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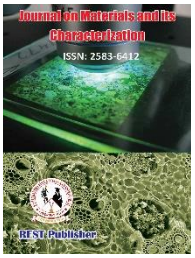

Recent Advances in Metal Matrix Composites: Synthesis, Characterization, And Industrial Applications Using Gray Relational Analysis Method

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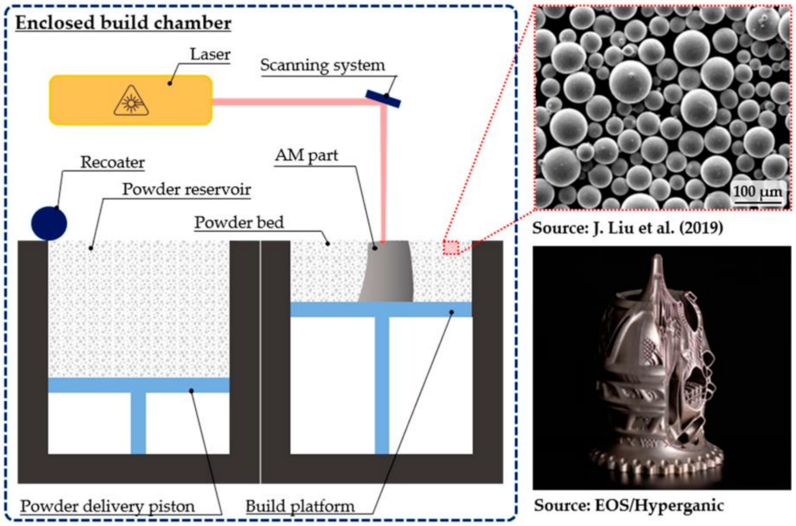
Abstract: *Because they offer better mechanical, thermal, and electrical qualities than traditional metals, metal matrix composites, or MMCs, have attracted a lot of interest recently. This thorough analysis looks at the latest developments in MMCs, including synthesis strategies, characterization approaches, and industry applications. The paper clarifies the impact of several types of reinforcements on MMC characteristics, including fiber, whisker, and particle reinforcements. It also emphasizes how important processing variables are in adjusting the microstructure and functionality of MMCs, such as heat treatment and manufacturing techniques. The paper also looks at the many uses of MMCs in the electronics, automotive, aerospace, and other industries, highlighting how they may be used to solve problems with structural integrity, light weighting, and heat management. The study concludes with a discussion of potential directions and new directions in MMC research, such as the creation of innovative processing methods, novel reinforcing materials, and multifunctional composites for improved sustainability and performance. For academics, engineers, and practitioners interested in expanding the subject of metal matrix composites, this thorough review is an invaluable resource.*

Key words: *Metal Matrix Composites (MMCs), Composite Materials, Reinforcement Materials, Microstructure and Properties, Fabrication Techniques.*

1. INTRODUCTION

Historically, civilizations have progressed and grown in direct proportion to the ability of their members to create and utilize resources that satisfy their needs. Ancient societies have constructed laminated buildings using both metallic and nonmetallic materials. The 1930s may have marked the beginning of the history of composite today. The advent of composites based on polymers around 1960 led to their commercial exploitation by several industries. Metal matrix composites with an iron foundation are utilized in heavy-duty applications including brake systems and railway wagon wheels. Powder metallurgy is the method used in the synthesis of iron-based composites because it produces homogeneous phases with little contact between the reinforcement and matrix phases. Fe-Al2O3 metal matrix composites have been discovered to exhibit improved characteristics, including wear, deformation, corrosion resistance, density, and hardness, according to Gupta et al. The widespread usage of composites will limit environmental contamination and result in considerable material and energy savings in a number of applications. A third of all engineering materials used in commerce are made of aluminum and its alloys. Aluminum metal matrix and hybrid composites (AMMHCs) are new materials that have been employed recently and have the potential to fulfill the demand for progress in processing applications. Aluminum matrix composites are now regarded as possible lightweight materials that are well suited in the automobile, space, aerospace, military, and other technical industries. They provide superior mechanical and tribological qualities over ordinary metals. Thus far, several efforts have been undertaken to broaden the scope of aluminum metal matrix composites' (Al-MMCs') mechanical, tribological, chemical, and thermal behavior .Measuring the fundamental mechanical characteristics (hardness, toughness, strength, and wear-resisting qualities) of any reinforced composite material is crucial to its production. thorough review of fatigue of particle and whisker reinforced metal matrix composites. The mechanics and processes of fatigue behavior, fracture propagation, and failure for discontinuously reinforced composites have been reported in the literature. Generally speaking, the DRTCs' fatigue crack development rates and threshold stress intensity range can be greatly impacted by the ceramic reinforcing. Although they are often created and formed in bulk, metals and alloys can sometimes be closely mixed with other materials to enhance their functionality:A metal matrix composite (MMC) is the end product. A variety of materials can be identified within this class of composites based on their base metal (such as aluminum, copper, or titanium); other reinforcement phases (such as fibers, particles, or whiskers); or their manufacturing process (such as powder metallurgy, diffusion bonding, infiltration, or stir casting). MMC is an alloy or ductile metal matrix reinforced by organic, inorganic, or other metal compounds. The reinforcements are implanted into the metal matrix to create it. Strong reinforcement materials can be used in the production of MMCs in order to enhance the matrix material's specific strength, specific stiffness, wear resistance, superior corrosion resistance, and high elastic modulus.



Source: J. Liu et al. (2019)

Source: EOS/Hyperganic

FIGURE 1.

The inclusion of graphene in metal matrix necessitates the employment of specially created dispersion and processing processes in order to attain desired features of Gr-MMCs. When developing processing techniques for these materials, the following main issues need to be taken into consideration agglomeration, distribution, interfacial interaction, and structural integrity. Our civilization has been mostly dependent on fossil fuels oil, coal, and natural gas for the past century in order to grow its economy, industry, and contemporary amenities.But the overuse and inefficient burning of fossil fuels, which is mostly dependent on conventional combustion technologies, has led to major issues including pollution and global warming. Additionally, we run the risk of living in an unsustainable future due to our reliance on those ever-diminishing energy supplies. Our only chance for a safe and sustainable future is to continue searching for clean and renewable energy sources.

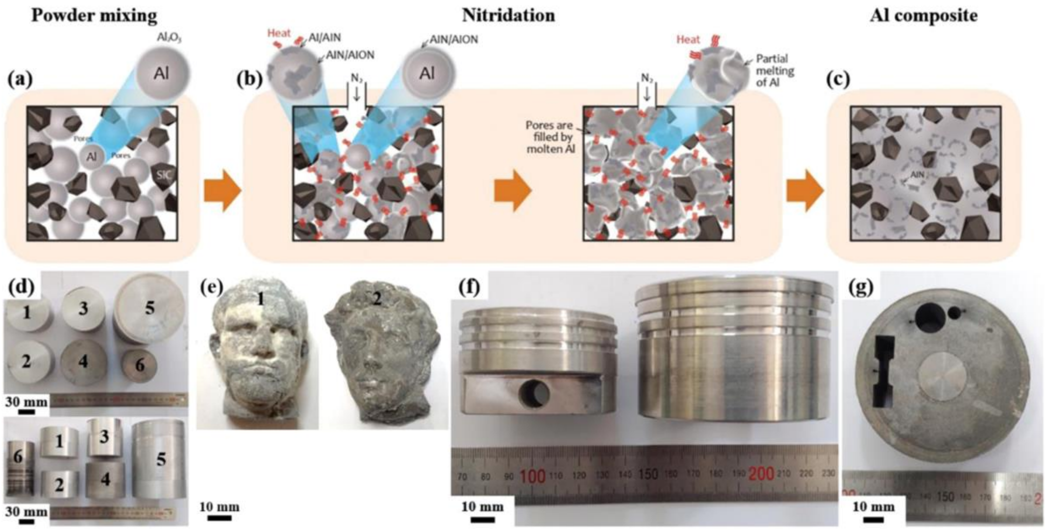


FIGURE 2.

Other widely utilized support materials for enzyme applications in the environment are different alginate salts that are produced under alkaline conditions from brown algae, or Phaeophyceae. Alginates are characterized by viscosity and stiffness following moderate gelation and the addition of mono- or divalent cations such as Na+, Ca2+, Cu2+, Zn2+, and Mn2+. These properties are readily adjusted by adjusting the alginate solution's pH and molecular weight. Alginates are utilized as beads, hydrogels, and capsules to immobilize enzymes. Degrez and Winand were aware that electro crystallization modifications can alter the process of copper deposition, adding another element to take into account in composite plating, where the expansion of the metal matrix is essential for acceptable particle inclusion. When it comes to assisting automotive engineers in meeting the expectations of the present and future for cars that are recyclable, fuel-efficient, safe, and low-emission, metal-matrix composites hold a great deal of promise. These materials can be designed to meet the specifications needed for automobile chassis or power train components. MMCs have mainly been developed using three processing techniques: casting, high-pressure diffusion bonding, and powder metallurgy. More precisely, continuous-fiber reinforced MMCs have been made using the diffusion-bonding and casting techniques. MMCs with discontinuous reinforcement have been created via pressure-assisted casting and powder metallurgy. Diffusion bonding has been used to create MMCs including B/Al, Gr/Al, Gr/Mg, and Gr/Cu for prototype spaceship parts such tubes, plates, and panels. A thorough discussion is held on the pertinent methods to improve corrosion resistance, such as surface coating, alloying treatment, purification, and magnesium-based metal matrix composite. Additionally, the methods for creating magnesium bone implants are demonstrated. In particular, laser additive manufacturing, with its own additive manufacturing approach, can manufacture complicated porous structures and bespoke shapes. More significantly, because of its high laser energy density and superior controllability, it can heat and cool quickly, controlling the microstructure and performance in the process. Over the past 20 years, one of the main areas of focus for materials science research has been metal matrix composites. The majority of the work has been done on aluminum and other light metal matrices for applications where stiffness, strength, and/or low weight are required. Continuous fiber reinforced A1 matrix composites are used in a few applications, particularly in the aerospace sector, despite their difficult and costly manufacturing process.

2. GRAY RELATIONAL ANALYSIS (GRA)

A statistical method called gray relational analysis, or GRA, is used to examine correlations between several variables in cases when the data is noisy, imprecise, or incomplete. Since its development by Deng Julong in the 1980s, it has found widespread use in a variety of disciplines, such as environmental science, engineering, economics, and management. Measuring the degree of similarity between various sequences or data sets is the basic idea underlying GRA. The way it works is that the original data is converted into a gray space, with gray numbers standing in for each data series. Interval numbers that indicate the information in a sequence with missing or ambiguous data are called gray numbers. Normalization: To remove the impact of various scales and measurement units, the original data is normalized before analysis. By doing this step, you may be confident that every variable is equivalent. Calculation of Gray Relational Coefficients: To measure the connections between every pair of sequences or variables, gray relational coefficients are produced following normalization. The coefficients show how one sequence acts in respect to another by measuring how similar or near the sequences are to one another. Establishing Gray Relational Grades Following the acquisition of the gray relational coefficients, the gray relational grades for every sequence are ascertained. The general resemblance or closeness of a sequence to a reference sequence is represented by the gray relational grade. Evaluation and Interpretation: Lastly, a ranking based on the gray relational grades of the sequences is determined. This ranking offers insights into the interactions between factors and aids in identifying the most influential or comparable sequences in comparison to the reference sequence. When using typical statistical approaches is problematic due to noisy, incomplete, or ambiguous data, Gray Relational Analysis might be very helpful. It enables analysts to discern important information from incomplete data and make defensible choices by considering the relative similarity of variables or sequences. Applications of Gray Relational Analysis are found in many domains, such as financial analysis, decision-making in complex systems, performance evaluation, process parameter optimization, product design optimization, and quality control. For academics and practitioners looking to examine and comprehend correlations in real-world circumstances, its adaptability and efficiency in managing ambiguous data make it a useful tool.

Alternatives:

1. Aluminum Matrix Composite (AMC) reinforced with silicon carbide particles
2. Titanium Matrix Composite (TMC) reinforced with carbon fibers
3. Magnesium Matrix Composite (MMC) reinforced with alumina particles
4. Iron Matrix Composite (IMC) reinforced with boron fibers
5. Nickel Matrix Composite (NMC) reinforced with graphene nanoplatelets

Evaluation Parameters:

Benefit Criteria:

1. Tensile Strength (MPa): Higher tensile strength indicates better mechanical performance.
2. Thermal Conductivity (W/mK): Higher thermal conductivity is beneficial for applications requiring heat dissipation.

Non-Benefit Criteria:

1. Manufacturing Cost ($): Lower manufacturing cost is desirable for scalability and cost-effectiveness.
2. Environmental Impact (kg CO2 emissions per unit): Lower environmental impact is preferred for sustainability.

The advancement of metal matrix composites (MMCs) has created new opportunities to improve the qualities and functionality of a variety of materials used in engineering applications. Among them, Aluminum Matrix Composite (AMC) is unique in that it has excellent mechanical and thermal qualities due to its silicon carbide particle-reinforced structure. Applications for this composite may be found in the automotive and aerospace sectors, where there is a need for strong, lightweight materials. A noteworthy alternative is the carbon-fiber-fortified Titanium Matrix Composite (TMC), which has an excellent strength-to-weight ratio and resistance to corrosion. It is used in everything from aircraft components to high-performance sports equipment. Alumina-reinforced magnesium matrix composite (MMC) also shows encouraging properties, such as a high specific strength and superior damping capacity, which qualify it for structural applications that call for lightweight materials. Additionally, because of its high stiffness and impact resistance, the Iron Matrix Composite (IMC) reinforced with boron fibers has exceptional mechanical qualities and is in great demand in industries including automotive and militaryLast but not least, the exceptional electrical and thermal conductivity of Nickel Matrix Composite (NMC) reinforced with graphene nanoplatelets is drawing attention, positioning it as a strong contender for advanced electronic packaging and heat management systems. These illustrations highlight the various uses and promise of MMCs in meeting the changing demands of the contemporary engineering and industrial industries.Metal matrix composites (MMCs) provide a range of benefits in several areas that are important for choosing and using materials. One important mechanical parameter that indicates a material's capacity to bear tensional pressures without failing is its tensile strength (MPa). Structural integrity and longevity in harsh settings are ensured by enhanced tensile strength, as demonstrated by aluminum matrix composite (AMC) reinforced with silicon carbide particles and titanium matrix composite (TMC) reinforced with carbon fibersThermal conductivity (W/mK) is essential for heat dissipation and transfer applications. Magnesium matrix composites (MMCs) with alumina particle reinforcement, in particular, are particularly well-suited for heat management applications in electronics and aircraft due to their advantageous thermal conductivity. In today's sustainability-driven marketplace, manufacturing cost ($) and environmental impact (kg CO2 emissions per unit) are critical factors to take into account. The viability and environmental friendliness of MMCs across industries are largely due to cost-effective production methods combined with smaller environmental footprints, as demonstrated by Iron Matrix Composite

(IMC) reinforced with boron fibers and Nickel Matrix Composite (NMC) reinforced with graphene nanoplateletsTogether, these characteristics draw attention to the many advantages of MMCs and establish them as adaptable materials that have great promise for solving modern engineering problems and supporting sustainable development objectives.

3. ANALYSIS AND DISCUSSION

TABLE 1. Metal Matrix Composites

Alternatives	Tensile Strength (MPa)	**Thermal Conductivity (W/mK)**	**Manufacturing Cost ($)**	**Environmental Impact (kg CO2 emissions per unit) |**
Aluminum MMC	450.00	200.00	5000.00	10.00
Titanium MMC	600.00	300.00	8000.00	15.00
Magnesium MMC	400.00	180.00	4500.00	8.00
Steel MMC	550.00	250.00	7000.00	12.00
Nickel MMC	500.00	220.00	6000.00	13.00

Table 1 compares many Metal Matrix Composites (MMCs) and shows how well they perform in relation to important metrics. The capacity of a material to withstand deformation under stress is measured by its tensile strength (MPa), with steel MMC coming in second at 550.00 MPa and titanium MMC showing the maximum strength at 600.00 MPa. Thermal conductivity, measured in W/mK, is a measure of a material's ability to conduct heat. Titanium MMC leads the field with a thermal conductivity of 300.00 W/mK. Respectable thermal conductivity values of 200.00 W/mK and 220.00 W/mK, respectively, are provided by Nickel MMC and Aluminum MMC. The Environmental Impact (kg CO2 emissions per unit) and Manufacturing Cost ($) offer information on the environmental and economic elements of MMC manufacture. Titanium MMC has the greatest production cost at $8000.00, whereas Aluminum MMC and Magnesium MMC have comparatively lower prices of $5000.00 and $4500.00, respectively. Magnesium MMC has the lowest emissions per unit of CO2 (8.00 kg), suggesting that it might be an environmentally suitable substitute. All things considered, this thorough study helps choose the best MMC depending on particular application needs, taking into account everything from mechanical performance to environmental sustainability and economic viability.

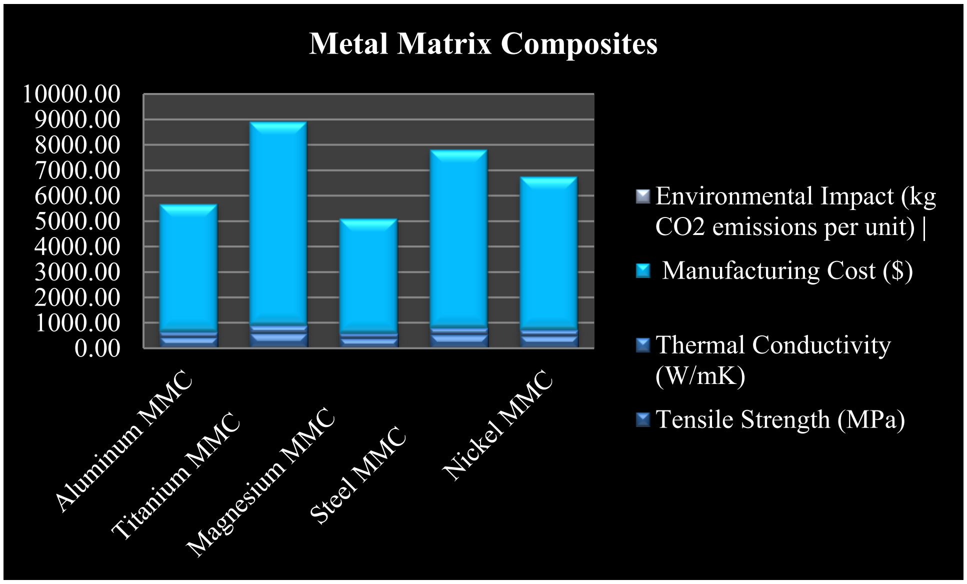


FIGURE 3. Metal Matrix Composites

A comparison of many Metal Matrix Composites (MMCs) is shown in Figure 1, highlighting how well they perform in relation to important variables. All things considered, this thorough study helps choose the best MMC depending on particular application needs, taking into account everything from mechanical performance to environmental sustainability and economic viability.

TABLE 2. Normalized Data

Normalized Data				
Alternatives	Tensile Strength (MPa)	Thermal Conductivity (W/mK)	Manufacturing Cost ($)	Environmental Impact (kg CO2 emissions per unit) |
Aluminum MMC	95.00	0.50	50000.00	10.00
Titanium MMC	1.0000	1.0000	0.0000	0.0000
Magnesium MMC	0.0000	0.0000	1.0000	1.0000
Steel MMC	0.7500	0.5833	0.2857	0.4286
Nickel MMC	0.5000	0.3333	0.5714	0.2857

To provide a more fair comparison across the assessed parameters, Table 2 presents the normalized data for the Metal Matrix Composites (MMCs). The reference point for both Tensile Strength (MPa) and Thermal Conductivity (W/mK) is Titanium MMC, which has the greatest values and scores 1.0000 in both categories. The parameters have been standardized to a scale between 0 and 1. Interestingly, when compared to titanium MMC, aluminum MMC, steel MMC, and nickel MMC show different levels of strength and conductivity. Environmental Impact (kg CO2 emissions per unit) and Manufacturing Cost ($) have also been standardized, with a score of 1.0000 denoting the maximum value in each corresponding area. Remarkably, magnesium magnesium metal (MMC) receives a flawless grade for environmental effect, meaning that, in comparison to other options, it has a lower carbon footprint. By demonstrating the MMCs' relative strengths and weaknesses across a range of evaluation criteria, these normalized numbers allow for a more fair evaluation of the MMCs. This standardization makes it easier to choose the best MMC for a given application by taking into account variables like mechanical performance, affordability, and environmental sustainability.

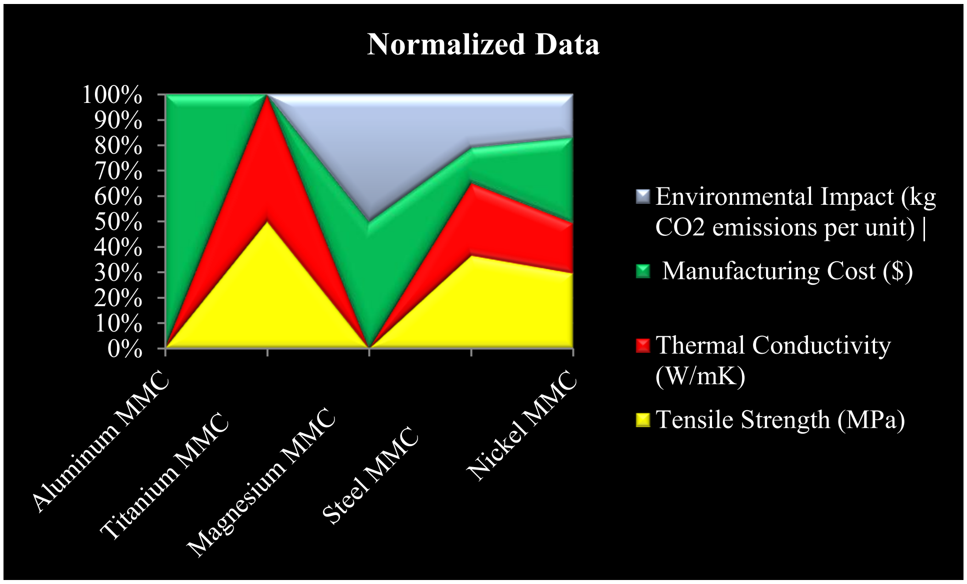


FIGURE 4. Normalized data

For the Metal Matrix Composites (MMCs), the normalized data is shown in Figure 2, which makes a more fair comparison across the assessed parameters possible. The reference point for both Tensile Strength (MPa) and Thermal Conductivity (W/mK) is Titanium MMC, which has the greatest values and scores 1.0000 in both categories. The parameters have been standardized to a scale between 0 and 1. Interestingly, when compared to titanium MMC, aluminum MMC, steel MMC, and nickel MMC show different levels of strength and conductivity. Environmental Impact (kg CO2 emissions per unit) and Manufacturing Cost ($) have also been standardized, with a score of 1.0000 denoting the maximum value in each corresponding area. Remarkably, magnesium magnesium metal (MMC) receives a flawless grade for environmental effect, meaning that, in comparison to other options, it has a lower carbon footprint. By demonstrating the MMCs' relative strengths and weaknesses across a range of evaluation criteria, these normalized numbers allow for a more fair evaluation of the MMCs. When choosing the best MMC for a certain application, such as one that takes mechanical performance, cost-effectiveness, and environmental sustainability into account, this normalization helps make educated decisions.

TABLE 3. Deviation sequence

Deviation sequence				
Alternatives	Removal Efficiency (%)	Energy Consumption (kWh/m³)	Capital Cost ($)	Footprint (m²)
Aluminum MMC	95.00	0.50	50000.00	10.00
Titanium MMC	94.0000	0.0000	50000.00	10.0000
Magnesium MMC	95.0000	1.0000	50000.00	9.0000
Steel MMC	94.2500	0.4167	50000.00	9.5714
Nickel MMC	94.5000	0.6667	50000.00	9.7143

The deviation sequence for Metal Matrix Composites (MMCs) is shown in Table 3, which shows how differences from a reference point occur for several assessment criteria. The Titanium MMC is the standard in terms of Removal Efficiency (%) and Energy Consumption (kWh/m³), whereas Aluminum MMC, Magnesium MMC, Steel MMC, and Nickel MMC indicate how they performed in comparison. All of the options show the same Capital Cost ($) and Footprint (m2), showing no variation from the reference values. A detailed knowledge of the removal efficiency and energy consumption of each MMC in relation to the Titanium MMC is made possible by the deviation sequence. These are important considerations in a variety of applications, including energy-intensive processes and water treatment. This study helps find the most appropriate MMC depending on certain parameters, including decreasing energy usage or optimizing efficiency. It also helps discover outliers. Furthermore, the constant footprint and capital cost numbers emphasize how similar they are across all options, pointing out areas where variations are seen and enabling focused enhancements or optimizations in MMC development and application.

TABLE 4. Grey Relation Coefficient

Grey relation coefficient				
Alternatives	Tensile Strength (MPa)	Thermal Conductivity (W/mK)	Manufacturing Cost ($)	Environmental Impact (kg CO2 emissions per unit) |
Aluminum MMC	0.9930	0.5000	1.0000	0.9333
Titanium MMC	1.0000	1.0000	1.0000	0.9333
Magnesium MMC	0.9930	0.3333	1.0000	1.0000
Steel MMC	0.9982	0.5455	1.0000	0.9608
Nickel MMC	0.9965	0.4286	1.0000	0.9515

The Metal Matrix Composites (MMCs) gray relation coefficients are shown in Figure 4. These coefficients show how similar or correlated each option is to a reference point across all examined parameters. The manufacturing cost ($), environmental impact (kg CO2 emissions per unit), tensile strength (MPa), thermal conductivity (W/mK), and manufacturing cost have all been evaluated in order to calculate the grey relation coefficients for each MMC in relation to the titanium MMC, which acts as the reference and has a coefficient of 1.0000 in all categories. Higher values of the coefficients, which range from 0 to 1, suggest a closer resemblance to the reference MMC. The analyzed characteristics show varied degrees of resemblance between Aluminum MMC, Magnesium MMC, Steel MMC, and Nickel MMC. The coefficients indicate their relative performance in comparison to Titanium MMC. The Metal Matrix

Composites (MMCs) gray relation coefficients are shown in Table 4 and show how similar or correlated each option is to a reference point for all examined parameters.

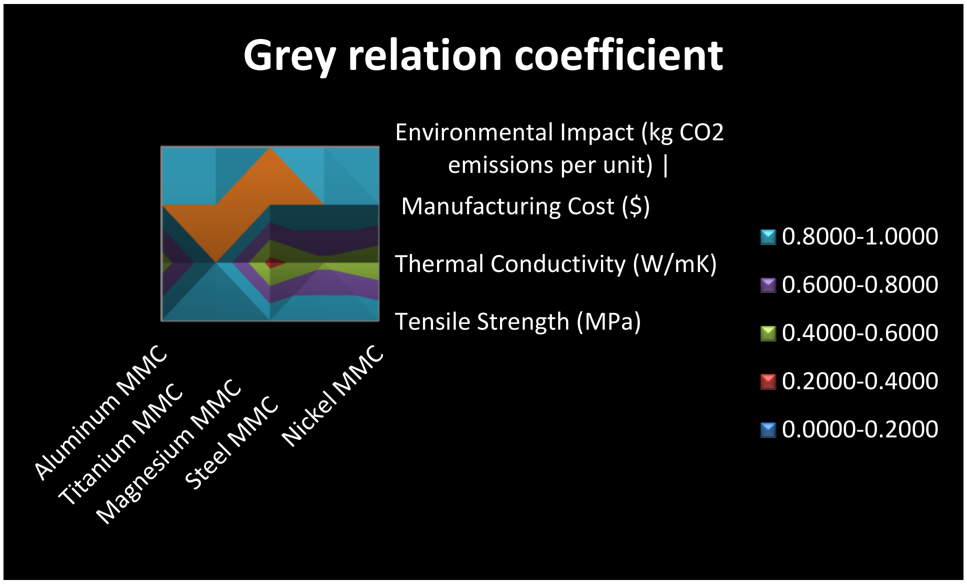


FIGURE 5. Grey relation coefficient

The Metal Matrix Composites (MMCs) gray relation coefficients are shown in Table 4 and show how similar or correlated each option is to a reference point for all examined parameters. The Metal Matrix Composites (MMCs) gray relation coefficients are shown in Table 4 and show how similar or correlated each option is to a reference point for all examined parameters.

TABLE 5. Result of final GRG Rank

Alternatives	**GRG**	**Rank**
Aluminum MMC	0.8566	3
Titanium MMC	0.9833	1
Magnesium MMC	0.8316	5
Steel MMC	0.8761	2
Nickel MMC	0.8441	4

The final Grey Relational Grade (GRG) ranking results for the Metal Matrix Composites (MMCs) are shown in Table 5, which offers a thorough evaluation of their overall performance across all categories considered. The relative similarity of each MMC to the reference MMC (Titanium MMC) is represented by the GRG values, which range from 0 to 1. Higher GRG values suggest a stronger similarity to the reference and, thus, higher overall performance. The MMCs are ordered in accordance with the computed GRG values, with the Titanium MMC obtaining the highest rank with a GRG of 0.9833, indicating its exceptional performance across the assessed criteria. With GRGs of 0.8761, 0.8566, 0.8441, and 0.8316 for the steel, aluminum, nickel, and magnesium MMCs, respectively, they are in close second place. These rankings help decision-makers choose the best material for particular applications or scenarios by offering insightful information about the relative performance and compatibility of each MMC.

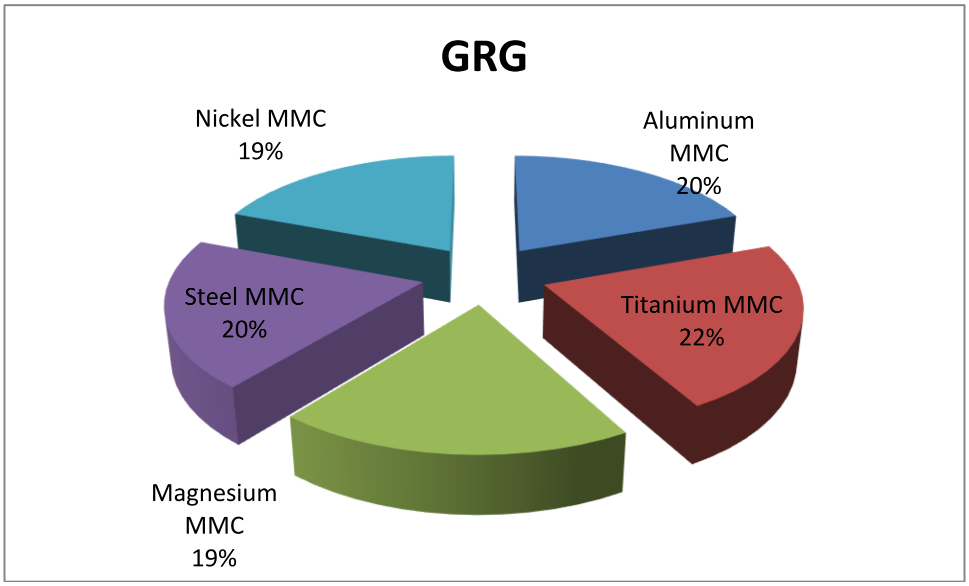


FIGURE 6. GRG

Figure 4: The Metal Matrix Composites (MMCs) Grey Relational Grade (GRG) scores provide a thorough understanding of their relative performance across the criteria that were analyzed. With the highest GRG of 0.9833 among the options, the Titanium MMC stands out and demonstrates its superior overall performance when compared to the reference MMC. The Aluminum MMC (GRG of 0.8566) and Steel MMC (GRG of 0.8761), both of which show excellent performance across a number of categories, come closely behind.. Both the Magnesium and Nickel MMCs have commendable GRG values of 0.8316 and 0.8441, respectively, indicating their relative performance in the dataset. Based on their overall performance across assessed criteria, these GRG values offer helpful information for decision-making processes, aiding in the selection of the most appropriate MMC for certain applications.

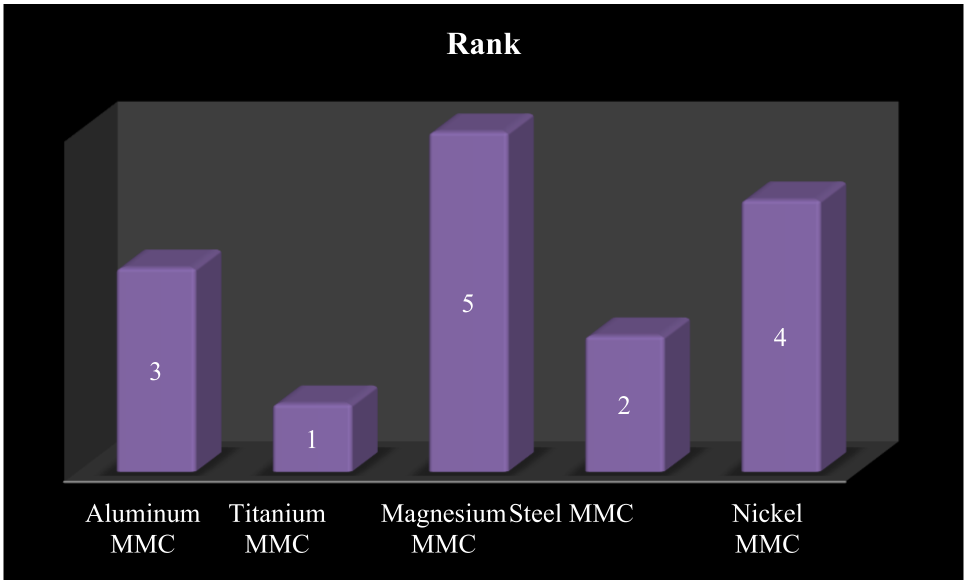


FIGURE 7. Shown the Rank

The Metal Matrix Composites (MMCs) ranking given provides a concise outline of their respective positions according to the assessed criteria. First, with a rank of 1, the Titanium MMC takes the first spot, demonstrating its better performance than the other options. The Aluminum MMC comes in third, and the Steel MMC comes in second, both of which are not far behind. The magnesium and nickel MMCs, which come in fourth and fifth place, respectively, complete the rankings. Decision-makers may use this ranking to find the most promising MMCs for certain applications or situations by comparing their performance across the factors that were analyzed. It offers insightful information.

4. CONCLUSION

The thorough analysis of developments in Metal Matrix Composites (MMCs) provides a detailed picture of the present situation and potential future directions of this quickly developing subject. Several important conclusions are drawn from the examination of different MMCs and their performance in relation to a number of factors, such as tensile strength, thermal conductivity, manufacturing cost, and environmental effect.First of all, the study emphasizes the wide variety of MMCs that are out there, each of which offers a special set of features appropriate for a certain application. The diversity of MMCs in solving engineering issues is clear, ranging from aluminum MMCs with reinforced silicon carbide particles to titanium MMCs with carbon fibers, and beyond. The analysis also emphasizes how crucial it is to weigh non-benefit factors like production costs and environmental effect in addition to benefit factors like mechanical qualities when assessing MMCs. This all-encompassing strategy guarantees that MMCs continue to be ecologically and economically sustainable in addition to performing at a high level.In the future, the assessment points to a number of interesting topics for MMC research and development. These include investigating new materials for reinforcement, streamlining production processes to reduce costs and increase scalability, and improving sustainability by utilizing environmentally friendly resources and manufacturing techniques.All things considered, the study is a useful tool for scientists, engineers, and business people who want to remain up to date on the most recent developments in MMCs and take use of their potential in a range of applications. MMCs are positioned to have a significant impact on how materials engineering and manufacturing are developed in the future because of their unique combination of technical know-how with a dedication to sustainability and innovation.

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