

# RECENT STUDIES ON PARTICULATE REINFORCED AZ91 MAGNESIUM COMPOSITES FABRICATED BY STIR CASTING – A REVIEW

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**Abstract:** Magnesium Metal Matrix Composites (Mg MMC) have been the focus of consideration by many researchers for the past few years. Many applications of Mg MMCs were evolved in less span of time in the automotive and aerospace sector to capture the benefit of high strength to weight ratio along with improved corrosion resistance. However, the performance of these materials in critical conditions is significantly influenced by several factors including the fabrication methods used for processing the composites. Most of the papers addressed all the manufacturing strategies of Mg MMC but no paper was recognized as a dedicated source for magnesium composites prepared through STIR casting process. Since STIR casting is the least expensive and most common process in the preparation of composites, this paper reviews particulate based Mg MMCs fabricated with STIR casting technology. AZ91 series alloys are considered as the matrix material while the effect of different particle reinforcements, sizes, weight fractions on mechanical and tribological responses are elaborated in support with micro structural examinations. Technical difficulties and latest innovations happened during the last decade in making Mg MMCs as high performance material are also presented.

**Keywords:** AZ91, ceramics, metal matrix composites, magnesium composites, particle reinforcement, stir casting

## 1. INTRODUCTION

Magnesium is the lightest metal with plenty of availability in the earth crust. Its density is 35% lesser than aluminum and it is 78% when compared to steel. Therefore, magnesium is selected as one of the alternate to steel and aluminum in many parts of an automobile and aerospace applications to promote fuel competence and to mitigate CO<sub>2</sub> emissions [1-3]. But, the pure form magnesium cannot be used directly in typical applications as it is very sensitive. This behavior restricted the magnesium in the further usage of high end products. Thus, to make available with good strength, corrosion resistance and formability, magnesium is commonly alloyed with some other elements [4,5].

Magnesium alloys are classified into two groups namely wrought alloys and cast alloys. Many researchers conducted experiments to bring the detailed potentialities and applications of these alloys [4-8]. The mechanical properties of magnesium wrought alloys are established to be better than cast alloys but the research growth is limited as it involves high production costs and limited formability at normal operating temperatures [7]. Hence, casting is the convenient process in handling the magnesium alloys for commercial applications.

The most renowned magnesium alloys are AZ series (Mg-Aluminum-Zinc) alloys. These alloying elements enhances the fluidity of casting to provide maximum possible strength to the prepared product. Though AZ alloys possess good tensile and moderate yield strength at normal temperature, the performance

of these alloys at higher temperatures i.e.  $>125^{\circ}\text{C}$  is limited [8]. To resolve this, reinforcements are added to magnesium alloys and the materials are commonly called as Mg MMCs. These materials can have improved high specific strength, stiffness, creep, damping, wear and fatigue properties than pure magnesium or magnesium alloys. These composites made their mark in all segments of an automotive and aviation industries and emerged as the materials of future.

The composites are mainly characterized by the nature of reinforcement. These reinforcements may be particles, fibers, whiskers... etc. D.J. Lloyd [9] presented a detailed explanation on particulate reinforced aluminum and magnesium composites with an emphasis on manufacturing methods and reactivity. It is further noticed from the Lloyd's work that particle reinforced Mg MMCs induce higher elastic modulus, strength and wear resistance with low cost of fabrication. Abhijit Dey et al. [10] reviewed various categories of particle reinforcements that are commonly introduced into magnesium and their alloys by clearly highlighting the advantages and disadvantages. Some novel contributions in the area of Mg MMCs are also happened in the recent years to achieve the greater yield in view of mechanical and tribological properties [11-15]. The number of works on Mg MMCs are keep on increasing and the same trend is expected to continue in the near future with different magnesium matrix alloys, reinforcement materials, fabrication methods, and innovations carried to achieve the desired properties. Therefore, this review paper addresses selective survey of particle reinforced AZ91 magnesium composites fabricated through STIR casting process from fundamentals to research happened particularly during the past decade.

## 2. FUNDAMENTALS

### 2.1. AZ91 Magnesium alloys

The name AZ series magnesium alloys is ascribed because of the alloying elements Aluminum(A) and Zinc (Z). The addition of aluminum to magnesium promotes hardness and castability while zinc improves strength without reducing % of elongation i.e. ductility [5]. Among various formulations of AZ series alloys, AZ91 alloys are popular and the number of articles publishing with AZ91 are mounting day by day [3]. Small variations in alloying elemental percentages made five sub classifications in AZ91 i.e. AZ91A, B, C, D, and E to make it ready for different applications. The composition of AZ91 alloys are given in Table 1.

AZ91A, AZ91B and AZ91D are die casting alloys among which AZ91A, B are used when the resistance to corrosion is not very much significant while AZ91D is high purity alloy with good sea water and atmospheric corrosion resistance. AZ91C and AZ91E are sand, investment, and permanent mould casting alloys [17].

Tab. 1. Different types of AZ91 alloys and their Chemical composition [16]

Type	AZ91A	AZ91B	AZ91C	AZ91D	AZ91E
Al	8.3-9.7	8.3-9.7	8.1-9.3	8.3-9.7	8.1-9.3
Zn	0.35-1	0.35-1	0.4-1	0.35-1	0.4-1
Mn	0.13 min	0.13 min	0.13 min	0.15 min	0.17- 0.35
Cu	0.10 max	0.35 max	0.10 max	0.030 max	0.015 max
Si	0.50 max	0.50 max	0.30 max	0.10 max	0.20 max
Fe	--	--	--	0.005 max	0.005 max
Ni	0.03	0.03 max	0.01 max	0.002 max	0.0010 max
Mg	Balance	Balance	Balance	Balance	Balance

The restrictions on Ni, Fe alloying elements makes AZ91E an exceptional corrosion resistance material among all AZ91 series alloys (Fig. 1). AZ91E and AZ91C can be welded with a stress relief while AZ91A, AZ91B, AZ91D are not suitable for welding [4,16].

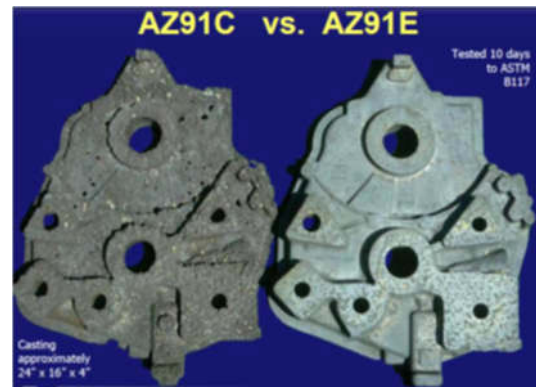


Fig. 1. Corrosion comparison of AZ91C and AZ91E [18]

### 2.2. Ceramic particles

Most of the ceramic particles are available in the form of oxides (e.g.,  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{MgO}$ ), borides, carbides (e.g.,  $\text{SiC}$ ,  $\text{B}_4\text{C}$  and  $\text{TiC}$ ), nitrides (e.g.,  $\text{Si}_3\text{N}_4$ ,  $\text{AlN}$ ) and elemental materials (e.g.,  $\text{C}$ ,  $\text{Si}$ ). Table 2 indicates some properties of ceramic particle reinforcements. These ceramic particles are often chemically reacted with the matrix material and/ or totally transformed into a new phase due to which the properties of the composite were significantly altered [7].

D.J. Lloyd [9] mentioned that the (i) application (ii) method of manufacturing the composites and (iii) cost of reinforcement are the pivoted points in the careful selection of reinforcement to prepare MMCs. However, homogeneous scattering of ceramic particles in the matrix and chemical kinetics between matrix and reinforcement also play a predominant role in exhibiting the characteristics of the composite.

Tab. 2. Few particle reinforcements and their properties [7]

Particle Name	SiC	B <sub>4</sub> C	Al <sub>2</sub> O <sub>3</sub>	BN	AlN	TiB <sub>2</sub>	TiC
Properties							
Crystal Type	Hex.	Rhomb.	Hex.	Hex.	Hex.	Hex.	Cub
Density [g cm <sup>-3</sup> ]	3.21	2.5	3.9	2.25	3.26	4.51	4.9
Coefficient of Thermal Expansion [10 <sup>-6</sup> K <sup>-1</sup> ]	4.7	5.0	3.6	0.8-7.5	5.5	4.5 – 6.5	7.4
Heat Conductivity [W m <sup>-1</sup> K <sup>-1</sup> ]	40	29	25	25	10	27	29
Elastic Modulus [GPa]	480	450	410	90	350	370	320

### 2.3. STIR casting process

STIR casting is one of the simple, vital and promising process in the manufacturing of Mg MMCs. In STIR casting, the reinforcement particles are introduced to molten metal and distributed by mechanical stirring mostly with an automatic stirrer. In case of magnesium composites, melting and stirring was done in an inert gas atmosphere to protect the melt from atmosphere. Schematic diagram of stir casting is represented in Figure 2a - b. STIR casting process can accommodate higher volume fractions without any damage to the reinforcement. However, the uniform distribution of reinforcement and the wettability between reinforcement and matrix are the main challenges in the preparation of composite to exhibit the desired properties [9,11,20]. Various strategies are adopted by the researchers to address this problem and are cited in the corresponding sections of the paper.

## 3. PARTICLE REINFORCED AZ91 MAGNESIUM METAL MATRIX COMPOSITES

Since careful selection of reinforcement will achieve the desired properties, the particle reinforced MMCs have arisen as vital materials as these always possess isotropic characteristics because of homogenous distribution. This section reviews various works carried with AZ91 based ceramic particle reinforced composites manufactured through STIR casting method.

### 3.1. Silicon Carbide (SiC)

The addition of Silicon Carbide particles (SiC<sub>p</sub>) will improve high stiffness, tensile elastic modulus, high temperature tolerance, corrosion and wear resistance [9-12,14].

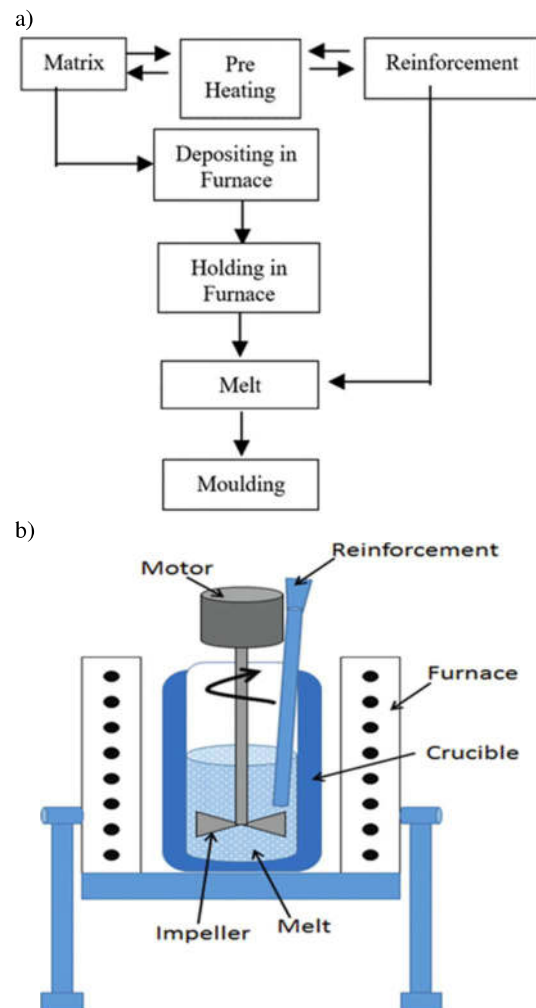


Fig. 2. STIR casting: a) procedure, b) setup in the preparation of composites [19]

P. Poddar et al. [21] fabricated SiCp reinforced Mg and AZ91D composites by STIR casting technique with a vol. fraction 15% and with an average particle size of 15  $\mu\text{m}$  and 150  $\mu\text{m}$ . Homogeneous dispersion of SiC particulates in AZ91D alloy is observed. An improvement in hardness and tensile modulus compared to monolithic alloy AZ91D is noticed due to the grain refinement because of SiCp addition. AZ91D alloy exhibited ductile type of fracture, whereas the fracture surfaces of AZ91D/ SiCp composites shown particulate breakage and SiC- AZ91D matrix debonding. X. J. Wang [22] conducted various interfacial studies on AZ91/SiC composites and stated that the interface between particle and matrix play significant role in the transition of loads. The particle/matrix interfaces can be categorized into three phases according to their morphological characteristics (Fig. 3). Detailed chemical reactions along with Interfacial Reaction Products (IRPs) at the particle/matrix interface are presented in support with EDAX spectroscopy.  $\text{Al}_4\text{C}_3$ ,  $\text{MgO}$ ,  $\text{Mg}_2\text{Si}$ ,  $\text{Mg}_{17}\text{Al}_{12}$  and  $\text{Al}_8\text{Mn}_5$  may occur at particle/matrix interface because of SiC addition to AZ91 due to which significant change in the properties are happen. Interface Type I is reported as an ideal condition for the enhancement of mechanical properties.

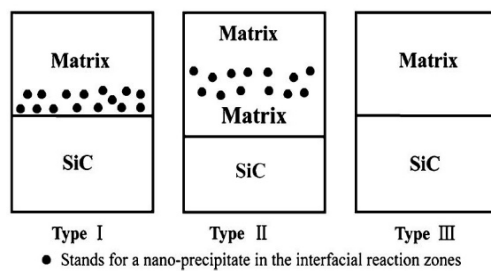


Fig. 3. Representation of interfaces according to morphological features [22]

A. Kandil [23] pre-treated the SiC particulates (average size 50  $\mu\text{m}$ ) over the temperature 1100  $^{\circ}\text{C}$  and induced into AZ91 matrix. Except AZ91 intermetallic compound  $\text{Mg}_{17}\text{Al}_{12}$ , no additional reaction takes place between the oxidized SiC and the molten AZ91 due to  $\text{SiO}_2$  formation on the surface of SiC because of pre-treatment. The oxidized SiC particles are also provided improved mechanical performance due to grain refinement while examinations of the fracture surface shown fine dimples and particle cracking regions as similar to earlier results [21]. Sujayakumar Prasanth et al. [24] produced AZ91 composites with different weight percentages of SiCp i.e. 5,10,15,20, and 25% with a mean particle size of 23 $\mu\text{m}$ . The electrical

conductivity and the coefficient of thermal expansion values of AZ91/SiCp composites found to be decreased with increase in wt.% of SiCp while the hardness and the compressive strengths are increased with an increase in reinforcement. Later, the sliding behavior of these composites was reported with regards to wear rate, wear resistance and coefficient of friction. The wear rate of the composite is found to be decreased and wear resistance is increased as such SiCp reinforcement induces the hardness and strength to soft and ductile AZ91 magnesium matrix due to oxidation, delamination, and abrasion wear mechanisms [25]. K. K. Ajith Kumar [26] and Abhilash viswanath [27] also evaluated physical, mechanical, tribological and creep phenomenon of stir cast AZ91/SiCp composites.

Though the properties of AZ91/ micro SiCp composites are encouraging, it always known fact that reduction in particle size can cause better grain refinement. However, thermal stability, wettability and uniform distribution of nano sized particles is major issue. Therefore, a modification in the STIR casting process such as Rheo-casting [28], Two step STIR casting [29] and STIR casting supported with ultrasonic vibration [15] have been implemented for the homogeneous distribution of nano SiCp in AZ91 Alloy. Zhao-hui et al. [30] fabricated AZ91 / nano SiCp based composites through ultrasonic method of dispersion in 0.1%, 0.3%, and 0.5% mass fractions. The microscopical characterization of these composites confirmed the uniform distribution of particles in the AZ91 magnesium alloy with aid of ultrasonic vibration. SiCp nano particles promoted heterogeneous nucleation of  $\alpha\text{-Mg}$  so that composite grains were refined and the mechanical properties increased dramatically relative to monolithic matrix alloy. Anil Kumar et al. [33] developed low cost vacuum based stir casting machine and conducted studies on AZ91/SiC composite with or without flux. Vacuum stirring process without flux yielded good properties because of low porosity values than flux assisted composites. A. Asgari et al. [34] developed composites with SiCp and AZ91 scrap as matrix. The yield strength of the composite was enhanced by 62.7 percent while toughness was improved by 46 per cent relative to the AZ91 magnesium alloy. The findings once again emphasized the recyclable advantage of magnesium by converting magnesium waste into successful product. Manoj Gupta et al. [5] reported the properties of SiC based AZ composites with various particle sizes and with different methods. Mechanical properties of some of the SiCp based AZ91 MMCs processed through stir casting procedures are mentioned in Table 3.

Tab. 3. Mechanical properties of SiC reinforced AZ91 Composites

Materials	Size of SiC <sub>p</sub>	Vol %	Method	Hardness	UTS in MPa	YTS (0.2%) in MPa	% of Elongation	UCS in MPa	Ref
AZ91D	--	--	STIR casting as cast condition	77.0 ± 0.9 VHN (50g)	--	--	--	--	
	150 μm	15		81.4 ± 1 VHN (50g)	--	--	--	--	
AZ91D + SiC	15 μm	15	STIR casting T4 condition	86.6 ± 1.5 VHN (50g)	--	--	--	--	[21]
	150 μm	15		82.2 ± 1.2 VHN (50g)	195 ± 2	122 ± 3	0.9 ± 0.1	--	
	15 μm	15		87.3 ± 1.1 VHN (50g)	204 ± 3	134 ± 2	1.2 ± 0.1	--	
		0	STIR casting	63 BHN	187	92	2.8	310	[24-27]
		5		82 BHN	184	119	1.1	317	
AZ91 + SiC	~23 μm	10		86 BHN	182	115	0.8	334	
		15		90 BHN	182	113	0.68	344	
		20		92 BHN	184	119	0.6	353	
		25		97 BHN	184	123	0.48	364	
AZ91D	--	--	Rheo casting as cast condition	62 VHN (0.5N)	--	--	--	--	
	150 μm	15		75 VHN (0.5N)	--	--	--	--	
AZ91D + SiC	15 μm	15	Rheo casting T4 condition	78 VHN (0.5N)	--	--	--	--	[28]
	150 μm	15		77 VHN (0.5N)	169	155	1.6	--	
	15 μm	15	81 VHN (0.5N)	199	182	1.8	--		
AZ91D + β SiC	50 nm	0	Ultrasonic assisted casting	--	174	104	3.6	--	[30]
		0.5		--	124	216	6.6	--	
	40nm	0	Ultrasonic assisted casting	63.5	133	65	2.2	--	[31, 32]
		0.5		64.8	180	140	2.1	--	
AZ91D + β SiC		1		66.8	191	141	2.4	--	
		1.5		71.1	146	99	1.5	--	
		2		73.2	137	117	1.3	--	

### 3.2. Alumina (Al<sub>2</sub>O<sub>3</sub>)

Though the properties of AZ91/SiC composites are promising, they are found to be very brittle. So, Al<sub>2</sub>O<sub>3</sub> is an another choice of reinforcement for the improved ductility with good tensile and compressive strength. These particles promote creep resistance as well [35]. However, limited works are identified with Al<sub>2</sub>O<sub>3p</sub> reinforced AZ91 composites fabricated through STIR casting in the recent years. Maher Mounib et al. [36] reported the reactivity of alumina in AZ91 Mg MMCs through the experiment carried out by melt stirring process coupled with an ultrasonic vibration.

Thermodynamic calculations and kinetics of these reactions indicated the formation of MgO and confirmed by EDS studies.

Yadav, S. D et al. [37] attempted hybrid processing method in which γ- alumina nano particles are added to AZ91 molten metal and was stirred by ultrasonic processing. Hardness, tensile and tribological characteristics of these composites was investigated in support with optical micrographs and X-ray diffraction studies. Mahmoud, M. G et al. [38] used Semi-Solid Rheocasting (SSR) technique to prepare nano α - Al<sub>2</sub>O<sub>3</sub> of ~80 nm reinforced AZ91

composites in 1, 2, 3 and 4% weight fractions. The microstructural images have  $\alpha$  and  $\gamma$ -phases along with an intermetallic compound  $Mg_{17}Al_{12}$  (Fig. 4).  $\gamma$ -phase is a eutectic compound reported as a very key feature in altering the mechanical properties. For 2 wt.%  $Al_2O_3$ , the hardness was improved by 17 % while 5% increase in wear resistance and 50% in corrosion resistance was observed. Sameer Kumar et al. [39] also adopted semi solid stir casting procedure to fabricate nano  $Al_2O_3$  reinforced AZ91E composites with an average particle size 50nm. The pre - heated particles are added to AZ91 melt at 590 °c and stirred with an automatic stirrer for 3 – 5 minutes at 450 rpm. The effect of weight fractions on the density, porosity, hardness and tensile mechanical behavior was investigated. The composites with 2 wt.% shown improved properties because of uniform distribution while the weight fraction beyond 2 % caused agglomeration of particles and resulted in reduction of properties as confirmed by microstructural analysis.

Tara Sasanka et al. [40-41] reported that semi solid STIR cast based 2 wt.%  $Al_2O_3/AZ91E$  composites exhibited higher wear resistance because of hard ceramic particles and uniform distribution in composite. To promote good wettability between matrix and reinforcement, Sameer Kumar et al. [42] prepared surface modified (Ni coated) nano alumina

particles using electroless plating method and introduced in to AZ91E alloy. The mechanical response of the composites with coated and uncoated reinforcement is mentioned in Table 4. An overall improvement of 20-30% hardness and tensile strength was observed in 2 wt.% Ni coated alumina reinforced composites. The fracture studies of these composites reported a mixed mode of ductile and brittle failure. A significant improvement in fatigue and impact behaviors of 2 wt.% Ni coated alumina reinforced composites has also been observed because of strong metal - metal bonding between matrix and reinforcement [ 43,44].

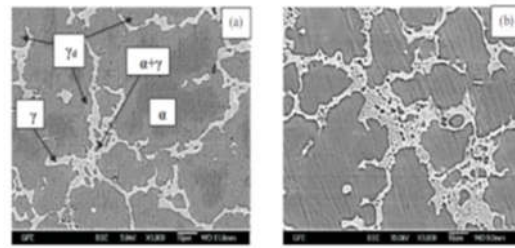


Fig. 4. SEM observation of: a) AZ91 alloy, b) AZ91 composite with 2 wt.%  $Al_2O_3$  reinforcement [38]

Tab. 4. Mechanical properties of Ni coated and Uncoated nano alumina in AZ91E composites as mentioned by Sameer Kumar et al [39, 42]

Un Coated alumina in AZ91E composites [39]					
Wt.%	Micro Hardness VHN	Young's Modulus MPa	Yield Stress MPa	Ultimate Tensile Strength, MPa	% of Elongation
0	64.94±2.64	43454.15	96.61±4.07	162.77±2.08	3.08±0.27
1	72.11±1.86	47033.92	122.54±2.84	178.39±3.03	2.92±0.34
1.5	73.61±2.57	48489.00	138.36±3.60	192.37±3.31	2.83±0.29
2	77.61±3.08	49913.55	146.21±3.11	205.52±2.74	2.65±0.31
2.5	75.45±3.81	51292.24	148.17±3.94	199.77±2.41	2.31±0.21
3	73.77±2.99	52194.14	150.95±4.02	188.26±3.69	1.94±0.26
Ni Coated alumina in AZ91E composites [42]					
1	77.56±2.05	48208.50	129.56±2.88	191.97±2.83	3.56±0.24
1.5	79.68±2.54	49345.20	146.55±3.09	207.07±3.01	3.44±0.32
2	87.94±1.57	51023.70	155.05±2.03	221.09±2.03	3.15±0.19
2.5	83.43±2.92	52234.56	157.17±2.05	215.45±3.23	2.71±0.33
3	78.36±3.90	53332.10	159.3±2.74	203.03±4.18	2.07±0.34

### 3.3. Other particle reinforcements in AZ91

In addition to Silicon Carbide ( $\text{SiC}$ ) and Aluminum Oxide ( $\text{Al}_2\text{O}_3$ ), other ceramic particle reinforcements are also being used in the preparation of Mg MMCs in view of desired properties and application.  $\text{TiC}$  particles ( $\text{TiC}_p$ ) play a critical role in the damping characteristics of MMCs. In addition, reinforcing the AZ series alloys with  $\text{TiC}_p$  greatly increase yield strength and tensile modulus while ductility is found to be slightly reduced [10]. Anil Kumar et al. [45] prepared AZ91/  $\text{TiC}_p$  composite with 3, 6, 9 and 12 weight percentages with a particle size of  $\sim 20$  microns. Hardness, tensile and compressive strength of the composite was observed along with wear behavior. The yield and ultimate tensile strength of the composite was initially lower than AZ91 alloy, but it was increased on further addition of  $\text{TiC}$  reinforcement. This was reported as poor performance of the processing technique at lower percentage of reinforcement as it was not created a good interface between brittle  $\text{TiC}$  particle and large secondary phase. However, at higher reinforcement percentages grain refinement was occurred and resulted in improved properties. Calcium added AZ91C alloy i.e. AZX915 based 12 wt. %  $\text{TiC}_p$  composites (particle size 5 -20  $\mu\text{m}$ ) was prepared by Nagaraj M. Chelliah et al. [46]. The wear behavior of AZX915 and AZX915/ $\text{TiC}_p$  composites under heat treatment are compared and observed that the wear rate of as cast composite is reduced by 2 times than the composite with heat treatment because of intermetallic precipitates of  $\beta\text{-Mg}_{17}\text{Al}_{12}$  and  $\text{Al}_2\text{Ca}$  phases. Boron Carbide ( $\text{B}_4\text{C}$ ) is known for high hardness, high modulus elasticity and fracture toughness with improved bond strength. M.E. Turan et al. [47] illustrated the wear behaviors of AZ91 with 50%  $\text{SiC}_p$  and AZ91 with 50%  $\text{B}_4\text{C}_p$  with an average particle size 45  $\mu\text{m}$ . The hardness values of AZ91 with 50%  $\text{SiC}_p$

are higher than the composites fabricated with AZ91 with 50%  $\text{B}_4\text{C}_p$  because of strong bonding between AZ91 and  $\text{SiC}_p$  as reported. Further it is observed that AZ91/ $\text{SiC}_p$  composites shown better wear resistance, wear depth and wear rate with increase in load Ponnappa et al. [48] developed Mg/ $\text{Y}_2\text{O}_3$  and AZ91D/ $\text{Y}_2\text{O}_3$  composites with average particle size 5 $\mu\text{m}$  through two step STIR casting method in 5,10,15 and 20% weight fractions. The X- Ray diffraction studies clearly shown the presence of interfacial/intermetallic products of AZ91 along with  $\text{Y}_2\text{O}_3$  while only magnesium was observed in Mg/ $\text{Y}_2\text{O}_3$  composites. (Fig. 5a - b). AZ91D/ $\text{Y}_2\text{O}_3$  composites exhibited good improvement in hardness, elastic modulus and tensile strength because of precipitation hardening and grain refinement.

Katarzyna N. Braszczyńska Malik and Elżbieta Przełoczyńska [49] fabricated and investigated the microstructure of AZ91 Mg MMC reinforced with  $\text{Ti}_6\text{Al}_4\text{V}$  particles (30% wt. fraction.) in as cast, solution treatment and T6 conditions. Apart from  $\alpha$  - Mg phase,  $\gamma$  eutectic phase has also been observed in as cast specimens. No new phases in the composite were observed due to the implementation of thermal treatments. Chun-Lei Zhang et al. [50] used a new liquid settling process for the preparation of TC4 ( $\text{Ti}_6\text{Al}_4\text{V}$ ) particle reinforced AZ91 alloy with an average particle diameter of 100  $\mu\text{m}$  in a volume fraction nearly equal to 50%. The methodology of this process in contrast to semi solid STIR casting, ultrasonic STIR casting is described in Figure 6. Apart from the former methods, the novel liquid settling process accommodated a high reinforcement percentage with uniform distribution. The ultimate tensile strength of the composites prepared through this process was improved by almost 30% than semi solid casting process and 10 % than STIR casting with ultrasonic setup.

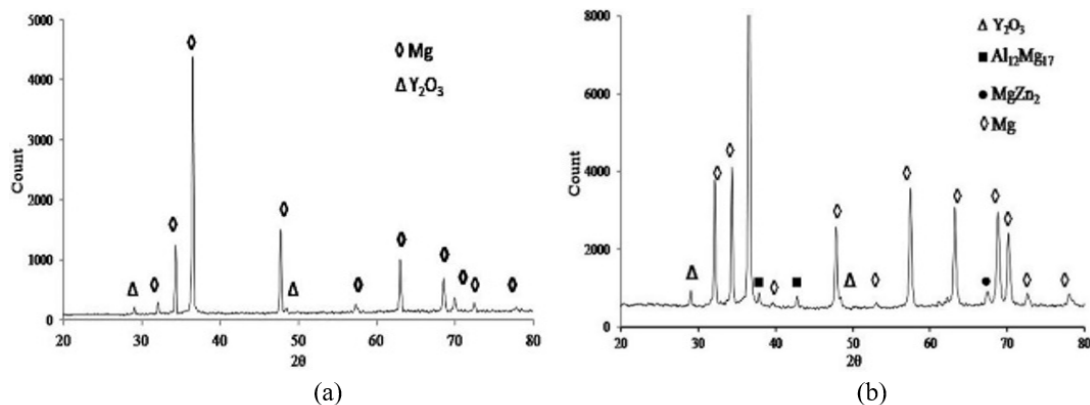


Fig. 5. XRD patterns of: a) Mg/  $\text{Y}_2\text{O}_3$  b) AZ91D/ $\text{Y}_2\text{O}_3$  composites

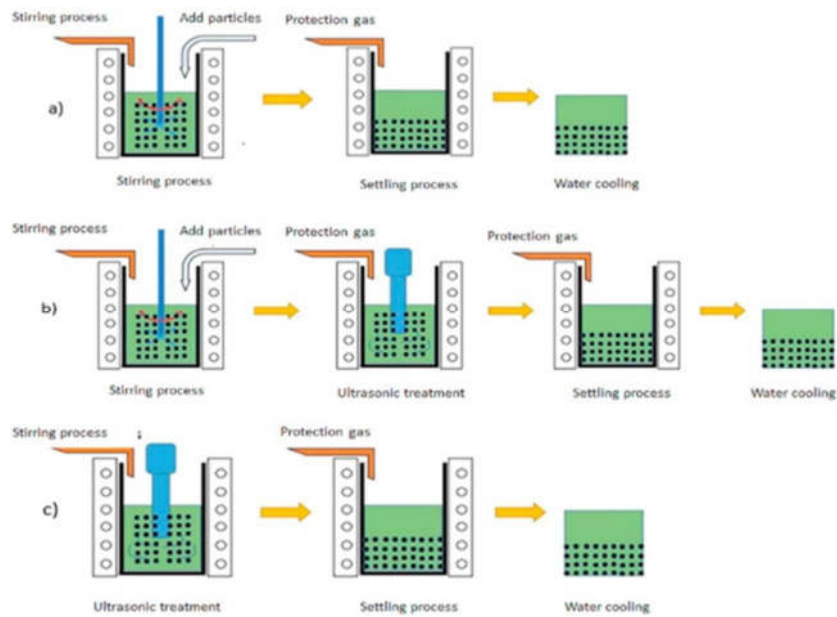


Fig. 6. Casting methods used by Chun-Lei Zhang et al.: a) semi solid method, b) ultrasonic method, c) liquid settling method [50]

Although a large number ceramic particles are available for reinforcement in AZ91 alloys, the selection of proper reinforcement and its interaction with matrix decide the performance of the composite. A good correlation between D.J. Lloyd [9] and published literature in Mg MMCs has been observed as most of the works are carried with SiC and Al<sub>2</sub>O<sub>3</sub> particles because of good compatibility and capable of producing broad range physical and mechanical properties with low cost of fabrication.

#### 4. PARTICLE BASED AZ91 HYBRID COMPOSITES BY STIR CASTING

Hybrid composites are the special purpose composites with more than one element as reinforcement. A few studies have also been carried out on AZ91 based hybrid composites to accommodate a large range of opportunities in aerospace and automotive sector. The advantage of hybrid metal matrix composites is combining various forms of reinforcement i.e. both particles and short fibres can also be employed. Qiang, Zhang [51] and E. Suneesh [52] stated the primary objectives in preparing the magnesium hybrid composites as (i) to optimize the performance of engineering materials (ii) to create a provision for mass production and (iii) to enhance the wettability. S. Ravi Kumar et al. [53] reviewed the feasibilities of AZ91 with SiC and Fly ash hybrid composites manufactured through STIR casting. E. Suneesh [52] et al. conducted a comprehensive review on Magnesium based hybrid composites in terms of processing methods, metallurgical behavior, and mechanical properties. Recent works carried by researchers in AZ91 based hybrid composites are listed in Table 5.

From the literature [54-61], the tensile strength, wear and creep resistance of the monolithic AZ91 alloys are observed to be significantly improved with adequate grain precision due to the addition of hybrid materials. It has also been evidenced that the ductile nature of brittle AZ91 alloys/composites is enhanced considerably. But the acceptance of these hybrid composites mainly relies on the careful handling of the reinforcement particles, strengthening mechanisms due to intermittent phases and interactions. Though the properties are encouraging, the research on magnesium based hybrid composites will become viable only with the development of economical processing methods.

#### 5. CONCLUSIONS AND FUTURE SCOPE

This paper reviewed the recent literature carried in the fabrication of AZ91 magnesium alloy based particulate composites through STIR casting process during the last ten years to the best our knowledge. Most of the works are identified with AZ91D and AZ91E as a matrix material to gain the advantage of good mechanical behavior with improved corrosion resistance. SiC, Al<sub>2</sub>O<sub>3</sub>, TiC, B<sub>4</sub>C are the most common reinforced ceramic particles introduced into AZ91 alloy among which SiC and Al<sub>2</sub>O<sub>3</sub> are the major choice by many researchers due to compatibility with AZ91. Size and weight fraction of the particles are also observed to be most significant parameters in achieving uniform distribution and grain refinement of Mg MMCs. The influence of these parameters on the physical, mechanical and tribological properties of the composites are presented and correlated with metallurgical investigations.



Tab. 5. Recent works on AZ91 based hybrid composites fabricated via stir casting

Author	Matrix	Reinforcements	Wt %.	Particle size	Findings	Ref.
Xia zhou et al.	AZ91	SiC	0.3	30 nm	Mechanical Behavior	[54]
		CNT	0.7	50 nm		
Mohammed Ali et al.	AZ91	SiC	1-3	--	Wear Behavior	[55]
		Al <sub>2</sub> O <sub>3</sub>	3-1	--		
B. M. Girish et al.	AZ91	SiC	1-3	37 – 50 μm	Wear Behavior	[56]
		Graphite	1-3	37 – 50 μm		
I. Aatthisugan et al.	AZ91D	Boron carbide (B <sub>4</sub> C)	0, 1.5	--	Mechanical and Wear Behavior	[57]
		Graphite	1.5 ,0	--		
N. Nafeed et al.	AZ91E	SiC	5	50 μm	Wear Behavior	[58]
		Graphite	10	50 μm		
Shruti et al.	AZ91	SiC	15 -25	30 μm	Mechanical and Wear Behavior	[59]
		Al <sub>2</sub> O <sub>3</sub>	5 -20	--		
Sadanand sarapure et al.	AZ91	SiC	0-3	27 μm	Mechanical Behavior	[60]
		Graphite	0-3	27 μm		
S. Jayabharathy et al.	AZ91	TiO <sub>2</sub>	1-2	--	Mechanical and Wear behavior	[61]

Though particle reinforced composites shown superior properties, the studies on chemical reactions and interfacial characteristics are reported only by few researchers. The interfacial studies to be much more analyzed to understand the nature of the composite. STIR casting technique is found to be the most common practice in manufacturing of Mg MMCs but the homogeneous distribution and maintain good interface strength is the major challenge. Some works are reported with process innovations such as semi solid STIR casting, ultrasonic vibration assisted STIR casting and liquid settling methods in the preparation of AZ91 composites. However, the application of these methods in commercial products has to be reported. The future directions of current investigation may include newer particle reinforcements, simulation studies for understanding matrix – particle interactions, wettability enhancement methods, development of energy efficient casting procedures...etc. to produce high quality particle reinforced AZ91 Mg MMCs for the sustainable green growth.

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## Nomenclature

### Symbols

$\alpha, \beta, \gamma$ of Mg	–	Different phases of Magnesium alloys
Subscript 'p'	–	Particle Reinforcement
T6	–	Heat Treatment Procedure

### Acronyms

Mg	–	Magnesium
Mg MMC	–	Magnesium Metal Matrix Composites
Al	–	Aluminum
Zn	–	Zinc
Mn	–	Manganese
Cu	–	Copper
Fe	–	Iron
Ni	–	Nickel
Si	–	Silicon
AZ	–	Magnesium – Aluminum – Zinc Alloys
AZ91	–	Mg 90 % , Al 9% , Zn 1% alloy
AZ91 A-E	–	AZ91 alloys
Mg <sub>17</sub> Al <sub>12</sub>	–	Intermetallic Compound of Mg-Al-Zn Alloy
UTS	–	Ultimate Tensile Strength
YTS	–	Yield Tensile Strength
UCS	–	Ultimate Compressive Strength
IRP	–	Interfacial Reaction Products
BN	–	Boron Nitride
AlN	–	Aluminum Nitride
SiC	–	Silicon Carbide

Al <sub>2</sub> O <sub>3</sub>	–	Alumina
Y <sub>2</sub> O <sub>3</sub>	–	Yttrium Oxide
TC4	–	A titanium alloy with Ti6Al4V combination
TiO <sub>2</sub>	–	Titanium Dioxide
TiC	–	Titanium Carbide
B <sub>4</sub> C	–	Boron Carbide
CNT	–	Carbon Nano Tubes
XRD	–	X- Ray Diffraction
SEM	–	Scanning Electron Microscope

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