Review On Development, Nanoparticle Reinforcement and Sustainable Materials For Enhancement Of Mechanical Properties In Aluminium Hybrid Metal Matrix Composites

Sarvadey Ashwin Kumar[1], *Sricharan* Chaganty[1], *Varunn* Rajesh[1], *K* Sunil Kumar Reddy[1*], *Nimmagadda* Babu[2], *A. H*. Shnain[3]

[1]Department of Mechanical Engineering, Gokaraju Rangaraju Institute of Engineering and Technology, Hyderabad, Telangana, India.
[2]KG Reddy College of Engineering & Technology, Hyderabad, Telangana, India.
[3]Department of Refrigeration and air Conditioning Techniques engineering, College of technical engineering, The Islamic University, Najaf, Iraq.

Abstract. Aluminium alloys are popular in many advanced applications and are considered to be an essential class of engineering materials mainly due to their desirable combination of low density, high strength, and cost-effectiveness compared to competing materials. Aluminium metal matrix composites and hybrid metal matrix composites will further enhance these properties by incorporating hardened particles as reinforcements. Hybrid metal matrix composites are second-generation composites that exhibit superior mechanical properties due to the synergistic combination of different reinforcement combinations. Various combinations of reinforcing particulates are being explored. The fabrication of the hybrid composites is done using a stir casting route, which will significantly influence the mechanical properties, microstructure and reinforcement distribution. Aluminium HMMCs offer lightweight, high strength, good wear resistance, and other properties that allow them to be extensively used in the structural, aerospace, marine, and automotive industries. Hybridization of metal alloys provides flexibility in designing components and quality control during manufacturing. Thus, this review paper is focused on the fabrication and characterization of hybrid Aluminium metal matrix composites, advancements in their mechanical properties, recent developments and applications.

Keywords: Aluminium Hybrid metal matrix composites, Nano Particles, Stir Casting, Mechanical Properties

* Corresponding Author: kskr1707@gmail.com

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1 Introduction

Since composite materials offer special combinations of material properties like low density, superior wear resistance, high strength and stiffness, etc. that are not possible with monolithic materials alone, they have revolutionized several industries, from simple structural to automotive, marine, construction, aerospace, and electronics [1, 2]. As a result, the need for materials with improved qualities has never been greater. Because composite materials allow for a tailored design and material optimization to meet the current demand or application requirements [7,8], they are preferred over monolithic materials because of their enhanced properties [1]. This gives engineers the flexibility to create complex, lightweight structures with complex geometries that fulfil functionality in a sustainable and cost-effective manner.

The two primary components of a composite material are the matrix material and the reinforcing material. Each of these components has unique physical or chemical properties, and when combined, they create a material with improved qualities.

Depending on the kind of matrix material that is employed, composite materials are categorized as Polymer matrix composites (PMCs), Metal matrix composites (MMCs), and Organic matrix composites (OMCs) [3,8]. Because each form of composite material has distinct qualities, uses, and attributes, it may be used in a wide range of sectors. Several criteria, such as production constraints, financial concerns, and environmental circumstances, must be considered when choosing the right type of composite material.

A subclass of composite materials known as metal matrix composites are made of metal that has been reinforced with fibres, whiskers, or ceramic particles. These materials have special benefits over unreinforced materials [9, 10]. They are advised for high-performance applications and were created in the 1970s [15]. The primary goal of these MMCs is to decrease the weight of composites relative to typical metals and enhance the mechanical and thermal characteristics [15] of the metal, making them appealing and adaptable materials for high-performance applications such as automotive, aerospace, marine, and defence [11]. To improve various mechanical and thermal characteristics, ceramic reinforcing particles are incorporated into the matrix to create Metal Matrix Composites (MMCs) [12,13].

2 Hybrid Composites

The second generation of composite materials, known as hybrid metal matrix composites (HMMCs), are sophisticated materials that combine two or more types of reinforcements inside a metal matrix [14]. The purpose of the reinforcements, which might be whiskers, fibres, or particles, is to improve the particular qualities of the composite material. The primary goal of reinforcements in HMMCs is to increase the composite's strength and stiffness. Reinforcements are essential to improving the material's qualities. A customized property may be applied to the composite material by choosing various reinforcement kinds, sizes, and volume fractions [1,26]. The application needs, such as mechanical or thermal performance, material compatibility to provide adequate bonding, and uniform distribution throughout, determine which reinforcements should be used within the composite, and cost and availability.

Currently, there are several ways to incorporate reinforcements, including powder metallurgy, stir casting, and in-situ fabrication. However, stir casting is the most widely used method due to its user-friendliness; in this method, the reinforcements are combined with a molten material matrix and then solidified to form a composite material. Generally, depending on the type of manufacturing technique employed, numerous elements impact the final product, therefore integrating reinforcements necessitates careful evaluation of the required qualities and application requirements. In automobile engineering, hybrid composites play a major role in components such as shafts, brake disks, brake pads, callipers, disk brake callipers, frames, piston rods, piston pins, and braking systems [37]. Hybrid Metal matrix composite materials offer several advantages across various industries due to their unique properties and versatility. Some of the crucial advantages are a high weight-to-strength ratio [1,2,37, 20,21], high thermal conductivity [1,2,11,37], High thermal conductivity [1,2,11,37], Tailorable properties [7,8], Cost efficiency [1,2,7,8], and Environmental sustainability [1,23,17].

3 Reinforcements

The materials used to make reinforcements may be categorized, with some examples being whiskers and platelets, as well as metallic and ceramic particle reinforcement (MPR and CPR) and organic and inorganic fibre reinforcements (OFR and IFR). The choice of reinforcement is a crucial factor that greatly influences how AMMCs or AHMMCs are tailored, even if each kind of reinforcement has special qualities and benefits over the others [39].

Some of the key selection criteria include the reinforcement's elastic modulus, tensile strength, density, melting temperature, thermal stability, coefficient of thermal expansion, size and shape, compatibility with the matrix material, and wettability. Other considerations include the reinforcement's cost and form. Numerous researchers state that TiC, TiB_2, Al_4C_3, B_4C, Al_2O_3, SiC, and ZrB are the commonly used particle reinforcements [3]. SiC, B_4C, Al_2O_3, and TiC are low-density, high-hardness materials that are also used for applications involving aluminium that require high elastic modulus, good wettability, and thermodynamic stability [3, 39].

Particulate reinforcements are used in Metal Matrix Composites (MMCs) in particular to improve qualities like wear resistance, stiffness, and thermal conductivity. Materials like SiC or Al_2O_3 are used in these reinforcements. Aluminium Hybrid Metal Matrix Composites (AHMMCs) combine particle reinforcements with primary and secondary reinforcements, such as fibers or laminates, to provide a combination of qualities suited to particular uses. These particles are employed as primary reinforcement in AHMMCs and as single reinforcement in AMMCs because of their exceptional qualities.

To improve a matrix material's characteristics, nanoparticle reinforcement entails integrating nanoscale particles—usually with at least one dimension less than 100 nanometres into the matrix. It is recognized as a fascinating sophisticated material with many structural and physical applications [4]. More specifically, nanoparticle reinforcements are essential for enhancing mechanical, thermal, and electrical properties in Metal Matrix Composites (MMCs). These nanoparticles, which are uniformly distributed throughout the matrix material and increase the composite's overall qualities, include SiC, Al2O3, and Carbon Nano Tubes [10].

The enhanced mechanical qualities that nanoparticle reinforcement offers set it apart from traditional reinforcements. Because of their increased surface area to volume ratio and improved load transmission mechanisms, nanoparticles are more robust and stiffer than conventional micron-scale reinforcements. Additionally, the addition of nanoparticles to the composite improves its thermal conductivity, which makes it ideal for applications like electrical gadgets and automotive components that demand effective heat dissipation. Additionally, incorporating nanoparticles facilitates the development of lighter MMCs with comparable or superior mechanical properties, rendering them particularly appealing for aerospace and transportation applications. Moreover, certain nanoparticles, notably CNTs, possess the capability to enhance the electrical conductivity of MMCs, thus expanding their potential applications in electrical and electronic domains [10].

4 Manufacturing Methods

There are three primary categories of manufacturing techniques that are employed in the production of AHMMCs. These include liquid phase processes like stir casting, which incorporates dispersed particles into a molten metal through agitation; semi-solid processes like spray and rheo casting, which atomize molten metal into fine droplets that solidify upon contact with a substrate; and solid phase processes like powder metallurgy, which produces metal parts through compaction and sintering [20,34]. The microstructure and interfacial connection between the matrix and reinforcement are impacted by these production techniques. The greater difficulty in producing fibre composites made of plastic has led to the widespread acceptance and popularity of metal matrix composites. Solid-phase manufacturing is expensive because it needs expensive products like powder or foil and has high initial operations costs. At the same time, liquid-based manufacturing techniques are generally less expensive comparatively and are also easy to regulate the process, which makes it a widely acceptable and available manufacturing method. High-temperature melt is utilized in this casting method to encourage the chemical interaction between the reinforcements and the matrix. This might occasionally lead to material deterioration and the failure to achieve the desired characteristics. Table 1 compares a few common production techniques; stir casting is widely used because it is inexpensive, does little harm to the reinforcement, and has many applications [14]. It also has benefits including flexibility, ease of use, and suitability for large-scale manufacturing [22]. If the reinforcement is not distributed uniformly throughout the matrix during the manufacturing process, the reinforcements' intended properties will not be transferred to the composites. Several times, including before and after the stirring and solidification of reinforcements, have an impact on the distribution of reinforcement.

Table 1: comparison between various popular manufacturing methods [32].

Method	**Size and Shape Range**	**Metal Yield**	**Possible Damage on reinforcement**	**Cost**
Powder Metallurgy	Varied shapes, limited sizes	High	Reinforcement fracture	Expensive
Squeeze Casting	Limited	Low	Thermal degradation of reinforcements	Reasonably less expensive
Spray Casting	Limited shape, large size	Medium	Fragmentation or fracture due to high speed	Expensive
Mechanical Stir Casting	Varied range both	Medium	Little damage	Less Expensive
Electromagnetic Stir Casting	Varied range of both	High	Little to no damage	Less Expensive

4.1 Stir Casting Process

Figure 1 depicts the stir casting schematic setup. Metal matrix composites (MMCs) are made by stir casting, a liquid-state manufacturing technique that involves mechanically stirring molten aluminium to disperse reinforcements (ceramic, particles, or short fibres), usually in powder form [11,15]. It is essential to thoroughly clean the surfaces before churning in order to reduce interactions between the reinforcement and matrix. The qualities of the composite can be impacted by the introduction of reinforcing particles, which can trap contaminants like slag and metal oxides. Throughout the casting process, a motor-driven agitator is employed to keep the particles from settling and guarantee a consistent distribution. Before the slurry is cast, it is stirred for a few more minutes [36].

Traditionally, stir casting involves melting the matrix and forcefully stirring it to form a vortex at the surface, where reinforcing material is added. Before casting, a few minutes more of mixing are required. A new development in mixing entails heating the matrix above its liquidus temperature, cooling it to a semi-solid state, and then combining it with warmed reinforcement particles. Finally, it is heated once again and fully mixed. By using this method, the reinforcements have been evenly distributed and their mechanical qualities, such as hardness and impact strength, have been enhanced. As the weight fraction of SiC increases, the findings show a rising trend for hardness and impact strength [33].

To avoid matrix-reinforcement interactions, eliminate surface contaminants, and encourage the creation of a protective oxide layer, preheating reinforcement particles is frequently used. Different preheating temperatures and durations have been employed by researchers, including 1000°C for 1.5 hours [19], 1100°C for 1-3 hours [16], and 850°C for 8 hours [24].

By adjusting process variables such stirring conditions, temperature, and reinforcement distribution, stir casting provides a flexible and affordable way to produce MMCs with specific features [11,15]. It finds use in sectors including electronics, automotive, and aerospace that demand materials that are strong and lightweight.

Nevertheless, stir casting of MMCs has several drawbacks, including unequal reinforcement distribution, poor wettability, and cluster formation. All these restrictions can be addressed by attempting to create an innovative impeller shape. The image illustrates how little equipment is needed for the process, making it simple to make MMCs.

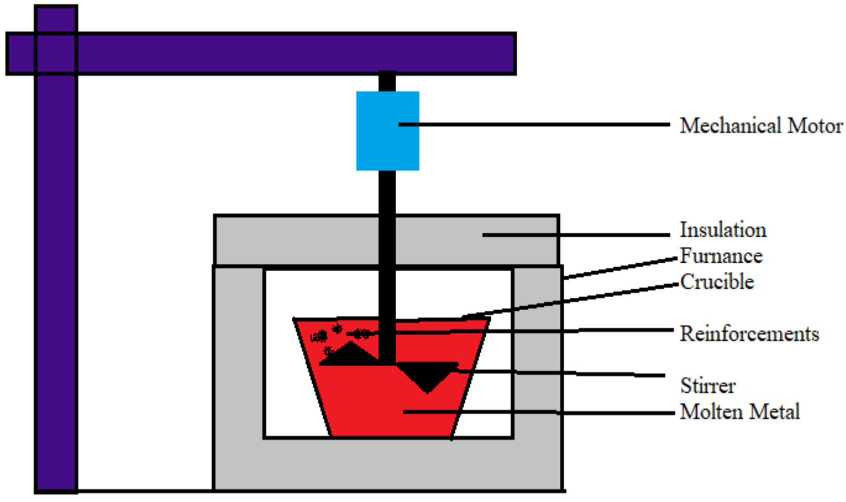

Fig 1: Schematic diagram of Stir casting setup

4.2 Mechanical Characterization

The mechanical characteristics of the composite may be ascertained by mechanical characterization, which will serve as the foundation for avoiding material failure when the composite is in use. Strength-related properties, elastic properties, and fracture toughness are a few of the crucial mechanical characteristics of composites. These characteristics are affected by a number of variables, including the kind, quality, and dispersion of reinforcement as well as the wettability of the matrix and the reinforcement particles. The finished product's microscopic images may be used to analyze how the reinforcements are distributed. The reaction between the matrix and the particulates will sometimes be too minor to be able to detect by a standard optical microscope, so in such cases, Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM) are effective. Correctly understanding the mechanical behaviour of aluminium in this case is crucial as they are employed in diverse areas, as stated before.

S. Kaliappan et.al (2022) investigated the impact of AlN-SiC nanoparticles on mechanical behaviour of Al-6061 and observed that the tensile properties, compressive strength and hardness of the composite increased with an increase in the volume fraction of nanoparticles [25]. V.S.S. Venkatesh et.al fabricated composite with nano SiC using ultrasonic-assisted stir casting and investigated its mechanical properties. The tensile strength increased with wt% of nanoparticles (0.5, 1%, 1.5%). It suddenly decreased at 2%, which was later concluded to be due to the difference in the thermal expansion coefficients between the matrix and reinforcements [26]. D. Joslin Vijaya et.al developed Ti and NbC nanoparticle-reinforced hybrid metal matrix composites to inspect the mechanical properties. The authors observed that the composites' Ultimate tensile strength, microhardness, and microhardness increased (0, 3, 6, 9, 12%) accordingly while the elongation decreased. The research concluded that AA7075 alloy is the most robust and suitable alloy for high and low-temperature applications [27].

The mechanical performance of aluminium reinforced with titanium particles has been examined by Sanjay Kumar Thakur et al**.** The micro and macrostructure data indicate that the porosity and density of the composite material increase with increasing titanium content. The mechanical characteristics show that the presence of a more robust, stiffer reinforcing material and a higher density of dislocation results in a rise in matrix and interfacial hardness [28]. Ali Mazahery and Mohsen Ostadshabani produced aluminium composites reinforced with nano Al_2O_3. They investigated the mechanical properties, and the addition of nanoparticles resulted in significant improvement of both compressive and tensile flow stress, and the nanoparticles improved the flexibility of composites [10]. As we know, the demand for heavy-duty materials and materials with high wear resistance and durability has skyrocketed in the last few years, and composites with superior hardness, toughness and wear resistance are preferred. One of these composite-reinforcement studied by Uvaraja VC et.al was done using SiC and B_4C nanoparticles and a notable 18% increase in these characteristics was achieved despite increasing the composite weight because both reinforcements were hard particles [2,20].

Mamoon A. A. Al-Jaafari (2021), The study investigated how the mechanical characteristics of aluminium alloys 6061 and 6082 were affected by the addition of nanoscale titanium dioxide (TiO2) particles. The results demonstrated that the composites' yield stress, ultimate tensile strength, and hardness were increased by adding TiO_2 nanoparticles up to 1.5 weight per cent. On the other hand, as the TiO_2 content increased, the composites' flexibility decreased. Reduced porosity, robust bonding between the reinforcement particles and matrix, and higher dislocation density are all responsible for the improved mechanical properties. These findings imply that 1.5-weight per cent TiO_2 nanoparticle-reinforced aluminium alloy composites have a lot of potential for use in sectors where high strength and hardness are required [28]. Suhandani, Mardy, et.al (2021) The motive of the study was to know how the mechanical characteristics of aluminium silicon (Al-Si) alloy were affected by the addition of Cobalt Oxide (CoO) nanoparticles and the melting temperature during stir casting. The results indicated that Al-Si with 0.015 weight per cent CoO melted at 800 °C had the maximum impact toughness, while Al-Si with 0.015 weight per cent CoO melted at 850 °C had highest hardness. This indicates that melting the reinforcements at the proper temperature is essential. As per their observations, the hardness values of all the composite materials have increased with the increase in CoO filler. This phenomenon may be explained by the effectiveness of the CoO filler particles, which increase the density of the Al-Si metal alloy particles by tucking them inside CoO particles, thus increasing the mechanical strength of formed composites [29].

4.3 Use of Sustainable Materials

MMCs are now a crucial component of most production components when it comes to material selection. Aluminium and magnesium have drawn a lot of interest as basis materials for MMCs and HMMCs because of their desired qualities. Considerable study has been done on sustainability issues related to reinforcements in the manufacture of composites because of environmental concerns. Research on sustainable materials made of agricultural and industrial waste, such as egg shells, coconut husk, rice husk ash, sugarcane bagasse, fly ash, red mud bamboo leaf ash, etc. has been done.

Power plants employ fly ash, as a byproduct of burning grey coal. There are two major kinds of fly ash and according to the varied quantities of elements, depending on the type of coal used to generate it. Numerous studies concluded that using fly ash as reinforcement improved the mechanical characteristics and reduced the rate of wear. Fly ash is renowned for its ability to lower the density of composite materials, resulting in lightweight, high-performing materials that may be used in heavy-duty applications such as transportation and aerospace [2,5,21].

Another waste material being used as reinforcement is eggshell, a significant source of food waste that ultimately comes to the disposal. Eggshells comprise 94-97% of $CaCO_3$, which has a lower density than synthetic $CaCO_3$[5]. Studies include the use of eggshells as reinforcement by either milling or carbonizing the shells, and the analysis reveals that the addition of eggshell particles resulted in grain refinement, an increase in yield strength, and a decrease in weight [5,6].

Another well-known industrial byproduct that is regarded as trash is red mud. It is a byproduct of the Bayers process used to make aluminium oxide, and since it contains significant levels of Fe_2O_3 and Al_2O_3, researchers are interested in using red mud. SiC and red mud were used in the study together with Al 2024 as reinforcements, and it was found that the reinforcements were evenly distributed. The density and porosity of the composite material decreased with the addition of red mud [5,40].

When reinforced with SiC and Fly ash, the Al hybrid composites emerge as a material with exceptional mechanical and physical properties. Its hardness, tensile strength, yield strength, and fracture toughness increase with nanoparticle content, and the overall strength-to-weight ratio also improves significantly. This makes hybrid composite an exceptional material for manufacturing automotive components [2,21].

A study by Alanemea et.al (2013) investigated the aluminium composites reinforced with ceramics and agricultural, waste bamboo leaf ash (BLA) and concluded that the hardness, density, tensile strength, and yield strength decreased with an increase in %of BLA. At the same time, the fracture toughness of the material was improved. The reduced density with increased agriculture waste reinforcement indicates that this composite is suitable for developing low-weight, high-performance components in the automobile and aerospace sectors [2,18].

A study by Prasad DS et.al exploring alumina particles and rice husk ash as nanoparticle hybrid reinforcements for developing aluminium composites illustrates that with the increase in ash particles, the hardness and tensile strength reduced significantly compared to its other hybrid counterparts. On the other hand, RHA, along with SiC, has enhanced all mechanical properties while reducing the density. This makes the yield a lightweight, cost-effective, and high-performance composite, highlighting the RHA's properties as a complementary reinforcement for many superior components and future research [2,35].

The use of these waste products as reinforcement in composites has been the subject of several research projects. Aluminium hybrid composites, which offer distinctive combinations of mechanical and physical qualities that transcend those attained by single ceramic reinforced composites, have emerged as the next stage in the continuous breakthroughs and innovations. To create AHMMCs, which are a green substitute for some reinforcements, material scientists have focused more on creating low-cost, high-performance materials and employing agricultural and industrial waste as reinforcement materials. In addition to addressing environmental issues, recycling, and using waste materials as green materials also provide energy and cost-effectiveness.

5 Conclusion

Aluminium hybrid composites represent a pivotal role in the advancement of material science by offering a versatile solution across various sectors with their exceptional attributes compared to other materials. With the incorporation of multiple reinforcements, AHMMCs deliver excellent strength, stiffness, thermal conductivity, and other tailorable mechanical properties that satisfies the demands of many industries. Stir casting still emerges as a favoured and versatile manufacturing method when it comes to Al based composites thanks to its simplicity and cost-effectiveness.

Additionally, the exploration of environmentally friendly reinforcing materials including industrial and agricultural reinforcements is taking place which undermines the commitment and work towards sustainability while offering alternatives to synthetic reinforcements. Moreover, ongoing research activities seek to introduce new manufacturing techniques, reinforcement materials for amplifying the performance and sustainability of the composites.

6 Nomenclature:

MMC: Metal Matrix Composites

AMMC: Aluminium Metal Matrix Composites

HMMC: Hybrid Metal Matrix Composites

AHMMC: Aluminium Hybrid Metal Matrix Composites

References

1. F.C. Campbell, Lightweight materials: Understanding the basics (2012) ASM international Materials Park, Ohio, Pg: 33-119.
2. J. Singh and A. Chauhan, Characterization of hybrid aluminium matrix composites for advanced applications – A review. Journal of Materials Research and Technology(2016), pg: 159-169.
3. I A Ibrahim, F A Mohamed, and E J Lavernia, Journal of Materials Science (1991) col 26 pg: 1137-1156.
4. Mandeep Singh, Deepak Bhandari, and Khushdeep Goyal. A review of the mechanical performance of nanoparticles reinforced aluminium matrix nanocomposites. Amterials today Proceedings vol 46 part 9 (2021) pg: 3198-3204.
5. Ndudim Henry Ononiwu, Ester T. Akinlabi and Chigbogu G. Ozoegwu. Sustainability in Production and Selection of Reinforcement particles in Aluminium Alloy Metal Matrix Composites: A Review. International Conference on Engineering for Sustainable World 1378(2019).
6. S. Shamim, H. Singh, C. Sasikumar, and D. K. Yadav. (2017) "Microstructures and Mechanical Properties of Al-Si-Mg-Ti/Egg Shell Particulate Composites," Materials Today: Proceedings (2017) pg:2887-2892.
7. Rino JJ, Chandramohan D, Sucitharan KS. An overview on development of aluminium metal matrix composites with hybrid reinforcement. International Journal of Science and Research (IJSR), India Online ISSN: 2319-7064.
8. N.Valibeygloo, R.Azari Khosroshahi, and R.Taherzadeh Mousavian. Microstructural and mechanical properties of Al-4.5wt% Cu reinforced with alumina nanoparticles by stir casting method. International Journal of Minerals, Metallurgy and Materials Vol20, (2013), Pg: 978.
9. Ali Mazahery and Mohsen Ostadshabani. Investigation on mechanical properties of nano-Al2O3-reinforced aluminum matrix composites. Journal of Composite Materials (2011), pg: 2579-2586.
10. S. R. Bakshi, D. Lahiri, A. Agarwal. Carbon nanotube reinforced metal matrix composites-a review, 2010 Institute of Materials, Minerals and Mining and ASM International Published by Maney for the Institute and ASM International.
11. John E. Allison, S. Gerald Cole," metal- matrix composites in the automotive industry: Opportunities and challenges", Journal of the minerals, metals and materials society volume 45, pg:19-24.
12. S. Vignesh., C. Sanjeev, Investigation on Surface Quality in Machining of Hybrid Metal Matrix Composite (Al-SiC B4C), International Conference on Thermal, Material and Mechanical Engineering (2012).
13. J. Hashim, L Looney and M S J Hashmi, "Metal Matrix Composites: Production by the Stir Casting Method", Journal of Material Processing and Technology, Vol. 92, 1999, pp 1-7
14. S. Gopalakannan, T. Senthivelan, S. Ranganathan, "Stastical optimization of EDM parameters on machining of aluminium hybrid metal matrix composite by applying Taguchi based Grey analysis" Journal of Scientific & Industrial Research vol 72(2013), pg 358-365.
15. Vijay Rana, Harish Kumar, and Amresh Kumar. Fabrication of hybrid metal matrix composites- A review of comprehensive research studies. Materials Today Proceedings vol 56(2022) pg: 3102-3107.

16. V. M. Kevorkijan and B. Sustarsic, “A new production Technology for Discontinuously reinforced Al-SiC Composites”, Key. Eng. Mater, 1997, pp 127-131.
17. S. Naher, D Brabazon and L Looney, “Development and Assessment of a New Quick Quench Stir Caster Design for the Production of Metal Matrix Composites”, Journal of Material Processing Technology, Vol. 166, 2004, pg:430-439.
18. Alanemea KK, Ademilua BO, Bodunrin MO. Mechanical properties and corrosion behaviour of aluminium hybrid composites reinforced with silicon carbide and bamboo leaf Ash. Tribol Ind 2013;35(1):25–35.
19. W. Zhou, Z. M. Xu, “Casting of SiC Reinforced Metal Matrix Composites”, Journal of Materials Processing Technology, Vol. 63, 1997, pp 358-363.
20. Uvaraja VC, Natrajan N. Optimization of friction and wear behavior in hybrid metal matrix composites using Taguchi technique. J Miner Mater Charact Eng 2012;11: 757–68
21. Boopathi M, Arulshri KP, Iyandurai N. Evaluation of mechanical properties of aluminium alloy 2024 reinforced with silicon carbide and fly ash hybrid metal matrix composites. Am J Appl Sci 2013;10(3):219–29.
22. P. K Jayashree, M. C Gowri Shankar, Achutha Kini, S. S Sharma and Raviraj Shetty, “Review on Effect of Silicon Carbide (SiC) on Stir Cast Aluminium Metal Matrix Composites”, International Journal of Current Engineering and Technology, 2013.
23. Christy TV, Murugan N, Kumar S, “A comparative study on the microstructures and mechanical properties of Al 6061 alloy and the MMC Al 6061/TiB2/12p”. Journal of Minerals & Materials Characterization & Engineering vol 9 (2010), pg:57–65.
24. S. Kaliappan, Shanmugam, Pradeep Johnson, M. Karthick, S. Sekar, Pravin P. Patil, M. K. S. Sai, K. P. Yuvaraj, and Venkatesan Govindaraajan, “Impact of AlN-SiC Nanoparticle Reinforcement on the Mechanical Behaviour of Al 6061-Based Hybrid Composite Developed by the Stir Casting Route”, Advances in Materials Science and Engineering, Vol 2022, Article ID 1399618, 8 pages.
25. V.S.S. Venkatesh, Ganji Prabhakara Rao, Lokeswar Patnaik, Nakul Gupta, Sunil Kumar, Kuldeep K. Saxena, B.D.Y. Sunil, Sayed M. Eldin, and Fatima Hiader Kutham Al-kafaji “Processing and evaluation of nano SiC reinforced aluminium composite synthesized through ultrasonically assisted stir casting process”, Journal of materials research and technology 2023;24, pp 7394-7408.
26. D. Joslin Vijaya, J. Pradeep Kumar and D.S. Robinson Smart, “Analysis of hybrid aluminium composite material reinforced with Ti and NbC nanoparticles processed through stir casting”, Materials Today: Proceedings (2021), https://doi.org/10.1016/j.matpr.2021.05.683.
27. Sanjay kumar Thakur, Manoj Gupta, “Improving mechanical performance of Al by using Ti as reinforcement”,Composites Part A:Applied Science and Manufacturing (2007), pg:1010–1018.
28. Mamoon A. A. Al- Jaafari, “Study the Effects of Titanium Dioxide nano particles reinforcement on the mechanical properties of Aluminum Alloys composite”, IOP Conf. Series: Materials Science and Engineering (2020), 1105 012062.
29. Mardy Suhandani, Poppy Puspitasari, Jeefferie Abd Razak, “Impact, Hardness and Fracture Morphology of Aluminium Alloy (Al-Si) filled Cobalt Oxide Nanoparticles at Various Stir Casting Temperatures”, Malaysian Journal on Composite Science and Manufacturing Volume 5, Issue 1 (2021) 11-20.
30. S. Venkatesan, and M. Anthony Xavior, “Characterization on Aluminium alloy 7050 Metal matrix composite reinforced with Graphene Nanoparticles, Procedia Manufacturing 30 (2019) 120–127

31. Macke A, Schultz BF, Rohatgi P. Metal matrix composites offer the automotive industry an opportunity to reduce vehicle weight, improve performance. Adv Mater Processes 2012;170(3):19–23
32. M.T. Sijo and K.R. Jayadevan / Procedia Technoogy 24 (2016) 379 – 385
33. M. Yilmaz and S. Altintas, "Properties of Al-Mg-SiC Composites Produced by a Modified Compo Casting Technique", In Proceeding of the 2nd Biennial European joint conference on Engineering Systems, 1994, pp 119-124.
34. Y. H. Seo and C. G. Kang, "Effects of Hot Extrusion Through a Curved Die on the Mechanical Properties of Al-SiC Composites Fabricated by Melt-Stirring", Composites Science and Technology, Vol.59, 1999, pp 643-654. M.T. Sijo and K.R. Jayadevan / Procedia Technology 24 (2016) pg: 385.
35. Prasad DS, Shoba C, Ramanaiahet N. Investigations on mechanical properties of aluminum hybrid composites. J Mater Res Technol 2014;3(1):79–85.
36. D Manoj Singla, Deepak Dwivedi, Lakhvir Singh, Vikas Chawla, "Development of Aluminium Based Silicon Carbide Particulate Metal Matrix Composite", Journal of Minerals & Materials Characterization & Engineering, Vol. 8, No.6, 2009, pp 455-467.
37. Macke A, Schultz BF, Rohatgi P, "Metal matrix composites offer the automotive industry an opportunity to reduce vehicle weight, improve performance". Adv Materials & Processes 2012, pg:19–23.
38. Tony Thomas. A, Parameshwaran.R, MuthuKrishnan.A, and Arvind Kumaran.M. Development of Feeding & Stirring Mechanisms for Stir Casting of Aluminium Matrix Comosites. International Conference on Advances in Manufacturing and Materials Engineering (2014) Pg: 1182-1191.
39. Mohit Kumar Sahu and Raj Kumar Sahu. Aluminum based hybrid metal matrix composites: a review of selection philosophy and mechanical properties for advanced applications. IjmperD vol 10 Special Issue, (2020) pg: 8-28.
40. J. Singh and A. Chauhan. Fabrication characteristics and tensile strength of novel Al2024/SiC/red mud composites processed via stir casting route," Transactions of Nonferrous Metals Society of China (2017) pg:2573–2586.