Influence of Stir Casting Technique on HMMCs- A Literature Survey

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Abstract: In a modern era of material science research, hybrid metal matrix composites (HMMCs) have played a vital role to fulfil all basic requirements for the application sectors of engineering as well as medical sciences and provided superior material properties than naturally obtained monolithic materials from the earth crust. HMMCs comprise a mixture of two or more reinforcements in the desired metal matrix to enhance the physical, chemical, mechanical, metallurgical, and tribological properties of the material. This paper focused on the analysis of different matrix, reinforcement, and enhanced properties of prepared composites formed through the stir casting technique. Furthermore, process parameters, challenges after fabrication, and various applications associated with hybrid composites have also been discussed briefly.

***Keywords* – HMMCs, Matrix, Reinforcement, Properties, Applications, Stir Casting**

I. INTRODUCTION

Hybrid composite materials are composed of two or more physically as well as a chemically distinct phase of matrix and reinforcement whose combination produces superior properties such as high stiffness, strength, light in weight, better fatigue, and toughness property, corrosion resistance and high strength to weight ratio which approved as an advanced material. The HMMCs based on the matrices were classified into three parts [1]:

- Metal Matrix Composites (MMCs) included aluminium, magnesium, copper, iron, titanium-based alloys used as a base matrix
- Polymer Matrix Composites (PMCs) included nylon, natural rubber, Bakelite, polyester, Teflon which used as a base matrix
- Ceramic Matrix Composites (CMCs) included silicon carbide, boron carbide, alumina, carbon, tantalum carbide, hafnium carbide, zirconium carbide which used as a base matrix

The metals, polymers, and ceramics were explored and widely used as base matrix materials. MMCs offered higher ductility than CMCs and better environmental stability than PMCs. MMCs also offered considerable improvement in transverse strength, shear strength, electrical and thermal conductivities, and resistance to erosion and abrasion [2]. As per the type of reinforcing agents, the composite further classified into particle-reinforced, fibre-reinforced and structural. The reinforcing phase may be either in the form of continuous fibres, short fibres/whiskers, and particulates which balanced the mechanical, physical, and tribological characteristics of composites [3, 4]. Further classification of reinforcements can be categorized into two broad types i.e. organic and inorganic, and processing techniques were used to fabricate HMMCs are presented in Table 1. Among all processing techniques, stir casting which also called the vortex method found to be the most economical route and allowed to fabricate very large or intricate shape components. The Properties of HMMCs fabricated by stir casting (shown in fig.1.) with squeeze attachment can be altered by varying different process parameters to achieve desired materials were as follows [5-7]:

- Reinforcement size (micron or nano)
- Reinforcement weight %
- Reinforcement preheat temperature
- Squeeze pressure
- Furnace/die temperature
- Stirring speed
- Stirring time
- Stirrer blade design and geometry

The examine properties of HMMCs are presented in Table 2. Various mechanical and tribological properties were examined after the fabrication of desired composites through testing instruments such as weighing balance, micro-hardness tester, universal testing machine, pin on disc tribometer, and dry abrasive tester. Generally, for metallurgical examination of raw materials or prepared hybrid composites, following XRD, FESEM/SEM, TEM, EDS/EDX, WD-XRF, and EBSD are important modes or techniques were employed to get required results:

- **XRD** (used to find out the present phase of material and also provide information on unit cell dimensions and structures)

Abbreviations: *HMMCs- Hybrid Metal Matrix Composites, XRD- X-ray Diffraction, FE-SEM/SEM- Field Emission - Scanning Electron Microscope, TEM- Transmission Electron Microscopy, EDS/EDX- Energy Dispersive X-ray Spectroscopy, WD-XRF- Wavelength Dispersive X-ray Fluorescence Spectrometer, EBSD-Electron Backscatter Diffraction, MgO- Magnesium Oixde, SiC- Silicon Carbide,* Al_2O_3*- Aluminium Oxide or Alumina,* B_4C*- Boron Carbide, TiC- Titanium Carbide, WC- Tungsten Carbide,* TiB_2*- Titanium Boride,* $ZrSiO_4$*- Zirconium Silicate, GSA- Groundnut Shell Ash, CNTs/MWCNTs- Carbon Nano-Tubes/Multi-Walled CNTs, PET- Polycarbonate and Polyester*

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- **FE-SEM/SEM** (provides information about the microstructure or surface topography i.e. surface finish or fractography analysis at high resolution)
- **TEM** (deals with details about the internal composition of very thin specimens such as tissue sections, fibres or molecules)
- **EDS/EDX** (microanalysis technique detects x-rays coming out from the samples during bombardment by an intense electron beam to figure out their chemical quantification of the analyzed section)
- **WD-XRF** (considered as a non-destructive analytical method to determine the elemental composition of material without their phase identification)
- **EBSD (**techniques include orientation mapping, texture measurements, phase identification, strain analysis, grain size, and grain boundary analysis)

Table 1 Important matrix, reinforcement and processing techniques used for fabrication of HMMCs

Matrix	A356, A359, A1100, A2024, A3021, A4015, A5028, A5083, A6061, A6063, A6082, A7050, A7075, A8090, AZ31B, AZ91, AZ91D
Reinforcements	SiC, B_4C, Al_2O_3, TiC, MgO, TiB_2, WC, $ZrSiO_4$, Graphite, Rice Husk Ash, Fly Ash, Red Mud, Coir, Bagasse Ash, Groundnut shell Ash, CNTs/MWCNTs
Processing Techniques	Powder Metallurgy, Pressure Infiltration, Stir Casting, Compo-casting, Rheo-casting, Microwave Sintering, Diffusion Bonding, Ultrasonic assisted casting

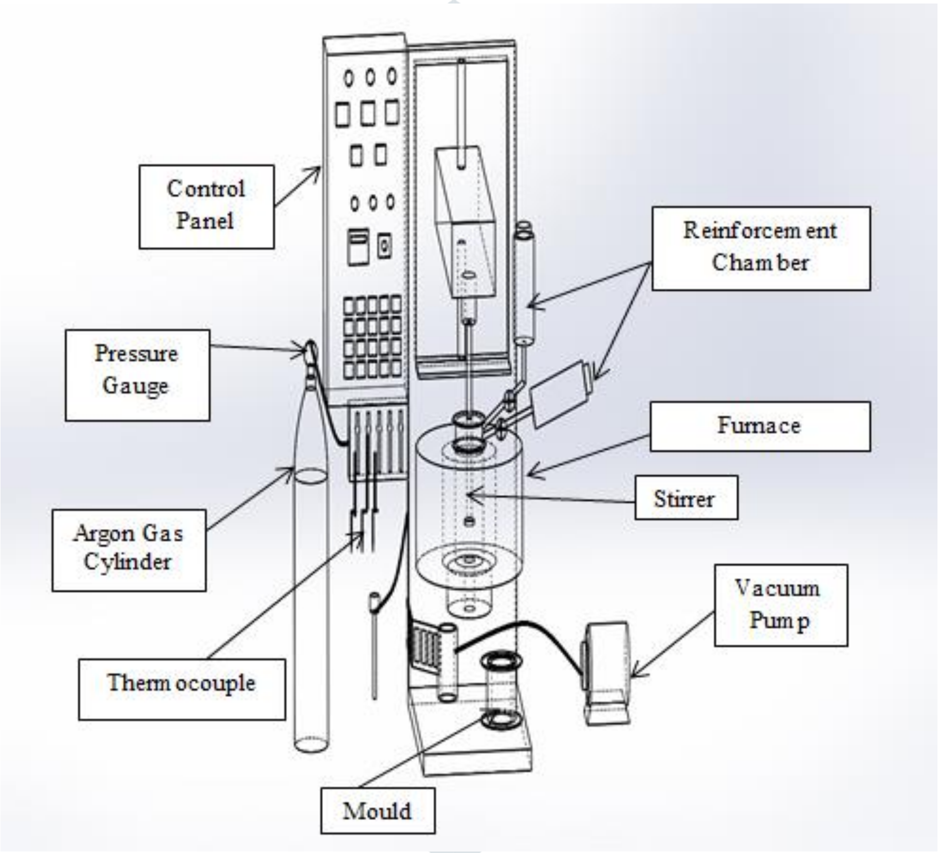

Fig. 1. Sketch of Bottom Pouring Stir Casting Furnace Set-up

Table 2 Properties of HMMCs

S.No.	***Types of Property***	***Examination***
1.	Physical	Density, Porosity
2.	Chemical	Corrosion resistance, Chemical affinity
3.	Mechanical	Tensile strength, Ultimate strength, Impact strength, Micro-hardness, Fatigue strength, Creep resistance
4.	Tribological	Weight loss due to wear, Wear rate, Coefficient of friction

Some pictorial views of tested material i.e. SiC powder by XRD, and FE-SEM are demonstrated in fig.2 and fig.3 respectively. The design of experiment (DOE) using Taguchi approach has become a much more attractive tool for practicing most of the researchers related to the fields of manufacturing and industrial engineering. It is a static approach that developed the mathematical models through experimental trial runs to predict the possible output based on the given input data or process parameters. Taguchi Orthogonal arrays are classified into three basic types:

- Two level designs- L4, L8, L12, and L16
- Three level designs- L9 and L27
- Mixed level designs- L8, L16, and L18

Furthermore, the Taguchi method (also known as orthogonal array design) was used for parameter optimization and the level of importance was determined using analysis of variance (ANOVA) [8-10].

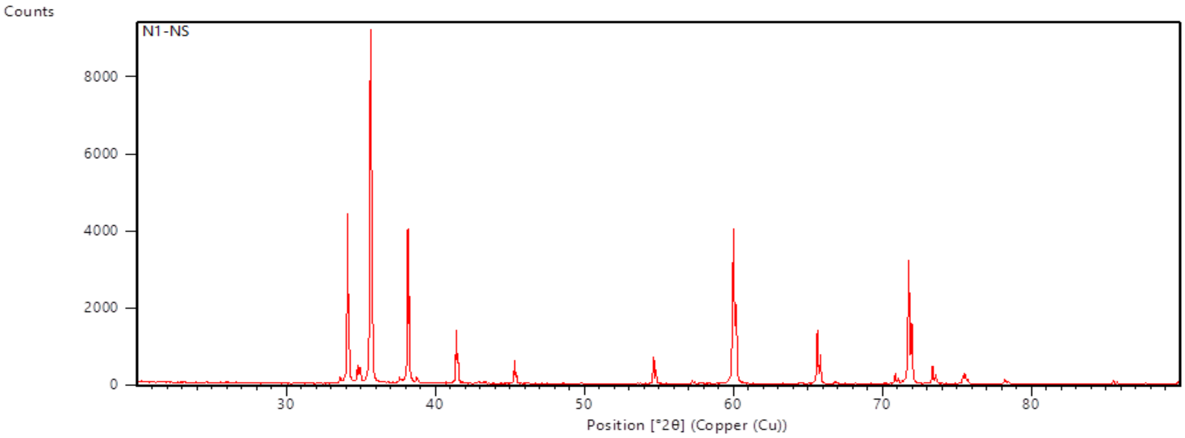

Fig. 2. XRD sample report of SiC powder

Fig. 3. FE-SEM sample report of SiC powder at magnification (500X)

II. STUDY OF LITERATURE

Alaneme et al. [11] investigated the mechanical properties of Al based hybrid composites reinforced with GSA and SiC different mix ratios (10:0, 7.5:2.5, 5.0:5.0, 2.5:7.5 and 0:10) constituted 6 and 10 wt.% of the reinforcing phase, while the matrix material was Al–Mg–Si alloy. The hybrid composites were produced by a two-step stir casting technique. Microstructural examination, hardness, tensile and fracture toughness testing were carried out to appraise the mechanical properties of the composites. The results show that with increasing GSA in the reinforcing phase, the hardness, ultimate tensile strength (UTS) and specific strength of the composites decreased slightly for both 6 and 10 wt.% reinforced Al–Mg–Si based composites owing to the amount of the oxides of Al, Si, Ca, K_2 and Mg present in the composition of GSA. However, the percentage elongation improved marginally and was generally invariant to increasing GSA content while the fracture toughness increased with increasing GSA content. GSA offered a favourable influence on the mechanical properties of Al–Mg–Si hybrid composites comparable to that of rice husk ash and bamboo leaf ash. Imran et al. [12] deals with the waste sugarcane bagasse-ash and graphite utilizing as reinforcement in fabricating of an aluminium alloy (Al-7075) based matrix hybrid composites. The aluminium matrix hybrid composites have been fabricated by stir-casting method at 750 °C. Casting was developed in circular metal mould having 5 circular slots of diameter of 21 mm and length of 250 mm. Adding bagasse-ash with varying reinforcement of three cases, in first case 2% constant with varying graphite 1%, 3%, and 5%, in second case 4%, and in third case 6% constant with varying same graphite percentage. The effect of the reinforcement has been performed through various mechanical tests. The mechanical properties measuring such as Brinell hardness and tensile strength of both the samples have been prepared as per the ASTM E23 and E8 standards. Results give out that there would be greater effect of reinforcing different bagasse-ash in aluminium alloy matrix hybrid composites. In the third case more enhanced mechanical properties have been achieved as compared to case one and two of bagasse–ash combination. It showed that the selection of bagasse-ash as reinforcement has one of the most significant criteria for the fabrication of aluminium matrix hybrid composites.

Prasad et al. [13] studied the damping behavior of hybrid composites has been investigated using dynamic mechanical analyzer (DMA). The composites were fabricated with 2, 4, 6, and 8% by weight of rice husk ash (RHA) and SiC in equal proportions using two stage stir casting process. Damping measurements of all the specimens were obtained by dynamic mechanical analyzer (DMA) at different frequencies in air atmosphere. Scanning electron microscope (model JSM-6610LV) was used to study the microstructural characterization of the hybrid composites. It was observed that the dislocation density, which results from the thermal mismatch between the reinforcement and the matrix and the porosity of composites, has a great influence on the damping capacity of hybrid composites. The dislocation damping mechanisms were discussed with regards to the Granato–Lucke theory. Vinod et al. [14] showed the composites of aluminium matrix with organic (rice husk ash, RHA) and inorganic (fly ash) reinforcement at different weight fractions were fabricated by double-stir casting. The tribological behaviour of the hybrid composites was investigated under dry sliding conditions using different applied loads, sliding distances and sliding speeds. The aims of this work are use of waste material and investigation of the tribological performance, economic issues, environmental impact on wear loss, and coefficient of friction to increase the lifespan of such materials. Attempts were made to examine the effect of addition of waste particles in the aluminium composites on the sliding wear rate, which is of significant importance in the engineering field. The wear mechanism was analysed based on the wear debris and examination of wear tracks on the worn surfaces. The results showed that the A356/10 %RHA–10 %fly ash hybrid composite exhibited superior wear resistance compared with the aluminium matrix for use in engineering applications.

KhademeelJamea et al. [15] prepared the composites under investigation via. two formulations. The first one was Al/SiC MMC by addition of Silicon Carbide (SiC) particulates to the Aluminum matrix, and the second was Al/MgO MMC by addition of Magnesium Oxide (MgO) to the Aluminum matrix. Weight percentages of 5%, 7.5%, 10%, 15% and 20% were applied. The composites were prepared by liquid state mixing technique. To ensure homogeneous dispersion of ceramic particulates in the Aluminum matrix, specimens were taken from different locations in each cast and subjected to microscopic observation after proper preparation where and volumetric fractions were investigated, micro-structural examination and micro-structural analysis were carried out using optical microscope. Tensile, wear, hardness, and impact tests were conducted as well, and then fracture surfaces observation was employed using Scanning Electron Microscope (SEM) equipped with energy dispersive x-ray analysis (EDX). Adding SiC, MgO particulates to the matrix increased the ultimate tensile strength (UTS), and hardness, and decreased elongation (ductility) of the composite compared with those of the pure Aluminum. Increasing weight percentage of SiC, MgO increased its strengthening effect, with higher strength, higher hardness, and finer grain size. Sarada et al. [16] attempted to produce aluminium hybrid metal matrix composite (LM 25+ Activated Carbon+ Mica) by stir casting method and compare the properties with conventional composites (LM25+ Activated Carbon) and (LM25+Mica). The specimens were tested for hardness using Brinell Hardness Tester and wear properties using Abrasive belt wear testing machine. The contributions of the reinforcement on the wear process and the wear loss have been investigated. Study of wear debris and worn surfaces was carried out using Light Optical Microscope (LOM). Result showed that the abrasive action was in the direction of sliding but the wear debris was finer and smoother for hybrid composite than conventional composites. Additionally, with the addition of hybrid reinforcement instead of single reinforcement the hardness and wear resistance of the composite were increased.

Srivastava et al. [17] deals with the abrasive water jet turning of newly developed hybrid MMC A359/ B_4C/Al_2O_3 produced by electromagnetic stir casting. The justification of the fabrication was revealed by microstructural images and x-ray diffraction results. The main aim of the study was to analyse the machining behaviour of produced hybrid MMC under abrasive water jet turning. The surfaces created at different traverse speed were discussed in terms of surface integrity and surface texture. Optical profilometer was used to generate surface roughness report and 3D visualization of the machined surface. Olympus LEXT OLS 3100 laser confocal microscope was used to collect 2D and 3D surface topographical details of the machined surface. Surface morphology was discussed by FE-SEM images to evaluate surface defects. Residual stresses and microhardness test through the depth profile were also carried out to analyze the machined surface and subsurface. It has been found a perfectly round, slightly undulated surface which showed ploughing nature. The results also revealed a higher rate of material removal with rough cutting. Sajjadi et al. [18] reported to improve the wettability and distribution of reinforcement particles within the matrix; a novel three step mixing method was used. The process included heat treatment of micro and nano Al_2O_3 particles, injection of heat-treated particles within the molten A356 aluminum alloy by inert argon gas, and stirring the melt at different speeds. The influence of various processing parameters such as heat treatment of particles, injection process, stirring speed, reinforcement particle size and weight percentage of reinforcement particles on the microstructure and mechanical properties of composites was investigated. The matrix grain size, morphology and distribution of Al_2O_3 nanoparticles were recognized by scanning electron microscopy (SEM), optical microscope (OM) equipped with image analyzer, energy dispersive spectroscopy (EDS) and X-ray diffraction (XRD). Also, the hardness and compression strength of samples were investigated. The results showed the poor incorporation of nano particles in the aluminum melt prepared by the common condition. However, the use of heat-treated particles, injection of particles and the stirring system improved the wettability and distribution of the nano particles within the aluminum melt. Also, it was revealed that the amount of hardness, compressive strength and porosity increased as weight percentage of nano Al_2O_3 particles increased.

Bhushan et al. [19] deal with the fabrication and microstructural investigations of AA7075– SiCp MMCs. 7075 Al alloy was reinforced with 10 and 15 wt.% SiCp of size 20–40 μm by stir casting process. The resulting as-cast composite structures were analyzed using scanning electron microscopy, X-ray diffraction (XRD), differential thermal analysis, and electron probe microscopic analysis (EPMA). SiCp distribution and interaction with 7075 Al alloy matrix was studied. The 7075 Al alloy–SiCp composite microstructure showed excellent SiCp distribution into 7075 Al alloy matrix. In addition to this, no evidence of secondary chemical reactions was observed in XRD and EPMA analysis. Decomposition step in derivative thermogravimetric curve was seen at temperature of 1257, 1210, and 1256 °C for 7075 Al alloy, AA7075/10 wt.%/SiCp (20–40 μm) and AA7075/ 15 wt.%/SiCp (20–40 μm) composites, respectively. So, these composites could be successfully used for applications where temperature does not exceed beyond 1250 °C. Radhika et al. [20] investigated tribological behaviour of aluminium alloy (Al-Si10Mg) reinforced with alumina (9%) and graphite (3%) fabricated by stir casting process. The wear and frictional properties of the hybrid metal matrix composites was studied by performing dry sliding wear test using a pin-on-disc wear tester. Experiments were conducted based on the plan of experiments generated through Taguchi’s technique. A L27 Orthogonal array was selected for analysis of the data. Investigation to find the influence of applied load, sliding speed and sliding distance on wear rate, as well as the coefficient of friction during wearing process was carried out using ANOVA and regression equations for each response were developed. Objective of the model was chosen as ‘smaller the better’ characteristics to analyse the dry sliding wear resistance. Results showed that sliding distance had the highest influence followed by load and sliding speed. Finally, confirmation tests were carried out to verify the experimental results and SEM studies were done on the wear surfaces.

Padmavathia et al. [21] investigated wear and Friction behaviour of Al6061 with various percentage volumes of Multiwall carbon nanotube and Silicon Carbide reinforcement through stir casting method followed by die-casting. Wear test was made by using Pin on Disc Apparatus on the prepared Specimen. It was found that, under mild wear conditions, the composite displayed a lower wear rate and friction coefficient compared to Aluminium. However, for severe wear conditions, the composite displayed higher wear rate and friction coefficient and it was clarified that the friction and wear behaviour of Al–SiC-MWCNT composite was largely influenced by the applied load and there exists a critical load beyond which CNTs could have a negative impact on the wear resistance of aluminium alloy. Also the hardness of the composite was increased by increasing the per-cent volume of reinforcement. Poria et al. [22] considered friction and wear of aluminium matrix composites reinforced with TiB2 micro particles processed through the stir casting method rather than in-situ techniques adopted by earlier studies. Different weight percentages of TiB2 powders having average sizes of 5 - 40 micron were incorporated into molten LM4 aluminium matrix by stir casting method. The friction and wear behavior were studied for Al-TiB2 composites prepared according to specific dimensions by using a block-on-roller type multi-tribotester at room temperature. Normal loads of 25 - 75 N and rotational speed of 400 – 600 rpm were used for the determination of friction and wear behavior. It is found that friction and wear decrease with an increase in percentage of TiB2 reinforcement in the composite, while friction and wear increase with applied load and speed. SEM studies revealed the presence of both abrasive and adhesive wear mechanisms with abrasive wear being predominant.

Reddy et al. [23] reported about the AA8090/MgO metal matrix composites were investigated under dry sliding wear test as for ASTM G99 standard. AA8090 base matrix reinforced with MgO nanoparticles was fabricated using stir casting technique. By using pin on disc apparatus the test was conducted by taking parameters like sliding distance, sliding speed, load and volume fraction of reinforcement. The result revealed that the addition of MgO slightly reduced wear rate of composites. If sliding distances and load increased, the wear rate drastically increased. Praveenkumar et al. [24] suggested AZ31B as Mg matrix material and hard Tungsten carbide (WC) particles as reinforcement material. Mg/WC composites reinforced with different weight proportions (0, 5, 10, and 15 wt.%) were made through stir casting method. The worn surface of manufactured Mg/WC composites and base Mg material were examined by SEM. The wear test results denoted that the AZ31B/15 wt% WC composites had excellent tribological behaviour when compared to the base magnesium matrix AZ31B alloy. The yield strength, flexural strength, tensile strength, and micro-hardness of the manufactured composites were improved by increasing the WC content. SEM images revealed the homogeneous distribution of WC particles throughout the Mg matrix. Sakthivelu et al. [25] attempted to synthesize aluminium metal matrix composites through stir casting technique. The matrix material chosen in this study was AA7050 and the reinforcement material was ZrSiO4. The composites AA7050, AA7050-10%ZrSiO4, and AA7050-15%ZrSiO4 were used. The wear behavior of the aluminium matrix composites was investigated by using pin-on-disc tribometer. The advanced material had substantial development in tribological behavior when the reinforcement percentage was increased. From the experimental results, it was confirmed that sliding distance of 1200 m, applied load of 3 N and sliding speed of 2 m/s result in minimum wear loss and coefficient of friction, while adding 10%ZrSiO4 to the AA7050.

Kumar et al. [26] presented, an aluminium-based metal matrix composite with in situ aluminium silicon carbide (Al_4SiC_4) particles had been developed by the incorporation of TiC particles in commercial aluminium melt through a stir-casting method. Microstructure evaluation in correlation to developed hardness and mechanical properties was performed. Furthermore, the dry sliding wear behavior of commercial aluminium and commercial aluminium–5 vol% Al_4SiC_4 composite was investigated at low sliding speed (1 ms^{-1}) against a hardened EN 31 disk at different loads. The wear mechanism involved adhesion and microcutting–abrasion at lower loads. On the other hand, at higher loads, abrasive wear involving microcutting along with adherent oxide formation was observed. The overall wear rate increased with load in the alloy as well as in the composite. Moreover, the overall wear rate of the composite was lower than that of the commercial aluminium at all applied loads.` The severe wear region at 39.2 N load in the case of the commercial aluminium–5 vol% Al_4SiC_4 composite was found to be delayed up to a longer sliding distance compared to commercial aluminium. The in situ Al_4SiC_4 particles offered resistance to adhesive wear. Accordingly, the commercial aluminium–5 vol% Al_4SiC_4 composite exhibited superior wear resistance compared to the commercial aluminium. Ram et al. [27] studied the hardness, microstructure and tribological behavior of as-cast magnesium/SiC composites produced by stir casting and processed by friction stir processing and results were compared with as-cast magnesium/SiC composite. Magnesium/SiC metal matrix composites containing SiC reinforcement were produced by stir casting route and subjected to friction stir processing at a tool rotation speed of 1300 rpm and a transverse speed of 50 mm min^{-1}. The outcomes of the study revealed that the friction stir processing (FSP) resulted in 45% improvement in the hardness, reduction in the grain size from 170 μm to 3 μm, and improved distribution of particles in the matrix of the developed composites. The tribological results exhibited that the wear resistance of processed composite was significantly improved and the coefficient of friction is lowered as compared to their counterparts. SEM and EDS analysis of worn surfaces were carried out to have in depth understanding of the wear mechanisms. Furthermore, hybrid composite materials have found widespread applications in automotive, civil engineering, electrical/electronics, and bio-medical sectors [28-32], also shown in Table 3.

Through the rigorous study of literature review, some important challenges were faced by many researchers related to HMMCs [33-35]:

- Uniform distribution of the reinforcement material over the selected matrix
- Wettability between matrix and reinforcement
- Porosity
- The chemical reaction of matrix and reinforcement material with atmospheric surrounding
- Wear conditions such as abrasive, adhesive and fretting

Table 3 Applications of hybrid composite materials in various emerging sectors

Automotive Sectors	***Civil Engineering Sectors***	***Electrical/Electronic Sectors***	***Bio-Medical Sectors***
Pistons & Piston rings Connecting rods Cylinder liners Chassis Brake discs & rotors Submarine Propellers Ball bearings Engine blocks Sprockets & Pulleys	Bridge deck and superstructures Coldwater/Oil/Gas/Sewer pipes Pavements Wind power turbine Blades Trusses	Transmission poles/Towers Smart chips and sensors Fuel Cells Printed Circuit Board Breadboard Antennas Superconductors Transformer radiator fins Nano-Transistors	Orthodontic fixtures Biopsy forceps PET face mask/shields Surgical/Dental Instruments

III. CONCLUSIONS

From the above study, stir casting is found to be the most simple and economical route for the fabrication of aluminium and magnesium-based HMMCs. Besides, process parameters of stir casting i.e. preheat reinforcement temperature, stirring speed, and stirring time play a vital role in producing high-quality composites. For better wettability between matrix and reinforcement, magnesium suggested as a wetting agent should be added during the fabrication of composite to enhance their physical, mechanical, and tribological properties.

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