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Recent studies on development in fabrication of Mg-metal matrix Hybrid composites - A research review

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***Abstract* :** The present paper review the current development of magnesium alloy, with more attention to improve the properties of AZ91 alloy for future applications. The drive force of utilizing magnesium alloys for automotive, aerospace and other industrial application due to its light weight. The microstructure, grain size, grain morphology and phase constituents were influence the properties of magnesium alloys. The modification of crystal structure through processing route, heat treatment, and alloying elements improves the mechanical, corrosion, biocompatible, and tribological properties of magnesium alloys. Apart the microstructural modification, addition of reinforcements, and coatings were also improves the properties of magnesium alloys. This article explore on the recent research on various reinforcements used to enhance the refinement of microstructure, improvement in hardness, tensile strength, ductility, wear and corrosion resistance of magnesium alloy in AZ91 E alloy.

Keywords: Mg-alloys, AZ91 alloy, Mechanical properties, Reinforcements.

I.INTRODUCTION :

The name magnesium has originated from the Greek word called Magnesia. It was first discovered in 1808 by Humphery Davy and later it named as magnesium (Mg) with HCP crystal structure. Which is a strong and silvery-white metal, when it exposed to air that gives a white brilliant light. The density of magnesium is 1.74 g/cm^3, is approximately 2/3 of aluminum, 1/4 of zinc, and 1/5 of steel [1-2]. Magnesium is considered to be an ideal material in the fields of aerospace, defense, aircraft and automotive sectors due to their lightweight, high specific strength, damping capacity, excellent castability and superior machinability [3].

II. An overview of Mg- alloys

The manufacturing of Mg-alloy was started in 1945 (María 2011), further continuously research has been carried out for the development of different graded Mg-alloys in cast and wrought form. The solubility of various elements in to the Magnesium [4] was explored in table 1.

Table 1. List of soluble, partially soluble and insoluble elements in Mg.

Soluble element	Partially soluble elements	Insoluble elements
Al, Cu, Li, Si, Ca, Sc, Mn, Co, Ni, Zn, Ga, Ge, As, Sr, Y, Zr, Pd, Ag, Cd, In, Sn, Sb, Ba, Au, Hg, Pb, Bi, Th, Pu	H, Be, Na, P, K, Ru, Te Cs	He, B,C, N,Ne, S, Ar, CR, Se, Kr, Rb, Nb, Mo, Rh, Hf, Ta, W, Po, Rn

The countable amount of additives added to the Mg-alloys improves the castability, strength, corrosion resistance, workability and weldability. As per the ASTM alphanumeric designation system Mg- alloys [1] are grouped by principal alloy composition was noted in table 2

Table 2. Designation of different graded Mg-alloys

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S NO	Designation	Principal alloy composition
1	M	Magnesium-manganese
2	K	Magnesium-Zirconium
3	AM	Magnesium-Aluminium-Manganese
4	AZ	Magnesium-Aluminium-Zinc-manganese
5	ZK	Magnesium-Zinc-Zirconium
6	EZ	Magnesium-rare earth metal-Zirconium
7	QE	Magnesium-silver-rare earth metal-Zirconium
8	WE	Magnesium-Yttrium rare earth metal-Zirconium
9	ZC	Magnesium-Zinc-Copper-Manganese
10	AS	Magnesium-Aluminium-Silicon-manganese
11	AJ	Magnesium-Aluminium-Strontium

II.I.I Processing Methods :

A wide variety of processing methods and technologies has been developed for Mg MMCs (Metal Matrix Composites), they divided into mainly three groups based on processing conditions [5-6] as (i) Solid State Processing, (ii) Vapor Processing and (iii) Liquid Processing were shown in Fig 1.

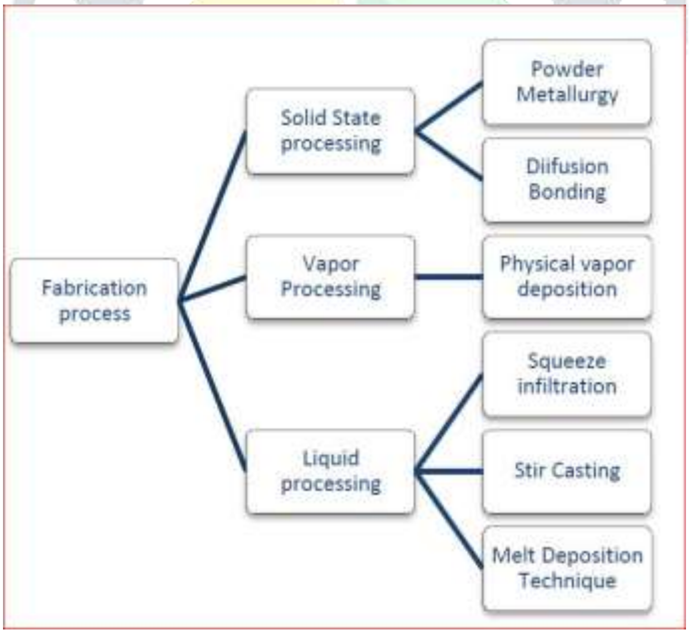

Fig. 1. Classification of Mg-MMC Manufacturing Process

Wide variety of Mg-composites were produced by using above listed techniques. The designation of different graded Mg-alloys [7] were tabulated in table 3.

Table 3. Classification of Mg- alloys

Cast Mg-alloys	Wrought Mg-alloys
ZK60, M1A, HK31, HM21, ZE41, ZC71, Electron 675, AZ31, AZ61, AZ80	AZ91, AM50, AM60, ZK51, ZK61, ZE41, ZC63, HK31, HZ32, QE22, QH21, WE43, AZ63, AZ81, Electron 21

The combination of alloy elements like Al-Zn, Al-Zn-Mn, Al-Cu, RE-Zr, Zr-Y, Zn-Zr- RE and many more were tried with magnesium (Tarek 2009 and Luo, Pekguleryuz 1994). Among them AZ series of alloys are the most commonly used, in which AZ 91 alloys are popular at room temperature with good strength and ductility. The temper designation [8] of the alloy was tabled in 4.

Table 4. Standard temper codes and process methodology for AZ91 alloy

S NO	Temper code	Methodology
1	T4	Solution treated to 686 K for 16-24 h
2	T5	Ageing at 335 K for 16 h
3	T6	T4 followed by quenching and subsequent ageing at 441K for 6 h

Most of the research that has been conducted till now useful in established the ability of different reinforcements and processing methods to modify the final characteristics of Mg-alloys.

II.I.II Characteristics of Reinforcements

Demanding on the material properties required the following points keep in to considerations in selection of reinforcements for suitable application. The properties required, matrix material and fabrication method are the key elements in selecting reinforcement materials [9].

a. Density
b. Bondability with the matrix
c. Coefficients of thermal expansion
d. Good wetting capability
e. Superior mechanical properties
f. Availability and ease of fabrication
g. Low corrosivity
h. Economical

Generally particulates, fibres, and whiskers are the most regular forms of reinforcements for MMCs. At end required properties from the resultant composite can be attained whenever the following conditions are satisfied [10-11].

a. Selection of reinforcement having adequate stiffness and strength
b. Compatibility of reinforcement with the matrix material
c. The ability of the processing method
d. Good matrix-reinforcement interface integrity
e. Minimal porosity

The ideal alloy for the automotive and biomedical applications among the various Mg- alloy system is magnesium alloy AZ91, due to its higher mechanical strength and corrosion resistance. The primary phase of the alloy is Mg (α phase) and the secondary phase of the alloy is $Mg17Al12$ (β phase) [12]. Figure 2 shows the typical microstructure of AZ91 alloy indicating the phase and β phase.

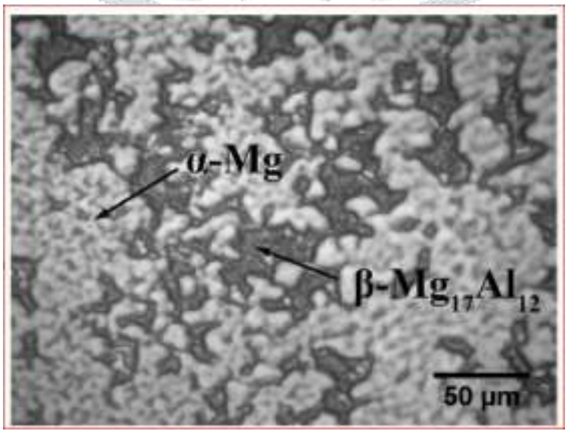

Fig 2. Microstructure of Mg-alloy with alpha and beta phases

II.I.III. Impact of different reinforcements on properties of AZ91 Mg-alloy

A lot of research studies were done on development of magnesium alloys for different industrial applications in past 2 decades. In fact pure magnesium is not recommended for all applications, it needs alloying or surface modifications for exhibit better properties than base metal. The main aim of this review is find the suitable reinforcements with optimum combinations for future and next generation applications.

II.II Grain Refinement

Some of the key alloying elements which refine the microstructure of AZ91 alloy are Ca, Ce, Y, Nd, and Sr. Study reported on the impact of Ce, Ca and Sr along grain boundaries on solidification causes the growth of α phase which refines the microstructure [13]. Further a reduction in grain size is observed and studied in AZ91 with addition of 0.8%Ce and 0.2% Ca or 0.2% Sr was reported [14]. The study reported that addition of Sr results in half the grain size of AZ91 alloy [15]. The other studies reported on deformation process of Mg- alloys through equal channel angular pressing [16–18], extrusion [19-20], accumulative back extrusion [21], hot rolling [22], high-pressure torsion [23], and high-ratio differential speed rolling [24] result in grain refinement. A refined microstructure with an average grain size of 0.5 μm is observed in the AZ91 alloy.

II.III Hardness

Hardness is a property of a material which measures the material's resistance against to plastic deformation. The study reported on the formation of fine grains and finely dispersed β phase (harder phase) in the matrix improves the hardness of the AZ91 alloy with addition of scandium [25]. The work reported that high hardness was found in highly strained regions, which undergone static and dynamic recovery which forms a new grains and dispersed β phase causes to hardness improvement [26]. Similarly study reported on effect of reinforcements like hard ceramic particles, ceramic whiskers, and fibers helps in improves the hardness of AZ91 alloy with a reinforce of SiCw [27]. Parallel study on reinforcement of Ce based metal in AZ91 alloy by roller melt spinning process refines the microstructure and improves the hardness to 206 HB [28]. The strength and hardness of Mg-alloys with different reinforcement [29] was shown in Fig 3.

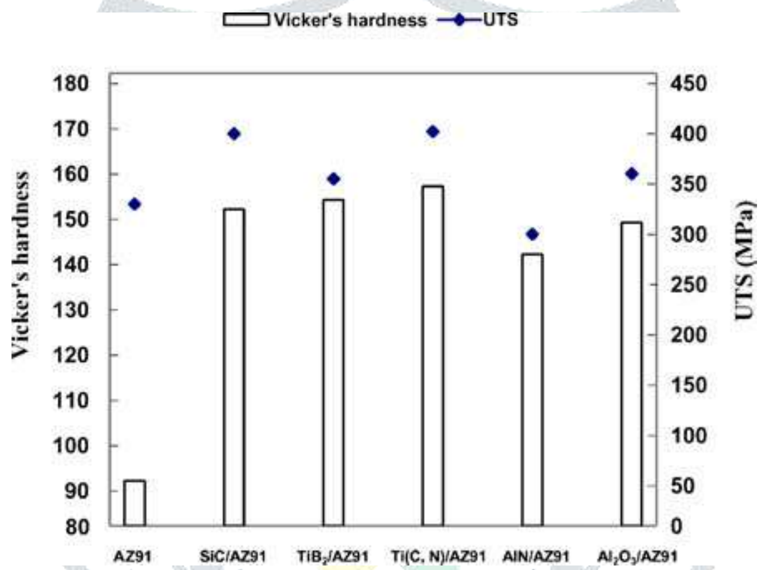

Fig. 3. Strength and hardness of AZ91 reinforced with different particles

II.IV Wear Resistance

The wear rate of AZ91 alloy is governed by the precipitates in the matrix. The wear is effected by factors like abrasion, oxidation, and bulk material transfer in the solution treated specimens. Basically a fine-grain structured alloy have more wear resistant than coarse grain structured alloy due to its higher hardness. The reported work concludes that remelting of AZ91 alloy using a continuous wave CO2 laser causes to refines its microstructure, which results in improves the hardness further it turns to get high wear resistance on the surface of the alloy [30]. The peak aged AZ91 alloy shows better wear resistance than a solution treated alloy where sliding velocity between 0.05 and 0.20 m/s against Al- alloy [31].

The reinforcement of rare earth (RE) elements in AZ91 alloy showed the improvement in wear resistance, perhaps addition of 3 %RE increases the wear resistance at testing temperature between 373 to 523 K was reported [32]. The similar studies reported on addition of ceramic particles like TiB2, TiC, SiC, WC, graphite and solid lubricant additives successfully improve the tribological characteristic of the AZ91 alloy. The observations of the study note that addition of above reinforcements with self-propagating high temperature synthesis was also improves the AZ91 alloy wear resistance [33-34].

II.V Ductility, Tensile Strength, Yield Strength

The strengthening mechanisms like grain refinement, partial dissolution, and disintegration of β phase in AZ91 alloy causes to improve the tensile properties. The study reported that SiC particles refines the microstructure and improves the tensile strength of the AZ91–SiC composite [35]. The work reported that Orowan strengthening mechanism and Hall–Petch effect on tensile and yield strength was studied [36]. The work reported on annealing of AZ91 alloy produces different β phases at specific temperatures, which influences its tensile properties. Heat treatment of AZ91 alloy at 423 K express the fine grains and dispersed β phase results exhibit high tensile strength [37]. The work study reported that reinforcements like Ca and RE would improves the tensile strength of AZ91 alloy, where 2%Ca induces the dissolution of β phase and formation of new Al2Ca phase, the fine grains and newly formed Al2Ca phase could improve the ductility and tensile strength by 20% [38]. Yield and elastic modulas of Mg-alloy with addition of SiC volume fraction [39] was shown in Fig 4.

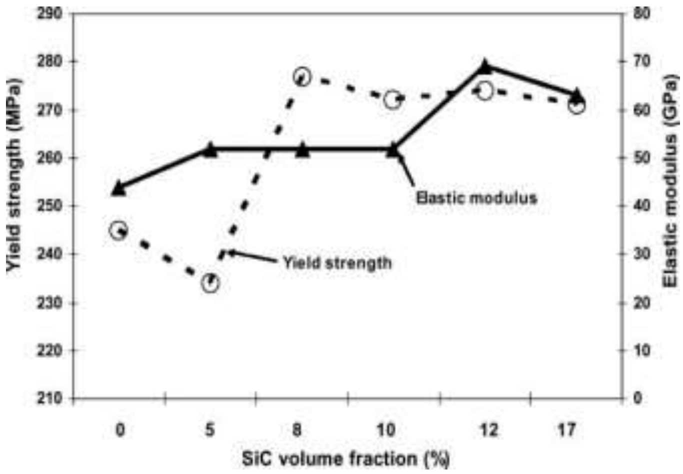

Fig. 4. Yield strength and elastic modulus of injected SiC/AZ91 composite

II.VI Corrosion Resistance

The common polarization method is known to be more effective in pitting corrosion, whereas other method like cathodic and anodic polarization method is found to be more effective in finding uniform and localized corrosion in AZ91 alloy [40]. The study reported that adding of new alloying elements improves the corrosion resistance of the AZ91 alloy. The formation of new intermetallic phase MgAl4Y in AZ91-0.3Y alloy reduces the continuity of β phase [41]. The study reported that surface activity of AZ91 alloy was reduced by applying the surface modification techniques which helps in improves the corrosion resistance. Some of the studies were addressed here, the work reported that Zr along with heat treatment process increases the corrosion resistance of AZ91 alloy treated in NaCl solution [42]. Another study says that reduction of galvanic contact between α phase and β phase increases the corrosion resistance of the alloy [43]. The addition of 1% Ca to AZ91 alloy increases the corrosion resistance of the alloy. The corrosion current AZ91 alloy containing Ca is lower than the as-cast AZ91 alloy. However, the tensile strength of AZ91–Ca decreases 15% with respect to the as-cast AZ91 alloy [44]. The surface modification can be done by microstructural and/or composition change. The surface composition change should provide good corrosion resistance and bio-compatibility [45]. The formation of TiO2 on the surface of AZ91–TiN coated samples and Al2O3 on the surface of AZ91–AlN increases the corrosion resistance in Hank's solution. The corrosion resistance of the coated AZ91 alloy is higher in Hank's solution than in 3.5% NaCl solution [46].

The challenging factors to the manufacturers [47] while utilizing the Mg-alloys was shown in fig 5.

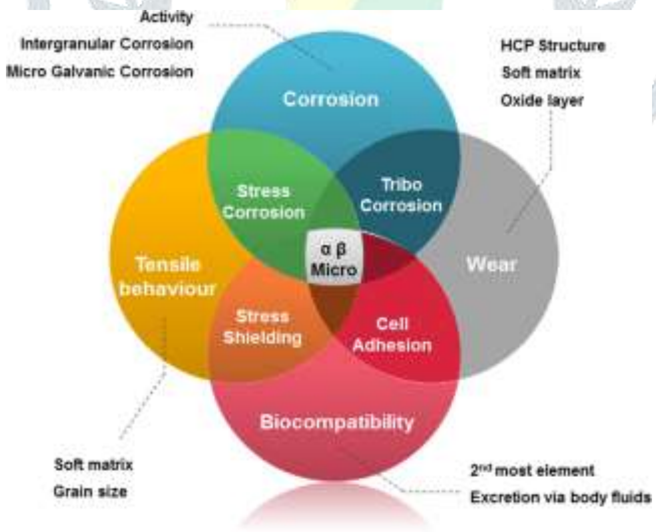

Fig. 5. Challenges of utilizing magnesium alloy for industrial and biomedical applications

The next generation Mg-alloys were developed from the basic Mg-alloys to meet industry requirements. The future directions of the Mg-alloys developed for various automotive applications required specific property was shown in Fig 6.

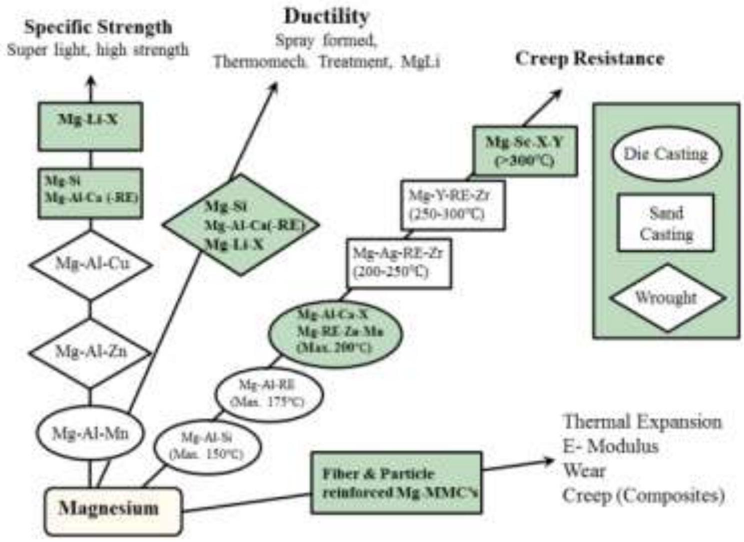

Fig. 6. Future directions of Magnesium alloy development for automotive applications

II.VII Fatigue Resistance

The study reported that, fracture mechanics effect on gravity and die cast composites made by AZ91 alloy, it seems that in gravity cast coarse grained structure intermetallic β phase will initiate the cracks. It also observe that in fine-grained die cast crack will initiate from the cast defects [48]. The another study says that Irrespective of the material fabrication route and type of loading, pores in the matrix act as nucleation sites for the cracks [49]. The parallel studies reported that the fatigue limit of gravity cast AZ91 alloy is lower in transverse load than axial load in high cycle fatigue analysis [50].

The study reported that in the rolled direction AZ91 alloy develops an anisotropic property which help in enhanced the fatigue resistance of an alloy and also peak stress and stress ratio has an effect on fatigue life of materials [51]. The study revealed that grain refinement can resist the crack initiation, which results on decreased slip distance in high pressure die cast of AZ91 alloys [52]. The study reported that, the fracture test results reveals that at T6 condition AZ91alloy exhibits improved fracture resistance [53].

II.VIII Creep Resistance

The improved creep properties were reported from the study, where AZ91 cast alloys were undergone solution heat treatment [54]. The β phase by virtue of its property which improves the creep resistance of AZ91 alloy, but β phase coarsens and softens at elevated temperatures, which in turn reduces the creep resistance of AZ91 alloy [55]. The work reported that, uniaxial tensile load was applied to study the creep characteristics of die-cast AZ91 alloy and AE44 alloy. The creep behavior of AZ91 is exhibits better results than that of AE44 at low loads [56]. The study reported on estimate the creep behavior of AZ91 alloy with the addition of Si and Sb by casting, the results reveals that IMC like Mg_2Si improves the creep life of AZ91 alloy, whereas the other compound Mg_3Sb_2 does not significantly improve the creep life [57]. Another study reported that, at high temperature dislocated grains were observed which causes to low stresses in AZ91 alloy. Addition of alloying elements such as Si, Sb, Sn, Ca, Bi, RE (except Ce) independently or in combination was improves the creep resistance of AZ91 alloy through the formation of new IMCs [58]. The published work revealed that influence of AZ91 alloy reinforced with 15%, 20% and 25% SiC by stir casting method has improves the creep behavior under various loading conditions [59]. The work reported that, addition of Ca and Sb facilitates the formation of new IMCs as Al_2Ca and Mg_3Sb_2, which in turn diminished the formation of β phase. This microstructural configuration improves the impression creep behavior of AZ91–Ca–Sb [60].

III. Conclusion:

From the result of various studies done on Mg-alloy are aimed to improve the material properties and similarly reduce the processing cost. A new approach was adopted to develop a hybrid composites under the class of discontinuously-reinforced Mg composites. Hybrid composites are compounds, consists of two or more kinds of reinforcements like metals and nonmetallic particulates added simultaneously to the base matrix. The hybrid composites have an ability to accommodate Mg-hybrid composites with optimized properties. It is essential for many applications in transport and automotive sectors. The extended series of AZ91 E derived from basic AZ91 alloy, which has many advantages than existing AZ91 Mg-alloy. The present review focus on development of new class of AZ91E with hybrid composites to explore better properties than present AZ91 alloy.

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