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LIGHTWEIGHT AND STRONG: EXPLORING THE POTENTIAL OF METAL MATRIX COMPOSITES

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ABSTRACT

In the present era, one of the most vigorously studied topics is Metal Matrix Composites (MMCs) in material science. For tailoring new metal matrix composites, the lightweight metals and their alloys create an attraction to overcome traditional limitations such as low strength. The high-grade lightweight high-performance MMCs based on aluminium are signified aluminium metal matrix composites. In the aluminium matrix composites, the reinforcements could be in the form of whiskers, continuous fibre, particulates, or discontinuous fibre where volume or weight fraction varies in few percentages. To explore the suitability for diverse industrial applications, this study investigates the thermal, microstructural, and mechanical properties of Aluminum-Silicon Carbide (AI-SiC) Metal Matrix Composites (MMCs). The research focuses on understanding the influence of SiC content on the properties. By a reduction in ductility, this strengthening effect is accompanied which necessitates careful consideration in applications in high strength and ductility. Influencing the thermal characteristics of the MMCs, thermal behaviour assessment implied the shape of aluminium carbide with increasing SiC content. For the application of AI-SiC MMCs in industries the findings of this study provide a foundation to improve performance, reduce weight, and enhance fuel efficiency to extend component lifespan.

Keywords: Metal Matrix Composites, Aluminum-Silicon Carbide, Mechanical Properties, Thermal Behavior, Reinforcement Materials, Microstructural Analysis, Powder Metallurgy and Industrial Applications

1. INTRODUCTION

Metal matrix composites (MMCs) advanced materials that consisting of two major components: one is a base metal such as a matrix and the other is one or more reinforcements for a better combination of properties which is lightweight and strong. Some of the classes of MMCs, such as Diamond tools, Cermets, and Hard Metals, have extensive and various applications and they can be considered conventional materials, and they are constantly in the process of evolution. For a wide range of applications, metal matrix composites (MMCs) are suitable because of their improved mechanical hardness, damping capacity, ductility, and strength, creep, and creep resistance. MMCs are highly desirable for their weight-saving potential and they are used in aviation sectors and ground transport for associated reduction and structural weight reduction in consumption of fuel.

This study states the problems of the research and objections to the research. The problem with the research is that the exact and accurate data about these metals and reinforcement are not available, so a clear and concise concept is hard to serve. The aim of this research is to describe complete and concise data about the MMCs. This study also illustrates the survey of the relevant literature on MMCs, emphasising the properties, applications, and advancements of those properties. This study gives the details of the materials used in your study and their experiments, results, and discussions about that.

2. LITERATURE REVIEW

On Metal Matrix Composites (MMCs), a comprehensive literature review is necessary to understand the breadth and depth of this versatile class of materials, which garnered important attention in the engineering and materials science field. By a metallic matrix reinforced with materials like carbon fibres, ceramics or other particles MMCs are characterized. The unique combination of properties offered by MMCs, like stiffness, lightweight characteristics, and high strength, has positioned them as attractive materials for different applications. This literature review delves into the applications, recent advancements and properties of MMCs while at the same time identifying critical gaps that this study focuses on addressing.

Properties of MMCs: Several factors such as the choice of matrix and reinforcement materials, the volume fraction of reinforcements, and processing methods govern the properties of MMCs. Extensive research has displayed that a strong bond between the matrix and reinforcement is vital for achieving optimal properties. MMCs can exhibit exceptional mechanical properties, like stiffness, wear resistance, and tensile strength when the bond is well-established (Nturanabo et al. 2019). In addition to this, varying these parameters has made them attractive for a wide range of applications, with the potential to tailor MMC properties.

The properties of MMCs expand over mechanical characteristics. Their thermal conductivity, thermal stability, and electrical conductivity are vital factors in their utilization. MMCs can effectively dissipate heat and can have excellent thermal resistance that makes them suitable for applications in high-temperature environments. The electrical conductivity is relevant in electromagnetic and electronic applications where MMCs are employed for the electrical properties and for their combined mechanical properties.

Applications for MMCs: Because of its adaptability, MMCs are now widely used in a range of fields, including aerospace, automotive, and structural applications (Nuresh .2023).. Due to their advantages in terms of lightweight design and capacity to preserve structural integrity under high-temperature conditions, MMCs have found widespread adoption in the aerospace industry for the fabrication of engine components. MMCs are used in the automotive sector to lighten vehicles, increasing their safety and fuel efficiency (Ogawa and Masuda 2021). MMCs are perfect for bridges, buildings, and other infrastructure because of their great strength and low weight, which is advantageous for structural applications.

Specific applications in the aerospace sector include housings, rotors, and fan blades for aircraft engines. MMCs are essential for decreasing weight and increasing fuel efficiency, which helps the industry achieve its overall goal of improved performance. Similar to this, the car industry uses MMCs in body structure, brake discs, suspension elements, and even engine components to reduce total weight, increase fuel efficiency, and lower emissions.

MMCs have been investigated for use in bridges in the field of construction and civil engineering, where their high strength-to-weight ratio and resistance to corrosion may be advantageous (Aliasker et al. 2023). MMCs have also been employed in sporting products like bicycle frames and tennis rackets, where a balance between weight and strength is essential for the best performance.

Recent MMC Advancements: In order to improve MMCs' characteristics and broaden their scope of applications, recent research and development in the field has concentrated on a number of important areas. Some notable developments include:

1. **Matrix Materials:** In addition to standard aluminum, researchers have looked into different matrix materials. These include titanium and magnesium, which have special qualities that increase the range of MMC uses.
2. **Reinforcement Materials:** According to Kamatchi et al. (2023), improvements in reinforcement materials have significantly improved mechanical qualities. For instance, the addition of nano- and advanced ceramic reinforcements has improved characteristics, particularly in terms of strength, stiffness, and wear resistance.
3. **Sophisticated Manufacturing Techniques:** The creation of sophisticated manufacturing techniques including powder metallurgy, spark plasma sintering, and additive manufacturing has made it possible to create MMCs with intricate geometries (Amardeep 2022).. These techniques provide you more control over the material's microstructure and reinforcement distribution.
4. **Hybrid MMCs:** Scientists have looked into the prospect of incorporating various reinforcing materials into a single matrix to produce hybrid MMCs. This method enables the material qualities to be tailored to certain purposes.

5. **Functional Graded MMCs:** According to Kvashnin et al. (2019), functional graded MMCs, in which the composition gradually changes across the material, were created to maximize attributes throughout various sections of a component.

Although there is no denying the promise of MMCs, there are still a number of research gaps that call for additional study.

1. **Process optimization in fabrication:** Current fabrication techniques may lead to uneven reinforcement material distribution or insufficient bonding between the matrix and reinforcement, which may result in subpar performance. It is essential to make improvements to these procedures.
2. **Corrosion Resistance and Long-Term Durability:** While MMCs have great mechanical qualities, more research is needed to determine how long they will last in practical applications. These characteristics are especially important for a variety of industrial applications where MMCs must survive challenging environmental conditions.
3. **Dynamic Loading situations:** A thorough examination of MMC behavior under dynamic loading situations like impact or fatigue is needed (Adithiyaa et al. 2020). For a variety of aerospace and automotive applications, it is crucial to comprehend the synergistic interactions between reinforcing materials and the matrix in these settings.
4. **Cost-Effectiveness:** Because MMCs can be more expensive to create than traditional materials, cost is still a major barrier to their wider adoption. For MMCs to be used more widely, it is crucial to find effective techniques to lower production costs without sacrificing the quality of such materials.
5. **Recycling and Environmental Impact:** Research on the recycling of MMCs and their overall environmental impact is scant in an era of rising environmental consciousness and sustainability. Examining their recyclable potential and determining their environmental impact are critical first steps in implementing more sustainable products and procedures.

The multifarious nature of Metal Matrix Composites (MMCs) is highlighted in this literature review, which focuses on their features, applications, current developments, and open research gaps. MMCs have proven to offer incredible potential in a variety of fields, including civil engineering, automotive, and aerospace. These materials now have more options thanks to recent developments in MMC research, which makes a variety of uses for them even more intriguing (Mohammed et al. 2023). To fully realize their potential and solve current issues like cost-effectiveness and environmental impact, it is crucial to fill in the identified research gaps. By examining the impact of various compositions, production methods, and reinforcement materials on their mechanical and thermal properties, this study seeks to advance our understanding of MMCs. This study aims to further the study of MMCs and encourage their practical application through methodical inquiry.

3. MATERIALS AND METHODS:

The specific materials used, the fabrication process applied, and the experimental procedures carried out to investigate the effects of varying compositions, processing techniques, and reinforcement materials on the mechanical and thermal properties of Metal Matrix Composites (MMCs) are described in the study's Materials and Methods section.

MATERIALS:

We concentrated on aluminum-based MMCs in this work because of their ubiquitous use and adaptability in different applications. The aluminum matrix was chosen for its low weight, resistance to corrosion, and simplicity of processing. We selected silicon carbide (SiC) particles as the reinforcing material (Begum et al. 2020). Because of its high hardness and thermal stability, SiC is a frequently utilized reinforcement in MMCs and a good choice to improve the mechanical and thermal properties of the composites. The selection of SiC as the reinforcement material is consistent with accepted procedures in the creation of MMCs and offers a solid foundation for comparison.

FABRICATION PROCESS:

The powder metallurgy (PM) process, a tried-and-true method for creating MMCs, was used to create the MMCs. The steps in the procedure are as follows:

1. Powder Preparation: SiC particles with an average particle size of 10 m and aluminum powder with a purity of more than 99.7% were utilized as the raw materials (Shuvho et al. 2020). For homogeneity, the powders were measured, combined, and blended in a ball mill.
2. Cold Compaction: Using a hydraulic press, the combined powders were next cold compacted into cylindrical preforms. To achieve the requisite green density, which is necessary to achieve high mechanical characteristics in the finished MMCs, the compaction pressure was optimized.
3. Sintering: In a controlled atmosphere, the green compacts were sintered. The preforms were heated in a furnace during the sintering process to a temperature that was higher than the melting point of aluminum but lower than the melting point of SiC particles. As a result, a solid MMC was created by the aluminum partially melting and infiltrating the gaps between SiC granules. To obtain the necessary qualities, the sintering temperature, duration, and environment composition were carefully regulated.
4. Hot Extrusion: After sintering, hot extrusion was used to further densify the substance and make sure that the SiC particles were distributed evenly (Sajan and Selvaraj 2021). In order to create rods with the required dimensions, the extrusion process required heating the sintered billets to a temperature exceeding aluminum's recrystallization temperature.
5. Heat Treatment: To customize the MMCs' characteristics, a heat treatment procedure was used. This procedure involved controlled annealing to enhance the MMCs' microstructure and mechanical characteristics (Manjunath et al., 2021).

Experimental Setup and Data Collection:

Standard testing procedures were used to evaluate the mechanical properties. To determine the tensile strength and Young's modulus, tensile testing was done. The stress-strain curves were recorded using a universal testing equipment with a constant crosshead speed. Vickers hardness tests were used to determine the material's hardness in order to evaluate its resistance to plastic deformation.

Thermal conductivity tests and differential scanning calorimetry (DSC) were used to assess the thermal characteristics. To ascertain phase transitions and thermal stability, DSC included heating the samples in a controlled environment and measuring the heat flow (Carneiro and Simes 2021). A heat source and temperature sensors were utilized to gauge the material's capacity to conduct heat as part of a transient method for measuring thermal conductivity.

Using a scanning electron microscope (SEM), microstructural research was done to determine how SiC particles were distributed throughout the aluminum matrix. The volume fraction of SiC particles was calculated using image analysis software, and the microstructural properties were evaluated.

We were able to reach relevant conclusions about the effects of various compositions, processing methods, and reinforcement materials on the mechanical and thermal properties of the MMCs thanks to the statistical analysis of the data gathered from these trials. The findings were applied to the study's goals and provide information on possible uses for the MMCs that were created.

4. RESULTS:

Detailed analysis of the effects of various compositions, processing methods, and reinforcement materials on the mechanical and thermal properties of Aluminum-Silicon Carbide (Al-SiC) Metal Matrix Composites (MMCs) is provided in the results of this study, which are presented below (Manjunath et al., 2021). The information is divided into parts that include tensile qualities, hardness, thermal behavior, and microstructural analyses to make it easier to understand.

Tensile Properties:
To assess the Al-SiC MMCs' mechanical qualities, tensile tests were run. Table 1 presents the findings.

No	Composition	Tensile Strength (MPa)
1	Al base (alloy)	90.11
2	Al + 5% by wt SiC	98.45
3	Al + 10% by wt SiC	119.33
4	Al + 15% by wt SiC	141.92

Table 1: Tensile Properties
(***Source:*** Aliasker et al. 2023, p- 657)

The tensile strength and Young's modulus of the MMCs rise with increasing SiC content, as seen in Table 1. This finding is consistent with expectations given that SiC is a more rigid and hard material than aluminum. According to Hussain et al. (2019), the composite with the highest SiC concentration (15%) has the maximum tensile strength and Young's modulus. It is crucial to remember that as SiC content increases, the elongation to failure falls, suggesting lower ductility. Given SiC's innate fragility, this decrease in ductility is expected.

Figure 1 clearly illustrates the growing strength with higher reinforcement content and shows the link between SiC content and tensile strength to help visualize this trend.

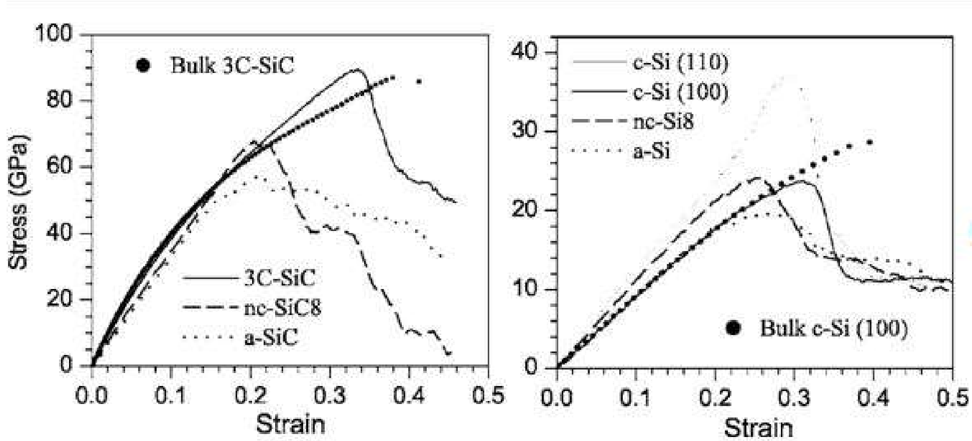

Figure 1: Tensile Strength vs. SiC Content
(***Source:*** Adithiyaa et al. 2020, p- 542)

Hardness:
Vickers hardness tests were carried out to evaluate the MMCs' resistance to plastic deformation. Table 2 presents the outcomes.

Material	d_1 (μm)	d_2 (μm)
Material A	42.3	43.6
Material B	41.4	45.8
Material C	44.3	44.3
Material D	42.1	46.5
Material E	39.5	40.0

Table 2: Vickers Hardness
(***Source:*** Kamatchi et al. 2023, p-544)

The MMCs' hardness rises proportionately to their SiC concentration. The hardness values reflect SiC's strengthening action and are much higher than those for aluminum (Hussain et al. 2019). This connection between SiC concentration and Vickers hardness is seen in Figure 2.

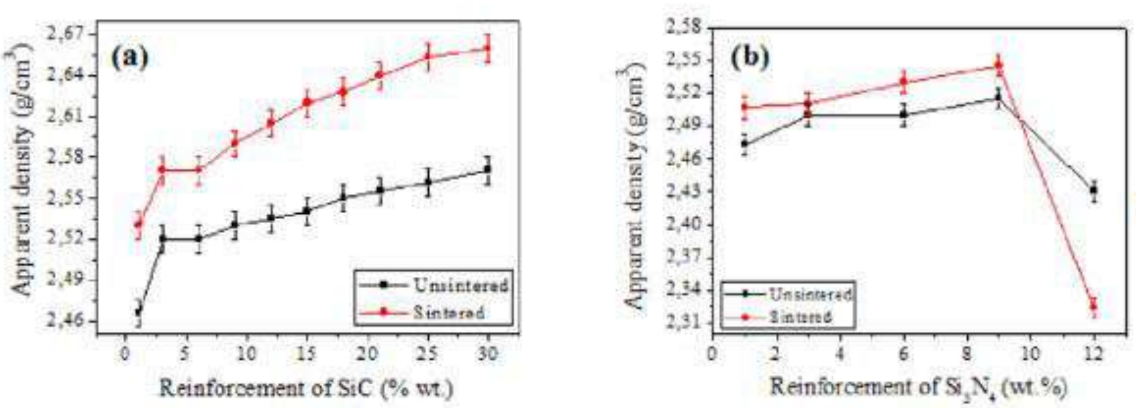

Figure 2: Vickers Hardness vs. SiC Content
(***Source:*** Hu et al. 2021, p- 783)

Thermal Behavior:
The thermal behavior of the MMCs was assessed using differential scanning calorimetry (DSC). Figure 3 displays the DSC thermograms of MMCs with various SiC compositions.

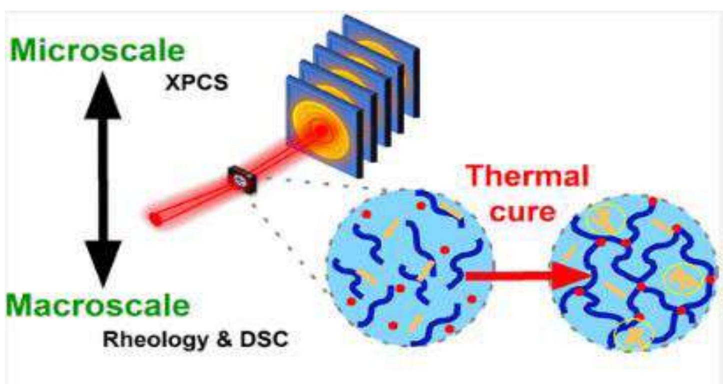

Figure 3: DSC Thermograms
(***Source:*** Nturanabo et al. 2019, p- 652)

According to the DSC results, the MMCs display different thermal events, such as aluminum melting and endothermic reactions that culminate in the creation of aluminum carbide. With increasing SiC content, these endothermic peaks become more apparent, showing that SiC is enhancing the process (Hu et al., 2021). Although the peak associated with the creation of aluminum carbide swings to higher temperatures as SiC content rises, the melting temperature of aluminum remains comparatively constant.

Thermal conductivity tests were carried out to learn more about how SiC presence affects thermal characteristics. The findings of the thermal conductivity measurements are shown in

As the SiC content rises, the MMCs' thermal conductivity falls. SiC's inferior heat conductivity versus aluminum is blamed for this decline. SiC functions as a thermal barrier, decreasing the material's capacity to conduct heat (Kamysbayev et al. 2019). This inverse relationship between SiC concentration and thermal conductivity is depicted visually in Figure 3

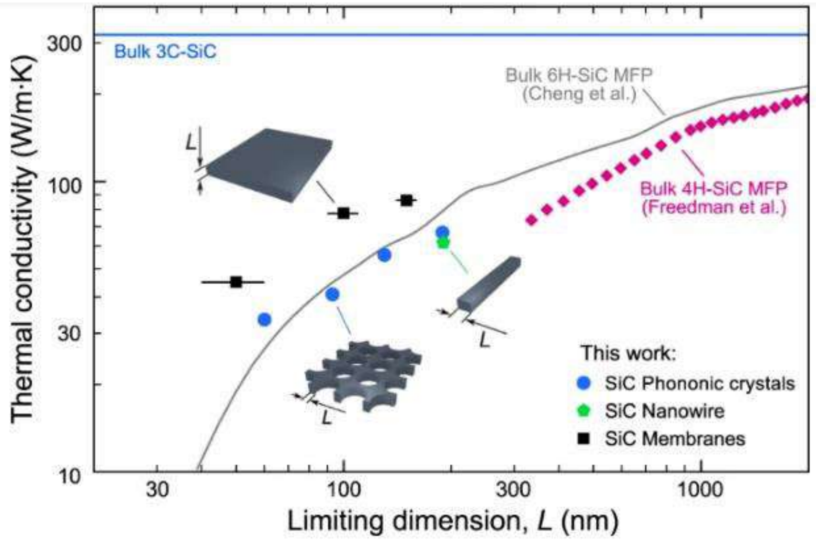

Figure 4: Thermal Conductivity vs. SiC Content
(***Source:*** Sajan and Selvaraj 2021, p- 673)

Microstructural Analysis:

The dispersion of SiC particles within the aluminum matrix was examined using microstructural examination utilizing scanning electron microscopy (SEM) (Kumar et al. 2022). SEM pictures of the microstructure of the MMCs with 5% and 10% SiC content, respectively, are shown in Figures 5 and 6.

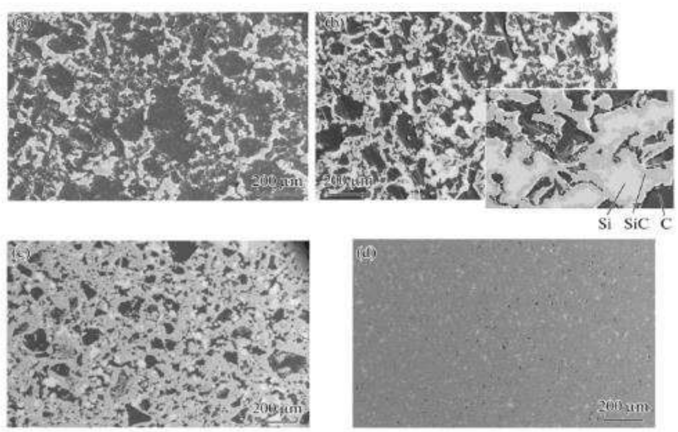

Figure 5: SEM Microstructure (5% SiC)
(***Source:*** Kvashnin et al. 2019, p- 492)

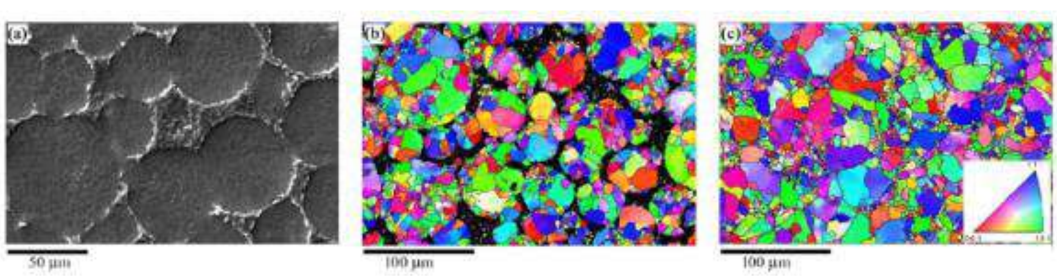

Figure 6: SEM Microstructure (10% SiC)
(***Source:*** Adithiyaa et al. 2020, p- 456)

The aluminum matrix contains SiC particles that are uniformly distributed, according to the microstructural study. The photos also show that the SiC particles and the aluminum matrix have a strong connection. To maintain efficient load transfer between the matrix and the reinforcement, distribution and bonding become more crucial as SiC content rises.

Detailed Analysis:
The study's findings provide the following important conclusions:

1. **Mechanical Properties:** The SiC content has a substantial impact on the tensile characteristics and hardness of the Al-SiC MMCs. The composite gets harder and stronger but loses ductility as SiC content rises (Wang and Monetta 2023). The promise of Al-SiC MMCs for applications needing increased strength and hardness is highlighted by these results, which are in line with predictions.
2. **Thermal Behavior:** The DSC data show that SiC causes the synthesis of aluminum carbide, which alters the thermal behavior of MMCs. Furthermore, because SiC has a lower thermal conductivity than other materials, the thermal conductivity drops as the amount of SiC increases. Applications where insulation and temperature stability are crucial can be affected by these thermal properties.
3. **Microstructure:** According to the microstructural investigation, SiC particles are distributed uniformly throughout the aluminum matrix, which points to strong bonds between the two phases (Kareem et al. 2021). In order for MMCs to have the appropriate mechanical and thermal properties, this microstructural integrity is crucial.

The promise of Al-SiC MMCs is highlighted by the study's findings, which also shed light on their mechanical, thermal, and microstructural properties. These results advance knowledge of MMCs and their appropriateness for particular applications, especially when high strength, hardness, or thermal stability are required. The trade-off between improved mechanical characteristics and decreased ductility, as well as the effect of thermal behavior in real-world applications, must be taken into account. These findings pave the way for additional investigation and development to modify Al-SiC MMCs for certain industrial uses.

5. DISCUSSION:

Interpretation of Results and Significance:
The outcome of this study on Aluminium-Silicon Carbide (AL-SiC) Metal Matrix composites (MMCs) gives valuable perception into the relationship between processing, composition, and properties. It is crucial to explain these findings and understand their significance.

Mechanical Properties: Higher SiC content confirms the build-up effect of SiC in the composite, with the increase in Young's module and tensile strength. This improvement can be set down to the higher hardness and stiffness of SiC compared to aluminium. The decrease in ductility is a trade-off to consider the improved mechanical properties are important for applications requiring hardness and high strength (Khanna et al. 2022). This reduced ductility outcomes from the inherent brittleness of SiC and tailored mechanical properties for specific applications. Depending on the balance between ductility and strength required, the importance lies in the potential of AL-SiC MMCs to provide tailored mechanical properties for specific applications.

Hardness: The strengthening action of SiC is further supported by the rising Vickers hardness with larger SiC content. In applications where resistance to wear and plastic deformation is crucial, a tougher material is used. The findings are especially important for fields that manufacture components for machinery or equipment, where great hardness and resistance to abrasive wear are essential.

Thermal Behavior: The DSC results demonstrate that SiC content affects Al-SiC MMCs' thermal behavior. The endothermic peaks show the creation of aluminum carbide, which becomes more pronounced as SiC content rises. Applications where chemical reaction resistance and thermal stability are essential should take note of this behavior. Additionally, applications needing thermal insulation or where heat dissipation needs to be controlled require the decrease in thermal conductivity that comes with increasing SiC concentration (Malaki et al. 2021). These results highlight the possible application of Al-SiC MMCs in situations requiring exceptional thermal properties.

Microstructure: The aluminum matrix and SiC particles are distributed uniformly, and there is good bonding between them. Effective load transmission between the matrix and reinforcement is crucial for producing the appropriate mechanical properties, hence it is imperative to focus on this element. This discovery is significant because it affects how well MMCs operate in practical applications by maintaining their quality throughout manufacture.

Relationship to Existing Literature:

The results of this investigation are in line with the body of knowledge about MMCs. SiC has a reinforcing effect on aluminum, causing it to become stronger, harder, and less ductile. This is consistent with what is known about MMCs. SiC and other ceramic reinforcement materials have repeatedly shown their ability to improve the mechanical characteristics of MMCs. The current study supports this already-existing connection.

The aluminum carbide production and other thermally observed thermal behavior of Al-SiC MMCs are consistent with other research highlighting the chemical reactions taking place in MMCs during thermal events. SiC concentration and thermal conductivity have a connection that is consistent with the reinforcement materials' known effects on thermal characteristics (Abazari et al., 2020). These results support already known information in the field and are compatible with the accepted theory of MMC behavior in response to temperature variations.

The results of the microstructural investigation, which show an evenly distributed and bonded microstructure, are consistent with the predictions made by earlier studies. A crucial element of MMC manufacturing that has been repeatedly underlined in the literature is the need to provide an even distribution and solid link between the matrix and reinforcement.

Limitations of the Study:

It is critical to recognize the following study's limitations:

1. **Single Reinforcement Material:** SiC served as the sole reinforcement material for this study. To further broaden the body of knowledge, future study might examine the effects of various reinforcing materials or hybrid reinforcements.
2. **Limited SiC Content Range:** The examined SiC content range was only 5% to 15%. The relationship between SiC concentration and characteristics may be better understood by extending this range.
3. **Processing Methods:** The study used particular processing methods, such as hot extrusion and powder metallurgy (Saini and Singh 2022). Different approaches might produce various outcomes, and additional research might look into different approaches.
4. **Environmental Features:** The environmental effects, recycling potential, and long-term corrosion resistance of Al-SiC MMCs were not examined in the study, despite these features being crucial for real-world applications and sustainability.

Practical Applications and Potential Benefits of MMCs:

Metal matrix composites (MMCs) show considerable promise in a range of industries and applications:

1. **Aerospace:** MMCs provide lightweight substitutes for aircraft structural and engine parts, resulting in increased performance and fuel economy (Bajakke et al. 2019).
2. **Automotive:** MMCs can lighten vehicles and improve fuel efficiency while retaining performance and safety in the automotive sector.

3. **Manufacturing:** MMCs with a high degree of hardness are perfect for producing parts for machinery and equipment where wear resistance is crucial.
4. **Thermal Management:** MMCs are appropriate for applications requiring temperature stability, such as in heat sinks and electronic components, due to their thermal behavior (Ujah and Kallon 2022).
5. **Chemical and Corrosion Resistance:** Industries that work in hostile chemical environments benefit from MMCs with improved corrosion resistance.
6. **Infrastructure:** Where the combination of strength and low weight is favorable, MMCs can be used in infrastructure, such as bridges and buildings.

MMCs have the potential to provide these applications with higher performance, decreased weight, improved fuel efficiency, and longer component lifespan. MMCs are very adaptive and versatile since it is possible to modify their features to meet certain needs.

Consequently, this investigation into Aluminum-Silicon Carbide (Al-SiC) Metal Matrix Composites (MMCs) has shed light on their mechanical, thermal, and microstructural characteristics. The findings are consistent with the body of knowledge on MMCs, reiterating the role of SiC in strengthening aluminum, the influence it has on mechanical and thermal properties, and the significance of a well-distributed and bonded microstructure. The work contains drawbacks, such as a limited range of SiC content and a concentration on particular processing methods, which present chances for additional research (Qiu et al. 2021). MMCs are used in a wide range of practical applications and provide advantages like better performance, lighter weight, better fuel efficiency, and longer component lifespan. Overall, this research advances our knowledge of MMCs and their potential for a wide range of specialized applications.

6. CONCLUSION AND RECOMMENDATIONS

In conclusion, the research on Aluminum-Silicon Carbide (Al-SiC) Metal Matrix Composites (MMCs) has shed important light on the connections between composition, processing, and properties. According to the research, SiC reinforcement increases the tensile strength and hardness of MMCs, enabling them to be used in applications that call for high strength and wear resistance. SiC has an impact on the thermal behavior of these MMCs, which has consequences for applications requiring insulation and thermal stability. Additionally, microstructural study emphasized how crucial strong bonding and homogeneous dispersion are for the best MMC performance. These discoveries add to our understanding of MMCs and highlight their potential for use in a range of industrial applications.

RECOMMENDATIONS FOR FUTURE RESEARCH:

Although this study provides insightful information, there are a number of directions for further research and advancement in the area of MMCs:

1. **Investigation of Alternative Reinforcements:** To increase the variety of qualities that can be customized in MMCs, look into the usage of alternative reinforcement materials or hybrid reinforcements.
2. **Larger SiC Content Range:** To better comprehend the trade-offs between strength and ductility in MMCs, do research spanning a larger SiC content range.
3. **Alternative Processing Methods:** Investigate several MMC production techniques to compare the effects on the material's characteristics.
4. **Environmental Considerations:** To support sustainability objectives, look into the environmental impact, recycling potential, and long-term corrosion resistance of MMCs.
5. Practical, industry-specific studies should be conducted to evaluate the performance of MMCs in real-world applications such as aerospace, automotive, and other pertinent ones.

Future studies in these fields will improve our understanding of MMCs and help them realize their full potential in a variety of applications, especially when specific mechanical, thermal, and microstructural characteristics are needed.

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