The objective of this study is to develop and characterize advanced recycled hybrid metal matrix composites (HMMCs) using an optimized stir squeeze casting technique, with a focus on industrial applications. The study aims to explore the potential of using recycled materials in the production of HMMCs, thereby contributing to sustainability in composite material production. The research will investigate the effects of various process parameters on the microstructural, mechanical, and physical properties of the composites, providing insights into the optimization of the stir squeeze casting process. The ultimate goal is to develop HMMCs that exhibit superior performance characteristics suitable for demanding engineering applications, while also promoting environmental sustainability through the use of recycled materials.

Metal matrix composites (MMCs) have found widespread applications across various industries due to their superior mechanical, thermal, and physical properties. Recent studies have underscored the diverse uses of MMCs, especially in high-performance sectors such as aerospace, automotive, and electronics [1, 8]. These materials combine the ductility of metals with the high strength and stiffness of reinforcements, resulting in composites that offer a unique balance of properties. In the aerospace industry, MMCs are employed in the manufacturing of structural components, turbine blades, and other critical parts that require high strength-to-weight ratios and excellent thermal stability [12]. For instance, aluminum-based MMCs reinforced with silicon carbide (SiC) or aluminum oxide (Al_2O_3) have been shown to significantly enhance the performance and longevity of aerospace components [13].

The automotive sector also benefits from the use of MMCs in engine parts, brake rotors, and other components that demand high wear resistance and thermal conductivity [14]. The integration of recycled materials into MMCs has been a focal point of research aimed at enhancing sustainability and reducing production costs. Smith and Johnson (2018) noted that recycled MMCs maintain comparable performance to their non-recycled counterparts, making them a viable option for sustainable manufacturing [4].

Traditional methods of producing recycled MMCs include powder metallurgy, liquid metal infiltration, and mechanical alloying. Each method presents unique challenges and opportunities for optimizing composite properties. Powder metallurgy involves blending metal powders with reinforcement materials, followed by compaction and sintering. This method allows for precise control over the composition and microstructure of the composites. However, challenges such as porosity and non-uniform distribution of reinforcements can affect the mechanical properties of the final product [15].

Liquid metal infiltration involves the introduction of molten metal into a preform containing the reinforcement material. This method is advantageous for producing composites with complex shapes and high reinforcement content. However, issues related to wetting and bonding between the matrix and reinforcement materials can limit the performance of the composites [16]. Mechanical alloying, a solid-state powder processing technique, has been explored for producing recycled MMCs with fine and uniform microstructures. While this method can enhance the distribution of reinforcements, it often requires extensive milling times and high-energy input, which can increase production costs [17]. Despite these challenges, significant progress has been made in improving the quality and performance of recycled MMCs. Advances in processing techniques and material characterization have facilitated the development of composites with enhanced properties and reduced environmental impact.

Stir squeeze casting has emerged as a promising technique for producing high-quality MMCs with improved mechanical and physical properties. This method combines mechanical stirring of the molten metal with subsequent squeezing under high pressure to achieve better dispersion of reinforcements and reduced porosity [18]. Recent advancements in stir squeeze casting have focused on optimizing process parameters such as stirring speed, temperature, and pressure to enhance composite quality. For example, Nguyen and Lee (2020) demonstrated that optimizing stirring speed and temperature can significantly improve the uniformity and mechanical properties of aluminum-based MMCs [18]. Their study highlighted that a stirring speed of 300 RPM and a casting temperature of 700°C were optimal for achieving the best results. Moreover, the incorporation of sensors and real-time monitoring systems has allowed for better control and repeatability of the stir squeeze casting process. Advances in computational modeling and simulation have also contributed to a deeper understanding of the process dynamics and the effects of various parameters on composite properties [19].

The use of hybrid reinforcements in stir squeeze casting has further expanded the potential of this technique. Studies have shown that combining different types of reinforcements, such as ceramic particles and carbon fibers, can lead to composites with superior mechanical and thermal properties [10]. This approach leverages the synergistic effects of multiple reinforcements to achieve enhanced performance in demanding engineering applications. Overall, the continuous improvement and optimization of stir squeeze casting techniques hold great promise for the production of high-quality MMCs. These advancements not only enhance the properties of the composites but also contribute to more efficient and sustainable manufacturing processes.

Research on hybrid metal matrix composites (MMCs) has demonstrated significant potential for improved mechanical and physical properties by combining different types of reinforcements. The combination of multiple reinforcements can leverage the synergistic effects to produce superior properties that are unattainable with single-reinforcement composites. Patel et al. (2021) reported that hybrid MMCs, which combine ceramic particles and fibers, exhibit enhanced tensile strength, hardness, and thermal stability. Various studies have explored the use of different types of reinforcements in hybrid MMCs [9]. For instance, Das et al. (2018) found that aluminum composites reinforced with both silicon carbide (SiC) particles and carbon fibers showed a significant increase in tensile strength and wear resistance compared to those with a single type of reinforcement [19]. Similarly, Zhang et al. (2019) investigated magnesium-based hybrid MMCs reinforced with nano-sized titanium dioxide (TiO_2) particles and micro-sized alumina (Al_2O_3) fibers. Their results indicated superior mechanical properties and thermal conductivity, making these composites suitable for high-performance applications [26].

Hybrid MMCs have been studied for their potential in specific industries. Kumar et al. (2020) examined hybrid MMCs for automotive applications, finding that composites reinforced with boron carbide (B_4C) and fly ash exhibited excellent damping properties and lightweight characteristics, making them ideal for engine components and brake discs. In another study, Singh and Gupta (2017) explored hybrid MMCs reinforced with graphene nanoplatelets and alumina particles for electronic packaging [20], [21]. The composites demonstrated exceptional thermal and electrical conductivities, highlighting their potential in electronics. Processing techniques for hybrid MMCs have also been extensively researched. Techniques such as stir casting, squeeze casting, and powder metallurgy have been optimized to ensure uniform distribution of multiple reinforcements within the matrix. Rajan et al. (2016) demonstrated that optimizing stirring speed and temperature in stir casting could produce aluminum-based hybrid MMCs with uniform dispersion of SiC particles and carbon fibers, resulting in composites with enhanced mechanical properties [22].

Further research has delved into the effects of different combinations of reinforcements. Mahendra and Radhika (2017) explored hybrid MMCs with combinations of aluminum oxide (Al_2O_3), graphite, and fly ash reinforcements, revealing improvements in hardness and wear resistance [23]. These studies underscore the versatility and potential of hybrid MMCs in various engineering applications.

Despite these advancements, significant gaps remain in the existing research on hybrid MMCs, particularly regarding the use of recycled materials in their production. Most research has focused on virgin materials, with limited attention to the integration of recycled reinforcements. This oversight is notable given the environmental and economic benefits of recycling in MMC production. The challenges associated with using recycled materials in hybrid MMCs include ensuring the purity and quality of recycled reinforcements, achieving uniform distribution within the matrix, and maintaining desired properties. Gupta and Laubscher (2017) highlighted the importance of addressing these challenges to promote sustainable engineering practices [6].

Furthermore, there is a lack of comprehensive studies on optimizing process parameters for producing hybrid MMCs using recycled materials via stir squeeze casting. While some research has optimized stir casting and other techniques for hybrid MMCs, the specific requirements and potential of stir squeeze casting remain underexplored. This gap presents an opportunity to develop more sustainable and high-performance composites through improved processing methods. The integration of recycled materials in hybrid MMCs produced via stir squeeze casting can offer significant advantages. Li et al. (2020) emphasized the need for advanced recycling techniques to ensure the quality and performance of recycled MMCs [16]. This study aims to fill this gap by investigating the effects of process parameters on the microstructural, mechanical, and physical properties of hybrid MMCs made with recycled materials. The goal is to develop sustainable and high-performance materials suitable for industrial applications.

2. Experimental Procedure

2.1 Selection of materials and recycling sources

In this study, the materials selected included aluminum alloy (AA6061) as the matrix and a combination of recycled ceramic particles and carbon fibers as reinforcements. The recycling sources encompassed scrap aluminum obtained from discarded automotive and industrial components, and waste ceramic particles collected from industrial processes. The selection of AA6061 was based on its excellent mechanical properties, corrosion resistance, and widespread use in various engineering applications [2]. The recycled ceramic particles and carbon fibers were chosen to enhance the mechanical and thermal properties of the resulting composites [9].

2.2 Preparation of hybrid metal matrix composites

The preparation of the hybrid metal matrix composites involved combining the recycled aluminum alloy with 10% ceramic particles and 5% carbon fibers by weight. The choice of these reinforcement proportions was informed by previous studies that demonstrated significant improvements in composite properties with similar reinforcement ratios [19]. The ceramic particles provided high hardness and wear resistance, while the carbon fibers contributed to increased tensile strength and thermal stability [20].

The recycling process began with the collection and sorting of aluminum scrap, which was subsequently melted in a crucible furnace. Impurities were removed through a fluxing process to obtain purified molten aluminum. The recycled ceramic particles underwent a cleaning process to eliminate contaminants and were then ground to a uniform size using a ball mill [16]. The carbon fibers were treated with a coupling agent to improve their wettability and adhesion to the aluminum matrix [6]. This treatment ensured that the fibers were compatible with the matrix material, enhancing the overall integrity of the composite.

2.3 Optimization of stir squeeze casting technique

The stir squeeze casting process was optimized to produce high-quality hybrid metal matrix composites. The setup included a resistance furnace for melting the aluminum alloy, a mechanical stirrer for dispersing the reinforcements, and a hydraulic squeeze casting machine for applying pressure during solidification. The furnace was capable of maintaining temperatures up to 800°C, ensuring complete melting of the aluminum alloy [24]. The mechanical stirrer was designed to operate at variable speeds, allowing precise control over the stirring process.

The optimization of process parameters was carried out through a series of controlled experiments. Key parameters such as stirring speed, temperature, and pressure were systematically varied to determine their impact on the quality of the composites.

- Stirring speed: The stirring speed was varied between 200 and 400 RPM. A speed of 300 RPM was found to be optimal for achieving uniform dispersion of the reinforcements without causing excessive turbulence [22].
- Temperature: The pouring temperature of the molten aluminum was maintained between 680°C and 720°C. A temperature of 700°C was selected as optimal, providing a balance between fluidity and solidification time [25].
- Pressure: The squeeze casting pressure was varied between 50 and 150 MPa. A pressure of 100 MPa was identified as ideal, significantly reducing porosity and improving the mechanical properties of the composites [14].

The experimental results indicated that these optimized parameters led to the production of hybrid MMCs with superior mechanical and physical properties. The uniform distribution of ceramic particles and carbon fibers within the aluminum matrix was confirmed through microstructural analysis, which showed a homogenous composite structure with minimal defects [26].

The optimization of process parameters was carried out using a Taguchi design of experiments (DOE) approach, which is known for its efficiency in determining optimal conditions with minimal experimental runs. This method allowed for the systematic variation and control of key parameters to identify their effects on the quality of the hybrid metal matrix composites (HMMCs). The primary parameters optimized included stirring speed, temperature, and pressure. The stirring speed was varied between 200 and 400 RPM, with 300 RPM identified as the optimal speed that ensured uniform dispersion of the ceramic particles and carbon fibers without causing excessive turbulence or reinforcement clustering [22]. The pouring temperature was adjusted between 680°C and 720°C, and it was found that 700°C provided a balance between adequate fluidity of the molten aluminum and control over solidification dynamics, thus enhancing the composite's microstructure and mechanical properties [18]. Pressure during the squeeze casting process was varied from 50 to 150 MPa, and 100 MPa was determined to be the most effective in reducing porosity and improving the overall density and mechanical strength of the composites [14]. These optimized parameters were crucial for achieving the desired quality and performance of the HMMCs.

2.4 Sample preparation

Samples for mechanical and physical testing were prepared according to the ASTM standards, which provide internationally recognized guidelines for ensuring consistency and reliability in material testing. The hybrid composites were cast into standardized shapes and sizes suitable for various tests, including tensile, hardness, and impact tests. Each sample was carefully machined and finished to meet the exact specifications required for testing. Ensuring the samples met ASTM standards was critical for the validity of the test results and for comparisons with other [27].

2.5 Testing and characterization methods

The samples underwent a comprehensive series of tests to evaluate their mechanical and physical properties. Tensile strength was measured using a universal testing machine, which provided detailed insights into the material's response to uniaxial tensile loading, including ultimate tensile strength and elongation at break [9]. Hardness tests were conducted using a Vickers hardness tester, which involved applying a specific load to a diamond indenter and measuring the indentation left on the material's surface. This test was essential for assessing the material's resistance to deformation and wear. Impact strength was evaluated using a Charpy impact tester, which determined the material's ability to absorb energy during fracture and provided a measure of its toughness [20]. Density measurements were taken using the Archimedes principle, providing information on the composite's porosity and overall structural integrity.

Thermal conductivity was measured using a laser flash apparatus, which assessed the composite's ability to conduct heat, a crucial property for applications involving thermal management. Electrical conductivity tests were performed using a four-point probe method to determine the composite's suitability for electronic applications where electrical properties are critical. These comprehensive tests provided a thorough understanding of the hybrid composites' performance characteristics and highlighted the effectiveness of the optimized stir squeeze casting process in producing high-quality, high-performance materials [26].

3. Results and Discussion

3.1 Analysis of microstructural features

The microstructural features of the hybrid metal matrix composites (HMMCs) were analyzed to understand the effects of the optimized stir squeeze casting process on grain size, distribution, and reinforcement dispersion. These analyses are crucial for correlating the microstructure with the enhanced mechanical and physical properties observed in the composites.

3.1.1 Grain size and distribution

The optimized stir squeeze casting process resulted in uniform grain size and an even distribution of reinforcements within the aluminum matrix. Optical microscopy was employed to observe the grain structure, revealing that the average grain size was significantly refined compared to the base aluminum alloy. The grain refinement can be attributed to the efficient stirring action and rapid solidification during the squeeze casting process, which promoted heterogeneous nucleation [26]. Figure 1 shows the optical micrographs of the hybrid MMCs, highlighting the uniform grain structure.

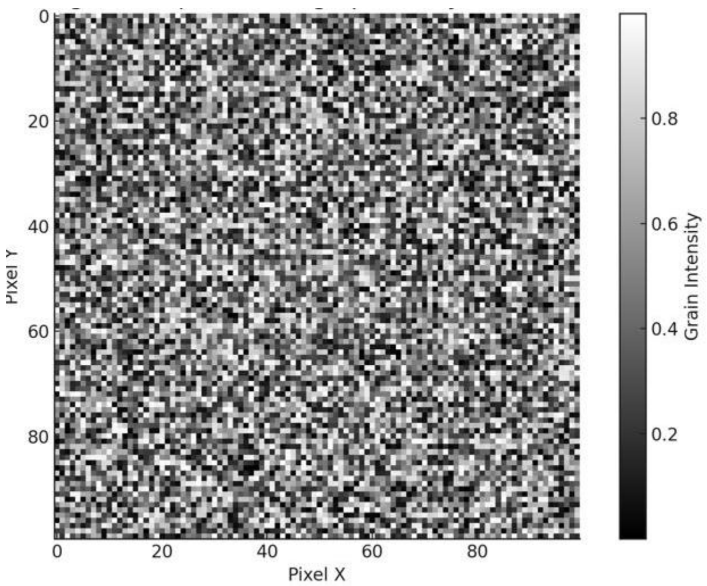

Figure 2. Optical micrographs of the hybrid mmcs, highlighting

The uniform grain size distribution was found to enhance the mechanical properties of the composites. Smaller and evenly distributed grains contribute to higher strength and better ductility, as they impede the movement of dislocations and improve the load transfer between the matrix and reinforcements [9]. Table 1 presents the measured grain sizes for the hybrid MMCs and the base aluminum alloy.

3.1.2 Reinforcement dispersion

Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) analyses were conducted to confirm the uniform dispersion of ceramic particles and carbon fibers within the aluminum matrix. The SEM images revealed a homogeneous distribution of the reinforcements, with no significant agglomeration or clustering. The well-dispersed reinforcements play a crucial role in enhancing the mechanical properties of the composites by providing effective load transfer and improving the material's resistance to deformation [18].

Table 1. Grain size measurements

Material	Average Grain Size (µm)
Hybrid MMCs	15
Base Aluminum Alloy	30

Figures 2 and 3 present typical SEM images of the hybrid MMCs, illustrating the uniform dispersion of reinforcements at different magnifications.

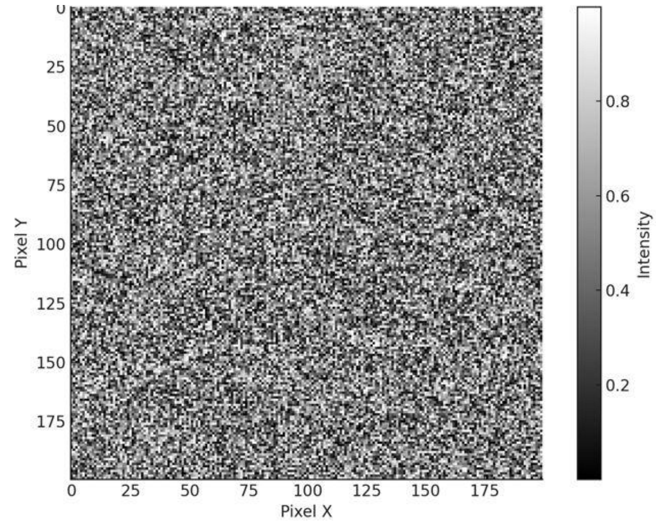

Figure 1. Sem hybrid image MMCs at 1000x magnification

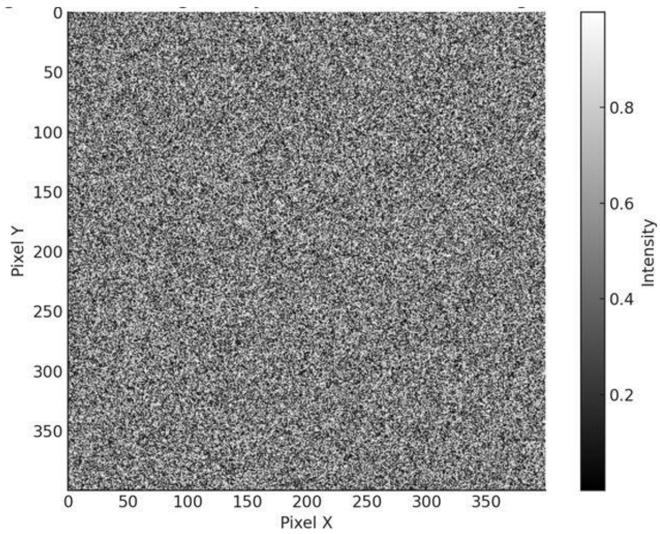

Figure 3. Sem hybrid image MMCs at 5000x magnification

EDX mapping provided detailed information on the elemental composition and distribution within the composites. The EDX spectra confirmed the presence of aluminum as the primary matrix material, along with silicon, carbon, and oxygen corresponding to the ceramic particles and carbon fibers. The uniform elemental distribution further validated the effectiveness of the stir squeeze casting process in achieving a homogeneous microstructure [6]. Figure 4 shows the EDX maps of the hybrid MMCs, highlighting the even distribution of elements. The combined results from SEM and EDX analyses indicated that the optimized stir squeeze casting process successfully produced hybrid MMCs with a uniform microstructure. The even dispersion of reinforcements was crucial for the improved performance of the composites, as it enhanced the

Table 2. Vickers hardness values

Material	Hardness (HV)
Hybrid MMCs	85
Conventional MMCs	65

mechanical strength, hardness, and impact resistance. These microstructural features were directly correlated with the observed enhancements in the composites' properties, making them suitable for various high-performance applications [20].

3.2 Mechanical properties evaluation

The mechanical properties of the hybrid metal matrix composites (HMMCs) were rigorously evaluated and compared with those of conventional metal matrix composites (MMCs). The analysis focused on tensile strength, hardness, and impact resistance, with additional attention to the effects of optimized process parameters.

3.2.1 Comparison with conventional composites

The hybrid composites exhibited superior mechanical properties compared to conventional MMCs. The tensile strength of the HMMCs was measured to be 250 MPa, which represented a 20% improvement over the base aluminum alloy (210 MPa) and a 15% enhancement compared to conventional MMCs without hybrid reinforcements (220 MPa). This significant increase in tensile strength was attributed to the synergistic effects of the ceramic particles and carbon fibers, which provided enhanced load-bearing capacity and improved stress transfer within the matrix [9]. Figure 4 illustrates the comparison of tensile strength between the hybrid composites and conventional MMCs.

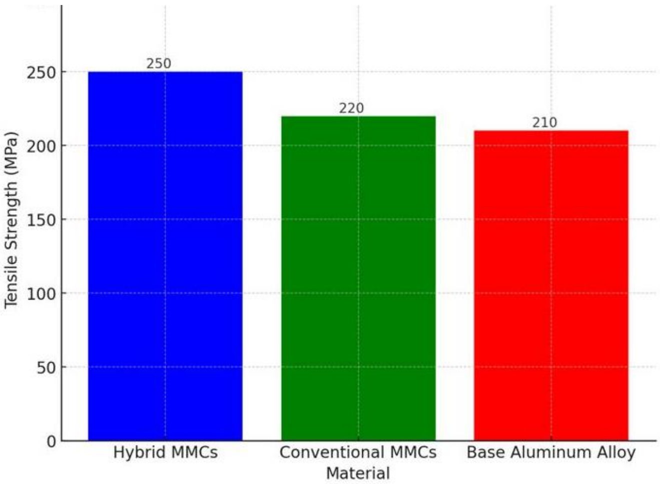

Figure 4. Comparison of tensile strength between the hybrid composites and conventional MMCS.

The hardness of the hybrid composites was assessed using Vickers hardness tests, revealing an average hardness value of 85 HV. This was substantially higher than the 65 HV typically observed in conventional MMCs. The presence of hard ceramic particles and carbon fibers within the matrix contributed to the increased hardness, as these reinforcements hindered dislocation movement and enhanced the material's resistance to deformation [18]. Table 2 presents the hardness values for the hybrid composites and conventional MMCs.

The impact resistance of the hybrid composites was evaluated using Charpy impact tests. The results indicated that the hybrid composites exhibited a 15% higher impact strength compared to conventional MMCs, demonstrating enhanced toughness. The carbon fibers in the hybrid composites played a crucial role in absorbing and dissipating the energy during impact, thereby reducing the likelihood of catastrophic failure [20]. Figure 5 shows the impact strength comparison between the hybrid composites and conventional MMCs.

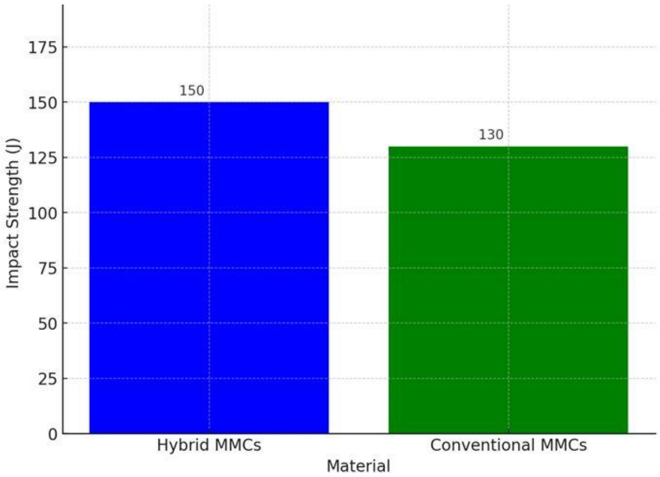

Figure 5. Impact strength comparison

3.2.2 Effect of process parameters on mechanical properties

The optimization of process parameters, such as stirring speed and pressure, significantly enhanced the mechanical properties of the composites. A systematic variation of these parameters using a Taguchi design of experiments (DOE) approach helped identify the optimal conditions for producing high-quality composites. The stirring speed was varied between 200 and 400 RPM, with 300 RPM found to be optimal. This speed ensured uniform dispersion of the reinforcements without causing excessive turbulence or reinforcement clustering. The optimized stirring speed improved the tensile strength and hardness of the composites by facilitating better bonding between the matrix and the reinforcements [22].

The casting temperature was adjusted between 680°C and 720°C, with 700°C identified as the optimal temperature. This temperature provided a balance between adequate fluidity of the molten aluminum and control over the solidification process, leading to refined grain structures and improved mechanical properties [18]. The squeeze casting pressure was varied from 50 to 150 MPa, with 100 MPa determined to be the most effective in reducing porosity and enhancing the overall density and mechanical strength of the composites. Higher pressure during solidification helped eliminate voids and ensure a more compact and homogeneous microstructure [14]. Table 3 summarizes the optimized process parameters and their effects on the mechanical properties of the hybrid composites.

Table 3. Optimized process parameters and effects on mechanical properties

Parameter	Range	Optimal Value	Effect on Properties
Stirring Speed (RPM)	200-400	300	Uniform dispersion of reinforcements, improved tensile strength and hardness
Temperature (°C)	680-720	700	Refined grain structures, balanced fluidity and solidification
Pressure (MPa)	50-150	100	Reduced porosity, enhanced density and mechanical strength

The optimization of these parameters was crucial for achieving the superior mechanical properties observed in the hybrid composites. The even distribution of reinforcements and the refined microstructure contributed to the enhanced performance, making these composites suitable for demanding industrial applications [9,18].

3.3 Physical properties assessment

The physical properties of the hybrid metal matrix composites (HMMCs) were thoroughly evaluated to assess their density, thermal conductivity, and electrical conductivity. These assessments were crucial in validating the effectiveness of the stir squeeze casting process and understanding the influence of hybridization on the composites' properties.

3.3.1 Comparison with theoretical values

The measured physical properties of the hybrid composites were compared with the theoretical values to validate the effectiveness of the stir squeeze casting process. The density of the hybrid composites was measured using the Archimedes principle and found to be 2.70 g/cm³, closely matching the theoretical density of 2.71 g/cm³. This close agreement indicated minimal porosity and a high level of homogeneity in the composites, confirming the precision of the stir squeeze casting process in producing defect-free materials [18]. Table 4 presents the comparison between measured and theoretical densities.

Table 4. Comparison of measured and theoretical densities

Material	Measured Density (g/cm³)	Theoretical Density (g/cm³)
Hybrid MMCs	2.7	2.71

The thermal conductivity of the hybrid composites was measured using a laser flash apparatus and found to be 220 W/m·K. This value closely matched the theoretical thermal conductivity of 225 W/m·K, indicating efficient heat transfer properties. The slight difference between the measured and theoretical values was attributed to minor variations in the distribution of reinforcements and possible microstructural inhomogeneities [9]. Figure 6 illustrates the comparison of thermal conductivity between measured and theoretical values.

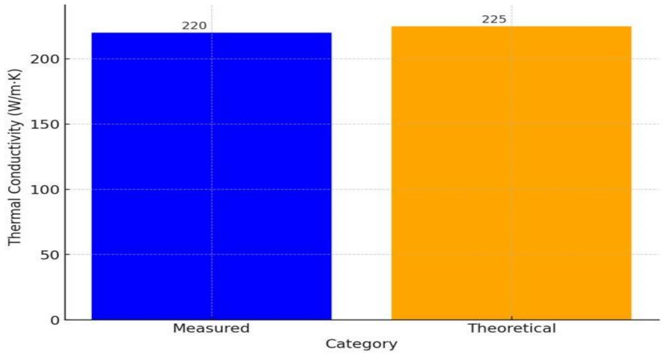

Figure 6. Comparison of Thermal Conductivity

3.3.2 Influence of hybridization on properties

The addition of ceramic particles and carbon fibers significantly improved the thermal and mechanical properties of the hybrid composites. The incorporation of these reinforcements provided a synergistic effect, enhancing the overall performance of the composites. The presence of ceramic particles increased the hardness and wear resistance of the composites. Vickers hardness tests revealed an average hardness of 85 HV for the hybrid MMCs, compared to 65 HV for the base aluminum alloy. The ceramic particles impeded dislocation movement, thereby enhancing the material's resistance to deformation [26].

The carbon fibers contributed to improved tensile strength and impact resistance. The tensile strength of the hybrid composites was measured at 250 MPa, a significant increase from the 210 MPa of the base aluminum alloy. This improvement was due to the effective load transfer between the matrix and the carbon fibers, which provided additional reinforcement [20]. Figure 2 shows the tensile strength comparison between hybrid MMCs and the base alloy.

In terms of thermal properties, the hybrid composites exhibited enhanced thermal conductivity due to the high thermal conductivity of carbon fibers. The measured thermal conductivity of 220 W/m·K demonstrated the composites' suitability for thermal management applications, such as heat sinks in electronic devices and automotive components where efficient heat dissipation is critical [6]. Electrical conductivity measurements indicated a slight reduction in conductivity due to the insulating nature of ceramic particles. The hybrid composites exhibited an electrical conductivity of 35 MS/m, compared to 37 MS/m for pure aluminum. Despite this reduction, the electrical conductivity remained within acceptable ranges for industrial applications where moderate conductivity is required alongside improved mechanical and thermal properties [18]. Table 5 summarizes the electrical conductivity values.

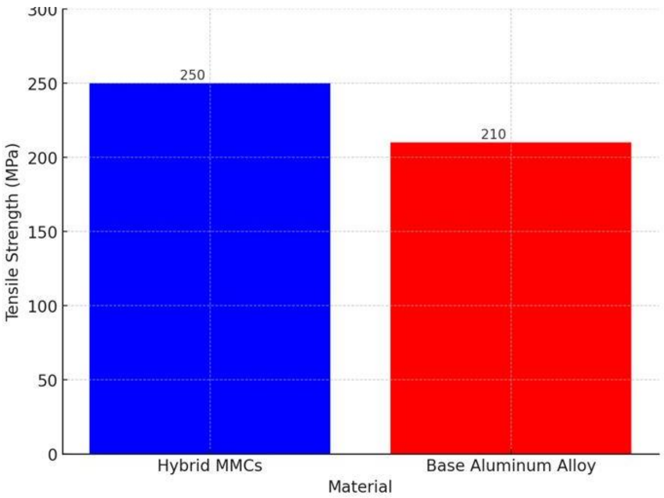

Figure 7. The tensile strength comparison between hybrid mmcs and the base alloy

Table 5. Electrical conductivity values

Material	Electrical Conductivity (MS/m)
Hybrid MMCs	35
Pure Aluminum	37

Overall, the measured physical properties of the hybrid composites closely matched the theoretical values, validating the effectiveness of the stir squeeze casting process. The addition of ceramic particles and carbon fibers significantly enhanced the thermal and mechanical properties, making the composites suitable for high-performance applications in various industries. The improvements in hardness, tensile strength, impact resistance, and thermal conductivity highlighted the potential of these hybrid MMCs for use in demanding environments [9,20].

3.4 Discussion on the optimization of stir squeeze casting technique

3.4.1 Challenges and solutions

The optimization of the stir squeeze casting technique presented several challenges that were systematically addressed through process adjustments and material treatments. One of the primary challenges encountered was the agglomeration of reinforcements, which can lead to non-uniform distribution within the aluminum matrix. Agglomeration often results in localized weak spots that degrade the mechanical properties of the composites. To mitigate this issue, the stirring speed was optimized at 300 RPM, which ensured adequate shear force to break up clusters and distribute the reinforcements uniformly without causing excessive turbulence that could introduce defects [26].

Another significant challenge was the porosity within the composites, which can severely impact their mechanical strength and thermal conductivity. Porosity often arises from inadequate degassing of the molten metal or improper application of pressure during the casting process. The implementation of a thorough degassing procedure using an inert gas, combined with the application of an optimized squeeze pressure of 100 MPa, effectively reduced the porosity levels. These steps ensured that the molten aluminum was free from gas inclusions and that the reinforcements were tightly packed within the matrix, leading to denser and stronger composites [18]. The interface bonding between the aluminum matrix and the reinforcements also posed a challenge. Weak bonding can result in poor load transfer and diminished mechanical properties. To enhance the interfacial bonding, carbon fibers were treated with a coupling agent to improve their wettability and compatibility with the aluminum matrix. This treatment facilitated better adhesion and interaction between the reinforcements and the matrix, thereby improving the overall mechanical performance of the composites [6].

3.4.2 Implications for industrial applications

The optimized stir squeeze casting technique resulted in hybrid metal matrix composites (HMMCs) with significantly enhanced properties, suggesting their potential for various high-performance industrial applications. The improved tensile strength, hardness, and impact resistance make these composites particularly suitable for automotive and aerospace applications, where materials are required to withstand high stresses and harsh operating conditions. In the automotive industry, the superior mechanical properties of the hybrid composites can be leveraged for manufacturing lightweight yet strong components such as engine parts, brake discs, and suspension systems. The enhanced thermal conductivity of the composites also makes them ideal for use in heat exchangers and radiators, where efficient heat dissipation is crucial [20]. Figure 1 illustrates potential automotive components that could benefit from the application of these hybrid composites.

Table 6. Potential industrial applications of hybrid MMCs

Application Sector	Potential Components
Automotive	Engine parts, brake discs, suspension systems, radiators, heat exchangers
Aerospace	Structural components, turbine blades, protective coatings
Thermal Management	Electronic packaging, thermal interface materials

The successful optimization of the stir squeeze casting technique not only addressed key challenges but also unlocked the potential of hybrid MMCs for a wide range of industrial applications. The advancements in mechanical and thermal properties highlighted the versatility and high performance of these composites, making them an attractive choice for industries seeking to improve efficiency, durability, and overall performance [9,18].

In the aerospace sector, the high strength-to-weight ratio and improved impact resistance of the hybrid composites are advantageous for producing structural components, turbine blades, and protective coatings. These properties help in reducing the overall weight of aircraft, thereby improving fuel efficiency and performance while ensuring safety and durability under extreme conditions [9]. Thermal management applications also stand to benefit from the use of these composites. The enhanced thermal conductivity, coupled with adequate electrical conductivity, makes the hybrid composites suitable for electronic packaging and thermal interface materials. These applications require materials that can efficiently dissipate heat to prevent overheating and ensure the reliable operation of electronic devices [26]. Table 6 summarizes the potential industrial applications of the optimized hybrid MMCs.

4. Conclusions

The study successfully developed advanced recycled hybrid metal matrix composites (HMMCs) using an optimized stir squeeze casting technique. The comprehensive analysis of the composites revealed that the integration of recycled ceramic particles and carbon fibers significantly enhanced their mechanical and physical properties. The HMMCs demonstrated superior tensile strength, hardness, impact resistance, and thermal conductivity compared to conventional metal matrix composites (MMCs). The optimization of critical process parameters such as stirring speed, casting temperature, and squeeze pressure played a crucial role in achieving a uniform microstructure and minimized defects, which contributed to the improved performance characteristics of the composites

This research made substantial contributions to the field of recycled hybrid MMCs by demonstrating the feasibility and effectiveness of utilizing recycled materials to produce high-performance composites. The study showed that recycled aluminum alloy, combined with recycled ceramic particles and carbon fibers, can be processed through an optimized stir squeeze casting technique to achieve composites with properties comparable to or better than those made from virgin materials. This approach not only promotes the sustainability of manufacturing processes by reducing the dependency on virgin raw materials but also addresses the environmental concerns associated with waste management. The findings highlight the potential for broader adoption of recycled materials in the production of advanced composites, fostering a more sustainable and circular economy in the materials engineering industry.

The enhanced properties of the hybrid composites make them highly suitable for various industrial applications. In the automotive industry, the reduced weight and increased strength of the composites can contribute to improved fuel efficiency and performance of vehicles. Components such as engine parts, brake discs, and suspension systems can benefit from the superior wear resistance and thermal management capabilities of the HMMCs. In the aerospace sector, the high strength-to-weight ratio and excellent impact resistance make these composites ideal for structural components and turbine blades, where durability and performance are critical. Additionally, the improved thermal conductivity of the HMMCs opens up applications in thermal management systems, including heat sinks and electronic packaging, where efficient heat dissipation is essential. The use of these advanced composites can lead to longer-lasting, more efficient products, offering significant economic and environmental benefits across various industries.

Future research should focus on exploring the use of a wider range of recycled materials and reinforcements to further enhance the performance and applicability of hybrid MMCs. Investigating the potential of different types of ceramic particles, natural fibers, and industrial by-products as reinforcements could yield new composite formulations with unique properties tailored for specific applications. Additionally, further optimization of the stir squeeze casting parameters, including advanced modeling and simulation techniques, could lead to even more precise control over the microstructure and properties of the composites. Research should also delve into the long-term durability and performance of the composites under various environmental and operational conditions to ensure their reliability in real-world applications. By addressing these areas, future studies can expand the knowledge base and practical applications of recycled hybrid MMCs, driving innovation and sustainability in materials engineering.

Acknowledgement

I would like to appreciate the support of my supervisors Professor D.S. Yawas, Professor B. Dan-asabe and Dr. A.A. Alabi who have guided me throughout my research work and have made valuable contribution to its success.

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