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# Review of Recent Studies in Magnesium Matrix Composites and their Fabrication Techniques

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## ABSTRACT

Magnesium matrix composites are very attractive materials for various applications of aerospace, defence organizations and automotive industry due to their low density, good mechanical and physical properties. The improvement of specific strength, stiffness, damping behaviour, wear behaviour, creep and fatigue properties are significantly influenced by the addition of reinforcing elements into the metallic matrix compared with the conventional engineering materials. This article represents different types of reinforcements and their effect on mechanical and physical properties magnesium and its alloy. Emphasis is also made on various fabrication techniques like friction stir casting, vacuum stir casting, Squeeze casting, Powder metallurgy, In-situ synthesis, Mechanical alloying and Pressureless infiltration. Most important applications of diverse magnesium MMCs are also examined critically in this work.
**Keywords:** Magnesium Matrix Composites, Fabrication Techniques, Stir Casting

## I. INTRODUCTION

Magnesium is the lightest structural metal, resulting in high specific strength and stiffness, therefore, very attractive for the automotive industry [1]. Magnesium also has a number of other desirable features including strong abilities for vibration damping and noise reduction, excellent liquid state formability and radiation insulation. Hence it is recognized as an environmental friendly engineering metal [2]. Therefore, magnesium alloys are becoming popular in the automobile industry as a means of reducing weight, increasing fuel efficiency and decreasing greenhouse gas emissions.

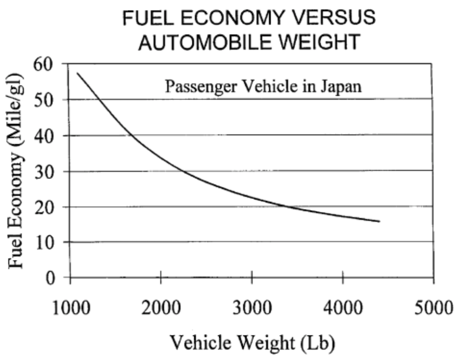


**Figure 1:** Fuel economy versus vehicle weight [3]

However, the application of magnesium alloys is limited evidently due to their low creep resistance at high temperatures, low strength, low modulus and significantly less wear resistance [4,5].Therefore, Reinforcements are needed to improve the properties of the magnesium metal and alloys . MMCs fabricated from magnesium would provide attractive alternatives to Aluminum MMCs. The most commonly used reinforcements are Silicon Carbide (SiC), Aluminum Oxide ($Al_2O_3$), and Titanium Carbide (TiC), Boron Carbide ($B_4C$), CNTs, Fibers etc. SiC reinforcement increases the ultimate tensile strength, yield strength, hardness, ductility and wear resistance of Mg and its alloys [8].

## II. METHODS AND MATERIAL

### Silicon Carbide Reinforced Magnesium Matrix Composite

S. Aravindan et al.(6) fabricated magnesium matrix composite by reinforcing silicon carbide particle with different volume percentage in magnesium alloy (AZ91D) by two step stir casting process. The effect of changes in particle size and volume fraction of SiC particles on physical and mechanical properties of composites were calculated under as cast and heat treated (T6) conditions. The experimental results were compared with the standard theoretical models. The results disclose that the mechanical properties of composites increased with increasing SiC particles and decrease with increasing particle size. Distribution of particles and fractured surface were studied through SEM and the presence of elements is discovered by EDS study. M.J. Shen et al. (7) reinforced two volume fractions (3 and 5 vol.%) of micron-SiC particles(1 mm) in AZ31B magnesium matrix composites by semisolid stirring assisted ultrasonic vibration method. The as-cast ingots were extruded at 350 C with the extrusion ratio of 15:1 at a constant ram speed of 15 mm/s. The microstructure of the composites was investigated by optical microscopy, scanning electron microscope and transmission electron microscope. Microstructure characterization of the composites showed relative uniform reinforcement spreading and significant grain refinement. The presence of 1 mm-SiC particles assisted in improving the elastic modulus and tensile strength. The ultimate tensile strength and yield strength of the 5 vol.% SiCp/AZ31B composites were concurrently upgraded.

M. Esmaily et al(8) elaborate the proficiency of the newly developed rheocasting (RC) technique in combination with the RheoMetal process for fabricating SiC particulate-reinforced AM50 and AZ91D matrix composites (Mg-based MMCs) was examined. The excellence of the MMCs was studied by examining the fraction of casting pores, number density of SiC clusters and the uniformity of SiC particles. Solid fraction, particle size and oxidation of SiC particles had strong impacts on the overall quality of the MMCs. The MMCs produced by 40% solid fraction and oxidized micron-sized SiC particles exhibited an excellent casting quality. A low-quality MMC was obtained when non-oxidized sub-micron sized SiC particles were employed. K.K.Deng et al. (9) fabricated theAZ91magnesium matrix composites reinforced with submicron-SiC particulates (0.2 m) along with six volume fractions (0.5, 1, 1.5, 2, 3, and 5 vol.%). Microstructure characterization of the composites showed significant grain refinement, relative uniform reinforcement distribution, and presence of minimal porosity. A strong basal plane texture was formed in bothAZ91alloy and SiCp/AZ91 composites during extrusion. Addition of submicron- SiC particulates results in weakening of the basal plane texture but simultaneously it improves the yield strength, micro-hardness, thermal stability, and elastic modulus.

M.J. Shen et al.(10) prepared bimodal size SiC particulates (SiCp) reinforced magnesium matrix composites with different ratios of micron SiCp and nano SiCp (MSiCp:N-SiCp ¼ 14.5:0.5, 14:1, and 13.5:1.5) were by semisolid stirring assisted ultrasonic vibration method. The AZ31B alloy and all as-cast SiCp/AZ31B composites were extruded at 350 C with the ratio of 12:1. Microstructural characterization of the extruded M14 þ N1 (MSiCp:N-SiCp ¼ 14:1) composite revealed the uniform distribution of bimodal size SiCp and significant grain refinement. Optical Microscopy (OM) observation showed that, compared with the M14.5 þ N0.5 (M-SiCp:N-SiCp ¼ 14.5:0.5) composite, there are more recrystallized grains in M14 þ N1 (M-SiCp:N-SiCp ¼ 14:1) and M13.5 þ N1.5 (M-SiCp:N-SiCp ¼ 13.5:1.5) composites, but in comparison to the M13.5 þ N1.5 composite, the average grain size of the M14 þ N1 composite is slightly decreased.

**Titanium Carbide Reinforced Magnesium Matrix Composite**

M Gobara et al. (11) fabricate a composite consisting of magnesium matrix reinforced with a network of TiCeTi2AlCeTiB2 particulates using a practical in-situ reactive infiltration technique. The microstructural and phase composition of the magnesium matrix composite (R-Mg) was investigated using SEM/EDS and XRD. The analyses revealed the complete formation of TiC, Ti2AlC and TiB2 particles in the magnesium matrix. Comparative compression tests of R-Mg and AZ91D alloy showed that the reinforcing particles improve the mechanical properties of Mg alloy. EIS and potentiodynamic polarization results indicated that the reinforcing particles significantly improve the corrosion resistance of the reinforced alloy in 3.5% NaCl solution. Also state that reinforcing the AZ91D alloy with a network of TiC, Ti2AlC, and TiB2 particulates increases the mechanical properties; notably compressive strength by 300% and Young's modulus by 320%. Furthermore, the density of the composite increased by 155% compared to that of the AZ91D alloy.

L. F Franco et al. (12) fabricated Metallic matrix composites (MMC) using Mg-AZ91 alloy and TiC as reinforcement by pressureless infiltration technique. The composites were wear tested against different AISI 4140, AISI 1045 and H13 steels. Wear resistance was calculated under dry sliding condition at different loads. Chemical analyses have shown the formation during the test of different oxides corresponding to the elements current in the composite. Universal wear mechanisms of the composites are basically type abrasion–adhesion. The wear resistance in all cases was better in the Mg AZ91E alloy than in the composite MgAZ91E/TiCp.

X.Y. Gu et al. (13) investigated the microstructure and mechanical properties of transient liquid phase (TLP) bonded TiC reinforced magnesium metal matrix composite (TiCP/ AZ91D) joints using aluminium interlayer. The concentration of Al in the joint centreline decreased with the increase in bonding time at a temperature of $460^{0}$C. The joint microstructure also changed from Mg solid solution, AlMg andAl12Mg17 compounds T0 -Mg,Al12Mg17 at this temperature. The increase of Al12Mg17 compound and aggregation of TiC particulates were the main reason for affecting the mechanical properties of joints. The joint shear strength of above 58MPawas obtained at the bonding temperature of $480^{0}$Cfor the bonding time of 20min.
Zhang Xiuqing et al. (14) investigated the mechanical properties and damping behaviour of TiC particulates reinforced magnesium matrix composites. The results revealed that the TiC particulates play a vital role on damping capacity and mechanical properties of the composites.

Tensile strength and damping capacity of the composites were improved compared to AZ91 Magnesium alloy. The damping characterization was explained with twinning, dislocation motion, grain boundary slip and interface slip. Wei Cao et al. (15) conducted a study on the damping behaviour and In situ synthesis of TiC reinforced magnesium matrix composites. It was found that, with the increase of reinforcement percentage, damping capacity of the magnesium alloy increased. The dislocation damping mechanism is an attributed to Improved damping capacities of composites. Interface damping has become a new contributor to the increase of damping capacity at elevated temperatures.

**Aluminium Oxide Reinforced Magnesium Matrix Composite**

Y. Chen et al. (16) elaborate the dynamic compressive mechanical behavior of AZ31-based nanocomposites is investigated for strain rates up to 2.5 × 103 s−1, using a split-Hopkinson pressure bar. Results indicate that when the grain size of AZ31 nanocomposites is close to 1 μm, the yield stress still follows the Hall–Petch law for quasistatic compression. The influence of strain rate on the flow stress of AZ31 nanocomposites is significant, and they exhibit negative strain rate sensitivity (SRS). This is postulated to be because the presence of nanoparticles elevates localized stress within the material when the strain rate is increased; hence, the applied stress required to activate tension twinning reduces correspondingly. The addition of nanoparticles (Al2O3) does not generate any positive influence on the compressive ductility of monolithic AZ31; this contrasts with significant enhancement in ductility for tension.

A. Banerji at el.(17) fabricated Mg alloy based composites were using Al2O3 fibre preforms incorporated in a squeeze cast Mg–6% Al alloy (AM60). AM60–x% (Al2O3)f, where x¼9, 11, and 26, samples were subjected to boundary lubricated sliding contact at 25 1C and 100 1C against AISI 52100 counterface within a load range of 1.0–5.0 N. The test parameters emulated ultra-mild wear (UMW) corresponding to wear conditions observed in automotive engine blocks. Wear rates of Mg composites were 104 times less than that of the unreinforced alloy. AM60–9% (Al2O3)f showed the highest rate of material loss compared to AM60–11% (Al2O3)f and AM60–26% (Al2O3)f. In the UMW regime, damage to the composites occurred in the following sequence: (i) fibre fracture and fragmentation; (ii) sinking in of the fragmented fibres; (iii) damage to Mg matrix causing high rate of material loss. Contact stress calculations, based on a micromechanical model that considered the fibres as asperities, indicated that at 1.0 N the initial contact pressure (2.8 GPa) exceeded the fibre fracture strength in compression. The normal stress on fractured fibres increased as they continued to be fragmented during sliding and became embedded into the matrix causing plastic deformation and localised pile up formation around the fractured fibres.. S. Jayalakshmi et al.(18) investigated the tensile behavior ofAM100magnesium alloy and its composites at different temperatures. The nature and distribution of precipitates influenced the inherent brittle nature of AM100 alloy and it dominates the tensile behaviour. At higher temperatures, the strengthwas attributed to the load carrying capacity of the fibres. The strength reduction is mainly due to averaging and softening of the matrix alloy, which indicates the addition to matrix flow properties.

P.P. Bhingole et al. (19) synthesized an AZ91 alloy matrix composites by in situ reactive formation of hard MgO and Al2O3 particles with addition of magnesium nitrate to the molten alloy. Formation of hard oxide due to in situ chemical reactions leads to increasing the ultimate strength, hardness and strainhardening exponent of the composites. The sliding wear resistance of the composites improved because of the presence of well-dispersed hard oxide particles and stronger interface that obtained from cavitations- enhanced wetting of reactively formed particles.

**Fabrication Techniques for magnesium matrix composites**

Until date, various processing methods have been employed for the fabrication of reinforced magnesium matrix composites such as Stir casting Squeeze casting Spray forming Powder metallurgy, Liquid–metal infiltration, rheocasting as shown in table 1.
Table 1– Classification of processing techniques employed for the fabrication of magnesium matrix Composites.

| Fabrication Techniques | | | | |
|---|---|---|---|---|
| Stir casting | Squeeze casting | Spray forming | Powder metallurgy | Liquid–metal infiltration |

Stir casting technique has been widely adopted for the fabrication of MMCs due to its simplicity, flexibility and applicability of the technique to large scale production of commercial components [20]. Composites fabricated by this technique involve melting of the matrix material followed by the addition of reinforcement to the melt with simultaneous stirring, followed by casting in a mold. Powder metallurgy is a conventional route used commonly for the synthesis of ceramic reinforced MMCs. MMCs fabricated by this method involves elemental blending and mixing of matrix powders and reinforcements, pressing it into green compacts of desired shape and size, followed by sintering under a controlled atmosphere at suitable temperatures [21] Squeeze casting is a die casting method based on slower, continuous die filling and high metal pressures. Laminar die filling and squeezing, which is the application of pressure during solidification, ensures that the component is free from blowholes and porosity, however, Squeeze casting aims no porosity and high quality castings for pressure tightness, heat treat-able and weld-able structure. In table 2, Comparison of different fabrication techniques was made in respect of cost, application and special comments were also mention.

## III. RESULTS AND DISCUSSION

**Table 2.** Comparison of MMCs techniques (22)

| Fabrication technique | Cost | Application | Comments |
|---|---|---|---|
| Diffusion bonding | High | Used to make sheets, blades, vane shafts, structural components | Handles foils or sheets of matrix and filaments of reinforcing element |
| Powder metallurgy | Medium | Mainly used to produce small objects (especially round), bolts, pistons, valves, high-strength and heat resistant materials | Both matrix and reinforcements used in powder form; best for particulate reinforcement; since no melting is involved, no reaction zone develops, showing high-strength composite |
| Liquid–metal infiltration | Low/medium | Used to produce structural shapes such as rods, tubes, beams with maximum properties in a uniaxial direction | Filaments of reinforcement used |
| Squeeze casting | Medium | Widely used in | Generally applicable to any type of |

| | | | |
|---|---|---|---|
| | | automotive industry for producing different components such as pistons, connecting rods, rocker arms, cylinder heads; suitable for making complex objects | reinforcement and may be used for large scale manufacturing |
| Spray casting | Medium | Used to produce friction materials, electrical brushes and contacts, cutting and grinding tools | Particulate reinforcement used; full-density materials can be produced |
| Compocasting/rheocasting | Low | Widely used in automotive, aerospace, industrial equipment and sporting goods industries; used to manufacture bearing materials | Suitable for discontinuous fibres, especially particulate reinforcement |

## IV. CONCLUSION

In this review article, current development in fabrication and reinforcement added for improving microstructure characteristic and mechanical property such as hardness, abrasive wear resistance, elastic modulus and tensile strength of magnesium matrix composites have been discussed. With regard to processing of reinforced magnesium matrix composites, a review of available literature shows that reinforcement used for magnesium and its alloys were SiC, TiC, Al2O3, Boron Carbides, CNTs, fibers. However for reinforcement these carbides in magnesium fabrication techniques used can be classified as casting (stir casting, squeeze casting, compocasting), solid state processing (powder metallurgy) and semi-solid processing (spray deposition). Among these techniques, the stir casting process is extensively adopted because of its simplicity, tractability and low cost for the fabrication of large size components. Though this method offers several advantages, it leads to porosity in the fabricated composites. However, composites produced by squeeze casting, compocasting and powder metallurgy exhibit lesser porosity compared to the composites produced by stir casting technique. Spray forming technique, though advantageous in producing a dense near net shape product, is limited to small sized components. In conclusion, considering from technical and economic factors, magnesium matrix composites appear to be promising MMC that can replace aluminum Metal Matrix Composite.

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