Critical assessment of strengthening mechanism of magnesium alloys: Review

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Abstract

Magnesium and its alloys have got great attention in recent times due to its potential to replace heaver alloys with equal strengths and lighter in weight, hence become potential materiel automobile, sports, aeronautical and biomaterials applications This study concentrates and summarizes the fundamental properties of magnesium and its alloys such as high strength, ductility non-corrosive behavior etc. Along with its developments in its physical metallurgy, forming process and strengthening mechanisms to enhance the mechanical strength followed by behavior of magnesium alloys under different working conditions and applications. A brief overview of the recent and systematic outline is reported for improvement of mechanical by strengthening mechanism along with its applications. This work would be very much helpful for the researchers to find the best strengthening method on looking on its various aspects of design, environment friendly behavior and optimum utilization of resources with saving the natural resources. Copyright © 2017 VBRI Press.

Keywords: Magnesium metallurgy, pyrotechnics, extraction process, strengthening mechanisms, mechanical properties.

Introduction

Sir Humphrey discovered and isolated magnesium in 1808, at that time magnesium was very less used as parent material for manufacturing of structure, however it was used as a major alloying element with aluminum. Then it was used in massive quantity at the time of world war first and world war second for aircraft and another defense equipment's **[1,2]**. The other uses of magnesium were such as pyrotechnics as deoxidation of steel and chemicals in the industries. Its demand increased due to its light weight and easy machining property, the density of magnesium is two third of aluminum density **[1,3]**. Magnesium has been classified as alkaline earth metal, it was known by the name of white stone and white earth in its old times. Magnesium is 9th most abundant material present in universe, 8th most abundant material in earth crust and 4th most common material in earth with iron oxygen and silicon. It occurs in combination of other materials in the form of ores and other compounds. Magnesium is obtained from sea water in form of chlorides and in earth crust as dolomites. It easily chemically reacts with water, nitrogen, carbon di-oxide and oxygen. Some undesirable properties of pure magnesium are poor wear resistance and poor corrosion resistance because of which it is not much used in pure form for different application. In place of it magnesium is alloyed with other elements such as aluminum, copper, rare earth metals, thorium, zirconium, lithium, manganese, silver, silicon, yttrium and zinc to increase its strength and to get desired mechanical properties. Magnesium is present in nature in ionic form. It lies in group 2, period 3 and block 5 with electron arrangement $1S^2$, $2S^2$, $2P^6$, $3S^2$ shown in **Fig. 1**. Only bivalent form of magnesium is found in nature. The reduction processes need to transfer 2 electrons to form stable magnesium shown in **Fig. 1. Table 1** and **Table 2** indicate the physical and atomic metallurgy of the pure magnesium **[4]**.

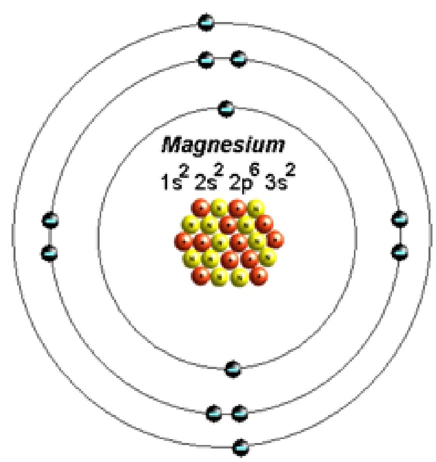

Fig. 1. Atomic structure of magnesium.

Magnesium is considered as the lightest material among other design materials. In weight it can be compared to plastics and in strength and toughness can be compared to a metal which is durable and have a long life.

Since these features of magnesium and its alloys are increasing its demand in manufacturing industry **[5]**.

Table 1. Physical metallurgy of Magnesium.

Atomic metallurgy of Magnesium	
Atomic radius	160 ppm
covalent radius	141 ppm
Electro negativity	1.76
Ionization potential	7.6462 ev
Atomic volume	13.97 cm3/mol
Thermal conductivity	1.56 W/cm-k
Oxidation state	1,2
Atomic Isotopes	78.99% - 24Mg 10.0% - 25Mg 11.01% - 26Mg

Magnesium and its alloys are considered as nonferrous material having low density, high ductility, moderate strength and good corrosion resistance. When magnesium is used as alloying element it improves characteristics such as strength, fabrication, mechanical etc. whereas it improves the weldability of aluminum **[6]**.

Table 2. Atomic metallurgy of Magnesium.

Physical metallurgy of magnesium	
Symbol	Mg
Atomic Number	12
Atomic Weight	24.305
Density	1.738 g/cm3
Melting point	923 k
Boiling point	1363 k
Heat of fusion	8.70 KJ/mol
Heat of vaporization	128 KJ/mol
Specific Heat Capacity	1.023J/g-k
Color	Silver
Radioactive	Non-Radioactive
Crystal Structure	Simple hexagonal

Magnesium came into use in automobile sector in 1920, its demand started increasing in sports car to give a competitive edge because of its light weight. After a decade the use of magnesium was done in commercial automotive firstly used by the German car manufacturer Volkswagen for the model Beetle in which 20 kg of magnesium was used. Its popularity is increasing day by day because of its environment friendly nature and other legislative influences; with some other factors such have fuel saving ability, which is the main concern of the world at presently. The use of magnesium in vehicles is lowering the overall weight of the part and improving the other working conditions. There have been large changes in automotive companies which have replaced mild steel and aluminum by magnesium for different components of the final product. Some of the leading companies which are replacing their components by magnesium are German motor works, Audi, DaimlerChrysler (Mercedes-Benz), Ford, Jaguar, Fiat and KIA Motors Corporation. It is also being currently used for gearboxes, steering columns, for air bag housings, steering wheels, seat frames and fuel tank covers. Some other benefits of magnesium include, it not only lowers the overall mass of the car, but also allows the shifting of the center of gravity of the car which is helpful in improving various handling and turning conditions. In addition, to its use, magnesium has led to the reduction frequency which in turn reduces the vibration and reduction in overall noise of the vehicle. Instead of assembly of steel parts single cast magnesium component have improved the strength of the material as the magnesium can be easily casted. The castability requires less tooling and gauges which automatically lowers manufacturing cost and reduces the losses **[7]**. This review work documents the data and developments which have been used in making magnesium alloys much more better for electronic, aerospace, sports, automotive and other useful applications. This review illustrates the importance and usefulness of these alloys which are been chosen, with the beneficial advantages followed with the weaknesses which are needed to be overcome to make the world better place to live with the help of these light magnesium alloys.

Extraction process of magnesium

Electrolysis

Magnesium is produced by electrolytic method. In this process mixing of seawater and lime is done in a settling tank. Magnesium hydroxide precipitates at the lower part of the tank, and is then filtered, after that it is mixed with hydrochloric acid, and then this solution is exposed to the method of electrolysis which in result produces magnesium metal **[8]**. The other name for electrolysis process is Dow process. Sea water and precipitated dolomite are treated with HCL to form $MgCl_2$ and then kept in electrolytic cell to produce Mg metal at cathode and Cl_2 at anode **[8]**.

Calcinations

In this process $MgCO_3$ is heated to produce MgO and then it is mixed with petroleum coke and pressed in briquette which is a solid block. These briquettes are heated to nearly about 2500 °C to form Mg in gaseous form, this gaseous Mg is cooled at 120 °C to get solid phase of magnesium while during heating the oxygen is separated from MgO **[8]**.

Pidegon process

It is also known by the name thermal reduction process. Thermal reduction process in which magnesium oxide and ferrosilicon are forced in air tight steel retort and then heated in vacuum giving vapors of magnesium which are then condensed to form magnesium crystals **[8]**.

Pure magnesium

The pure magnesium is rarely used because of its volatility seen at increased temperatures and is found corrosive in moist environment. Components designed for critical automobile and aerospace applications needs coating to provide long life and keep it working for long time **[9]**. Magnesium being an excellent material is readily being used commercially and is the lightest material with density of 1.7 g/cm^3, with this magnesium has an excellent property of dissipating heat, good electromagnetic shielding and high damping property. It is commonly found in the oceans of earth. Magnesium having low moderate temperature makes it melt easily for casting. It has also been observed in the study that it is chemically reactive and susceptible to corrosion generally in marine environment. Corrosion takes place mainly due to the impurities in the parent pure magnesium. Magnesium powder ignites easily when it is heated in air therefore it should be handled with extra care in its powdered form.

Nomenclature of magnesium alloys

According to American society of testing materials (ASTM) the magnesium alloys are classified and designated by two capital alphabets followed by the number. The alphabets define the major alloying element, the first letter is used for the element which has highest concentration and second letter defines the second highest concentration percentage. The numbers define the amount of major alloying elements; first number stands for weight percentage of first element followed by the second number defining the weight of second element percentage [**10**].

Table 3. ASTM codes for magnesium alloying elements.

ASTM Codes	Alloying Element
A	Aluminum
B	Bismuth
C	Calcium
D	Cadmium
E	Rare Earth
F	Iron
G	Magnesium
H	Thorium
K	Zirconium
L	Lithium
M	Manganese
N	Nickel
P	Lead
Q	Silver
R	Chromium
S	Silicon
T	Tin
W	Yttrium
Y	Antimony
Z	Zinc

The alphabet codes used for designation are shown in **Table 3.** For example: AZ91D here the magnesium alloy contains 9 % aluminum and 1 % zinc by weight. Some of the commercial magnesium alloys are Mg-Al, Mg-Al-Zn, Mg-Zn, Mg- Cu, Mg-Zn-Zr, and Mg-RE-Zn-Zr casting alloys and wrought magnesium alloys.

Table 4. Categorization of magnesium alloy series.

Alloy Series	Alloying Elements
AZ alloys	Mg-Al-Zn
AM alloys	Mg-Al-Mn
AE alloys	Mg-Al-RE
EZ alloys	Mg-RE-Zn
ZK alloys	Mg-Zn-Zr
WE alloys	Mg-RE-Zn

Different types of casting

Magnesium alloys are produced by different processes. Casting is one of the methods of producing**. Table 4** shows different series of magnesium alloys produced by inhibiting different alloying elements. Some of the major casting processes are being discussed in below study material.

Sand casting

Sand casting has been used as the oldest fabrication technique for metallic components. This process is highly in demand because of its high-volume process for commercial elements like cast iron, alloys and different components of magnesium. The casting process of magnesium is same as the other processes where the melt is poured in a mould which is disposable and made by compacting of sand. This solidified metal is removed from the mold as it is cooled. While performing the task some precautions are needed to be kept in mind while processing such as the molten magnesium reacts with moulding materials such as silica sand and moisture. The molten magnesium oxidizes to form voluminous oxides therefore the moulds must be designed for smooth flowing of fluid without any turbulence. With it the focus should be kept on minimizing the moisture content in the sand and making use of inhibitors within the sand mixture to form the mold and cores. Some of the other properties to be kept in mind while casting is melting point, boiling point, density, thermal conductivity specific heat, latent heat of fusion, coefficient this can be controlled by of linear expansion and volume heat capacity. Some of the magnesium alloys formed by sand casting process are reported in **Table 5**. It was found in the study that with the benefits of sand castings some defects are observed during the casting process such as oxide skin, shrinkage, microporosity, gravity segration, reacted sand inclusion and hot tearing. Some other types of the casting techniques are conventional gravity casting and counter gravity casting.

Table 5. Magnesium alloys formed by sand casting process.

Magnesium alloy	Alloy composition
AZ91	Mg-9% Al-1% Zn-Mn 1.0 60 150
EZ33 (ZRE1)	Mg-3% RE-2.6% Zn-Zr NA 150 200
ZE41 (RZ5)	Mg-4.2% Zn-1.3% RE-Zr 0.8 100 150
QE22 (MSR)	Mg-2.5% Ag-2.0% RE-Zr 0.7 75 125
WE43	Mg-4% Y-3% RE- Zr

High pressure die casting

Die casting is most economic process for the fabrication of magnesium and its alloys. In this process the molten melt is forced through a narrow opening which fills the mold at quick rate of nearly 20 m/s. after that an intensification pressure of about 40-1000 MP is applied at the time of solidification. This high pressure enables the areas to fill with metal ultimately decreasing the level of porosity and leads in improving internal integrity **[11]**. Die casting is most widely used for producing thin-walled parts with intricate shapes because of the high fluidity of liquid magnesium. In addition, the product formed by di casting has good part strength, and provides excellent surface finish with high dimensional precision **[12]**. As the thickness of part is increased, strength and ductility are inversely affected.

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Squeeze casting

Squeeze casting is termed as a combination of forging and casting process. It is done in two ways direct squeeze casting and in direct squeeze casting, in this process molten metal is poured slowly with a minimal amount of turbulence into the lower half of a die and an upper punch is pressed down on the metal once the die cavity is filled. The metal solidifies under this high, unidirectional pressure which in turn reduces any internal defects during solidification. Direct squeeze casting however, allows for the trapping of impurities within the metal as it does not have a runner system. Incidentally, this also results in high internal integrity material. Indirect squeeze casting involves molten metal being poured into an encasement. A plunger is then used to control the speed at which the metal flows into the mold which eliminates the gas bubbles within the casting. There is a lower material yield with indirect squeeze casting due to the greater material loss.

Direct squeeze casting

In this process has simple mould arrangement having upper part as punch through which pressure is applied and the lower part through which the cast part is thrown out. This process is economic as no extra parts are needed for clamping neither clamping force is needed and the whole material is used for casting, no extra material is removed as by product.

Indirect squeeze casting

In this process molten magnesium is injected inside the mould through injection canal. Some of the advantages of squeeze castings are less chances of porosity, high strength and increased ductility because of faultless structure and fine-grained structure, alloys which are difficult to cast can be casted easily by this process, its demand has increased of the production of magnesium composites.

DC casting (direct chill casting)

In nineteen thirties this process was used for production of aluminum billets, and recently it is used for producing magnesium billets. In this process the molten material is filled in dummy which is kept inside a water cooled mold jacket. When the molten material reaches the predefined point inside the mould the dummy is lowered down, and water is sprayed on the freshly made billet **[16]**. It is seen that DC casting is very much popular in light weight metal industry especially for aluminum, this process is economically beneficial and reliable with simple operating features keeping the investment low and this process provides flexibility. Magnesium components made by this process are also used as hand tools due to its high mechanical properties, low weight and high strength.

Thixo-casting

The term thixo was coined by peterfi in the year 1927. It was made by the combination of two words Greek words “thixis” which means stirring /shaking and the other word trepo which means turning/changing. The term thixoforming is generally used for describing the near net shape forming process from a partially molten alloy slug in a metal die. This process can be achieved by two ways thixo casting in which the shaping of the component is performed in closed die and thixoforging here the shaping of the part is done in open die **[17]**. In this process before casting solid billets are made from slurry these billets formed are reheated at the desired temperature of semi solid state this process is widely used for mass production **[18]**. This method is based on thyrotrophic properties of semi–liquid alloys. Some advantages of thixo casting are the process can be fully automated, it has high productivity, because of low consumption of energy it saves the cost, there is no problem of blow holes due to low shrinkage cooling, thin walled cast parts can be made easily by this process and have near net shape quality **[19]**.

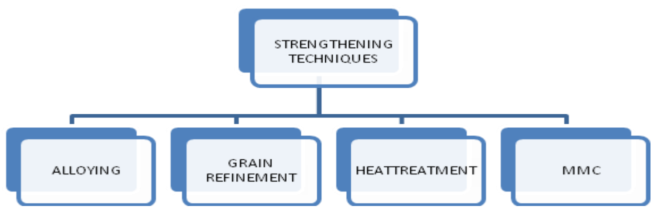

Fig. 3. Various strengthening mechanisms used for increasing the strength of the magnesium alloys.

Strengthening mechanism of magnesium

Some important strengthening mechanisms used for increasing the strength of the magnesium alloys are shown in the **Fig. 3.**

Alloying

Pure magnesium shows variety of good mechanical properties but with this have some weaknesses so to overcome the weaknesses of pure magnesium it is alloyed by mixing different elements to have the desired mechanical properties**.** Different element is added to magnesium to get desired mechanical properties, this process of mixing of element to parent material is known as alloying. Magnesium alloys shows an excellent specific strength and stiffness with dimensional stability due to its hexagonal crystal structure. Different elements are used for alloying magnesium to obtain different properties which are summarized in **Table. 5** with the effect of the alloying element on the alloy **[20-24]**. Different rare earth elements are used to improve the mechanical properties of magnesium. Magnesium alloys are generally classified into two types on the basis of their processing i.e. cast, magnesium alloys, ZK60, M1A, HK31, HM21, ZE41, ZC7, Elektron 675, AZ31, AZ61, AZ80, and wrought magnesium alloys, AZ91, AM50, AM60, ZK51, ZK61, ZE41, ZC63, HK31, HZ32, QE22, QH21, WE54, WE43, Elektron 21, AZ63, AZ81 **[25,26]**.

Aluminum

Magnesium aluminum shows reasonable mechanical properties, Al can be added up to 12.7 wt % at around 437^{o}C, it provides solid solution strengthening and if aluminum is added greater than 2 wt% it helps in formation of B phase and enhances the hardening of the alloy. Aluminum also helps in improving the castability and fluidity of the alloy with the increase in the tendency of shrinkage micro porosity and enhances the corrosion behavior of magnesium aluminum alloy **[26]**.

Zinc

Zinc is added to magnesium alloys to provide solid solution strengthening followed by improving fluidity. If zinc is added in higher amount it leads to the problem of hot cracking and also shows reduction in ductility **[27]**. If the concentration of zinc is more than 2 wt. % it could lead to micro porosity of sand casted magnesium alloys having aluminum 2 wt. %, 4 wt %, 8 wt %, 10 wt %. Zinc also plays an important role in accelerating the rate of precipitation during age hardening. Example AZ91D, AZ81.

Table 6. Characteristics of alloying elements and their effect on magnesium.

Element for alloying	Characteristics	Effects
Aluminum	Hardness	Increased
	Strength	Increased
	Ductility	Decreased
Beryllium	Oxidation	Decreased
Calcium	Oxidation	Decreased
Cerium	Corrosion resistance	Increased
	Yield strength	Decreased
Copper	Strength	Increased
	ductility	Decrease
Manganese	Corrosion resistance	Increased
Nickel	Yield and Ultimate Strength	Increased
	Ductility and Corrosion resistance	Decreased
Rare Earth Metals	High temperature creep	Increased
	Corrosion resistance	Increased
	Strength	Increased
Silicon	Corrosion resistance	Increased
Silver	Tensile strength at elevated temperature	Increased
Zinc	Corrosion resistance	Increased

Manganese

It is added to magnesium alloys to improve the corrosion resistance properties by extracting cathodic impurities like Fe by the formation of intermetallic compound. Some examples of manganese die casting alloys are shown in **Table 7**.

Table 7. Commercial name with composition of magnesium alloys.

Commercial Name	Composition
AZ 81	Al 8.0, Zn 0.7, Mn 0.22,
AZ 91D	Al 9.0, Zn 0.7, Mn 0.22
AE42	Al 4.0,RE 2.4,Mn 0.3
AM 20	Al 2.0, Mn 0.55
AM 50 A	Al 5.0,Mn 0.35
AM 60 B	Al 6.0, Mn 0.3
AS 41 B	Al 4.0,Si 1.0,Mn 0.37

Grain refinement

Grain refinement is a well-known technique of improving the properties of magnesium alloys. Two metallurgical phenomenons's which exploit the magnesium alloys are grain refinement and age hardening which helps in obtaining the desired improved microstructure and enhanced properties. The as-cast generally improves mechanical properties with structural uniformity of the microstructure. The rate of solidification is not rapid like sand casting, permanent mould casting, and direct chill casting **[27-29]**. Grain refinement is done to reduce the chances of defects like hot tears and porosity and provides nucleation sites during the thermo mechanical processing. Different grain refining techniques are being used for different magnesium alloys **[30]**. Fine refined grain microstructure helps uniform deformation with important in isotropic mechanical properties of HCP (Hexagonal closed pack structure) **[31]**.

Method of superheating

In this technique the melt is heated to elevated temperature (150˚C-260˚C) simultaneously followed by cooling to pouring temperature and staying for a short time before casting **[32]**. Grain refinement of magnesium-aluminum alloys is only possible if Al is present in more than 1 % wt. magnesium alloys containing Fe and Mn helps in promoting high grain refinement during super heating technique these should be added less than 1 % wt. Other elements such as Zr, Ti, be suppress the superheating technique during grain refinement **[33-35]**.

Carbon inoculation

It is another major grain refining technique for Mg-Al based alloys. It works on low operating temperatures, low processing time, crucible wear and less fading **[32]**. Carbon inoculation is possible if Al is added more than 2%wt. carbon can be added in different forms such as granular graphite, calcium carbide influx, organic compounds such as hexachlorbenzene, lamp black and lumps of magnetite can be used. Aluminum and carbon both are required to refine successfully the grain structure in the carbon inculcation technique **[36,37]**.

The elfinal process

This process was developed during the world war second in Germany, in this technique anhydrous $Fecl_3$ is plunged into the melts at temperature between 740ºC-780ºC **[68]**. This technique is suitable for both magnesium alloys containing aluminum and without aluminum. Zirconium is one of the best grain refiners for magnesium alloys, it is used to reduce the grain size of as-cast nearly magnitude of two orders and producing equiaxed and uniform microstructure **[39, 40]**. Peritectic mechanism is accepted of introducing Zr for grain refinement, Zr helps in promoting the nucleation of basic magnesium grains by peritectic reaction **[40]**. In the study it has also been observed that Zr dissolved at the time of pouring can do grain refinement of different magnesium alloys. Zirconium cannot be added to magnesium–aluminum alloy as it poisons the alloy and leads to formation of a new stable compound of zirconium and aluminum **[39]**.

Therefore, in replacement of zirconium zinc is added to the magnesium-aluminum alloys for grain refining. If zinc is added in large quantities, it can produce the effect of age hardening on suitable heat treatment **[41]**.

Metal matrix composite

Metal matrix composites are 1in demand because of their wide applications in different walks of life mainly in aerospace and automobile. It is gaining attention of the researchers due to its light weight, low density and high specific strength. These properties play a vital role in the fields of aerospace and automobile for reducing the consumption of fuel and bringing decrease in the exhaust gases emission, helping to bring the greenhouse gases level down **[42-44]**.

Metal matrix composites consist of class of materials having at least constituent materials out of the one is metal and other can be metal, nonmetal, fiber. Composite materials are flexible in selection hence the properties of the MMC can be tailored easily. The main drawback of MMCs is its high cost of processing and high cost of the reinforcement to be used. Magnesium metal matrix composites have many advantages over other magnesium alloys like having superior creep resistance at elevated temperatures, high strength, and high elastic modulus and with this comes decrease in ductility **[45,46]**. The required mechanical properties can be obtained by judicious selection of the size and type of reinforcement.

The element chosen for reinforcement should not be reactive and can withstand the elevated temperatures. The various enforcement added to the magnesium metal matrix composites are SiC (silicon carbide), Al_2O_3 (Aluminum oxide), TiC (Titanium carbide), B_4C (Boron Carbide). In **Table 8 [47, 48]** different reinforcement materials are shown with their effect on the mechanical properties of the magnesium metal matrix composite**.**

Table 8. Enhanced effect of reinforcement in the matrix.

Reinforcement	**Enhanced properties**	**References**
SiC	Good wear resistance in low load conditions	**[49]**
	High tensile strength Good hardness Good creep behavior	
Al_2O_3	High corrosion resistant Increase in sliding wear resistance High tensile strength	**[50]**
TiC	Increased ductility High elastic modulus Good damping capacity Good compressive strength Good hardness	**[51-53]**
B_4C	Wear resistance Increased wettability	**[54]**

Processing methods of MMC's

Magnesium metal matrix can be produced by different methods, the main challenge in processing of composites is of homogeneous distribution of the material to achieve defect free microstructure of the composite. Some of them are shown in the **Fig. 3**.

Heat treatment process

Heat treatment is one of the conventional methods of improving the strength of the metal, in this process the metal is heated to get change in its microstructure and improve the properties. The type of heat treatment depends on the composition of the alloy as cast or wrought. Solution heat treatment leads to increase in strength followed by maximum toughness and shock resistance, whereas precipitation heat treatment enhances the maximum hardness and high yield strength but with decrease in toughness.

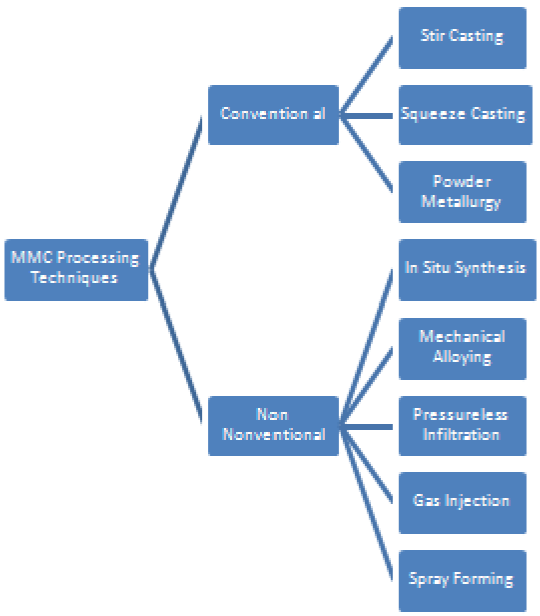

Fig. 3. Techniques for development of MMC's **[55, 56]**.

The heat treatment process is generally same as applied for aluminum and its alloys for fabrication. The temperature range is nearly same as used for aluminum processing. Heat treatment processes leads to improvement of mechanical properties of the magnesium casting alloys. These casting alloys are classified into six groups depending on its commercial importance and compositions. Magnesium–aluminum-manganese, magnesium-zinc-zirconium, magnesium-aluminum-zinc, magnesium-rare earth materials-zinc-zirconium, magnesium-rare earth- silver-zirconium. thorium, magnesium- thorium-zirconium-zinc. In wrought alloys the mechanical properties are developed through strain hardening, further the wrought alloys are strengthened by different heat treatment processes **[57]**. Wrought alloys are grouped into four classes, magnesium-aluminum-zinc, and magnesium-thorium-zirconium, magnesium-thorium–manganese, magnesium zinc-zirconium. Several heat treatment processes used for enhancing the mechanical properties of annealing. Wrought alloys of magnesium can be annealed strain hardened or tempered at temperature around 290- 450°C depending on composition of alloys and time duration in this procedure. The product is annealed at maximum temperature as most forming process of magnesium requires elevated temperature. The annealed wrought material is not so much in use **[58]**.

Stress relieving of wrought alloys

Stress relieving procedure is used too knockout the residual stresses induced in wrought magnesium material with the help of cold and hot working, straightening, welding, shaping and forming. It is observed that when extrusions are welded in form of hard rolled sheets, the longer time and lower stress reliving temperature are used to minimize the distortion. Precession while casting to close dimensional limits are necessary to avoid wrap age and distortion and preventing stress corrosion cracking this can be only achieved by making the cast components force from the residual stress. Magnesium casting generally does not contain high residual stress as the low modulus of elasticity of magnesium alloys which shows low production of elastic strain. residual stress is generated due to contraction of mold restrain while solidification due to known uniform cooling and quenching this effect can also be seen due to uneven machining operation and requires intermediate stress reliving before final machining.

Solution treating and aging

At the time of solution treatment magnesium aluminum zinc alloy components are loaded in furnace approximately at 260 °C followed by raising the solution treating temperature very slowly to remove fusion of eutectic compound and formability of voids. Time required for bringing the load from 260 °C to solution treating temperature depends on the size load composition weight and thickness of the part. After solution treatment, magnesium alloys are given an aging treatment to enhance hardness with yield strength. The aging treatments are used to relieve stresses and stabilize the alloys in order to prevent dimensional changes in future, mainly during or after machining. Yield strength and hardness are improved by this treatment at the expense of a slight amount of ductility. The corrosion resistance is also improved, making it closer to the 'as cast' alloy. Precipitation heat treatment temperatures are considerably lower than solution heat treatment temperatures.

Benefits of magnesium

Magnesium alloys have high productivity rate; they show high creep resistance up to 120 ºC with high damping capacity because of the ability to absorb energy elasticity followed by Magnesium alloys show good thermal conductivity because of rapid heat removal. And provides good machineability, good weldability and are readily available **[59]**. With these advantages magnesium and its alloys have some loop holes, when the magnesium alloys come in contact with electrolyte or dissimilar metals they build the tendency of galvanic corrosion. They are very difficult to be worked by cold working, have low elastic modulus, limited cold working, toughness, high degree of shrinkage on solidification and at last the most important factor they have high cost.

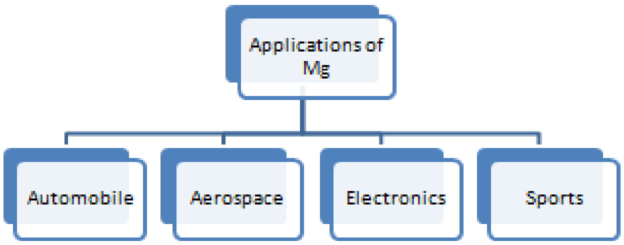

Fig. 4. Application of magnesium alloys.

Applications of magnesium

Magnesium and its alloys are favorably used in aerospace and automobile industries because of their good structural properties having good combination of elastic modulus of nearly 45 GPa and low density nearly two–third of aluminum and with good tensile strength of 160-365 MPa. Magnesium alloys shows maximum weight to strength ratio (density-tensile strength ratio) as compared to other structural materials **[60]**. It provides an excellent property of damping vibration and heat dissipation property which is an important factor for different automobile and aerospace industries as vibration is a kind of loss and affects the efficiency of the vehicle.

Automobile sector

With the increase in luxury and comfort in the automobile it has also increased the overall weight of the vehicle. The challenge in today's world it to reduce the weight of the vehicle by providing the best comfort and luxury to the customers. Magnesium is being looked as a rising star in the field of automobile because of its best quality being light, it is being used in different components of the vehicle to replace the other heavier metals which lead to the reduction in over-all weight of the component and vehicle **[61].** Magnesium and its alloys provide excellent mechanical properties, with better castability and low-cost fabrication, even complex structural design parts can be produced by casting due to its high fluidity **[62]**. It has been observed that magnesium thin sheets can show the same strength as compared to thick steel sheets, however are not at presently in much use because of its high cost **[59, 63]**. It is seen that magnesium can be a futuristic material which will be very helpful in increasing the mileage, low consumption of fuel, better designs and the most important factor of taking care of environment by reduction in emission of less carbon content in the atmosphere followed by the decrease in greenhouse gases due to low weight of the vehicle **[64]**. German car manufacturer Volkswagen has been using magnesium in their cars from a long back time around 1970^{s,} after that it is highly being used by other countries such as U.S.A, China, Japan, Korea and other developed countries followed by the other developing countries **[65-67]**. Use of magnesium for different automobile components is shown in **Fig. 5**. Some of the major alloys being used in automobile sectors are shown in **Table 9** and the figure shows the different components, these materials show high ductility followed by good impact resistance and better wears resistance. The major problem which is being seen in automobile sector is fractures during the impact loading conditions or during shock, but the alloys have shown excellent results in improving these properties which increases the life of the vehicle. Different components of magnesium are being used in automobile industry such as steering wheel cases, air bag plates, electronic control parts casing, transmission cases, and engine head casing. In present time magnesium alloys are been tested and are working in power transmission system as power trains and axels, these parts are showing better result than previously used materials and many other parts are being looked over to reduce the weight with efficient increase in overall efficiency of the vehicle.

Table 9. Use of magnesium alloys for different components in automobile sector.

Mg Alloys	Components	Reference
AM 50 AM60B AZ91 AZ91D	Steering wheel armatures Seat frames Drive brackets, clutch housing, mirror brackets, head lamp retainers, valve and cam covers, oil filter adapter housing, power window regulator housing	[**37,38,39**]
AS41B	Automatic transmission clutch piston and stator	

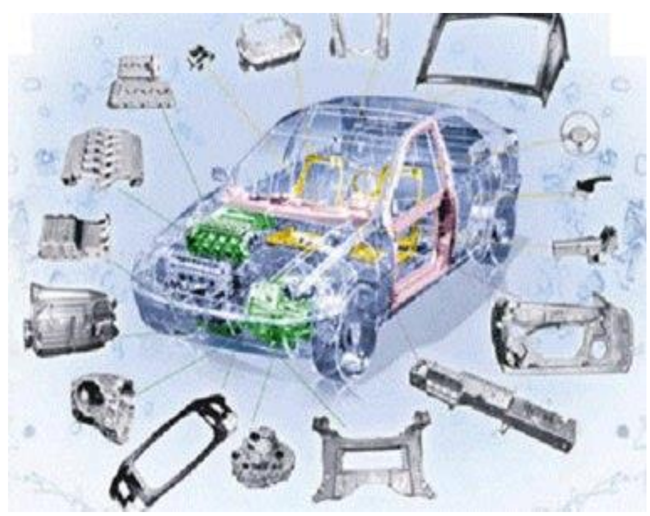

Fig. 5. Various magnesium alloy automobile components**.**

With this magnesium and its alloys provide flexibility to the design of the assembly as these different parts can be welded easily by simple welding technique and low cost.

As magnesium shows good damping behavior and easy weldability the parts which were earlier joined by nuts and bolts are simply attached by welding and reduce the chances of failure due to vibrations. But the problem in welding is the gas used for welding magnesium and its alloys is harmful to the atmosphere and increases the greenhouse effect. Efforts are being done and substitutes being tried to replace the shielding gas used for welding of magnesium alloys. This could be a good research area and would help in reducing the weight by the less use of joining materials such as nut bolts rivets etc. And would be helpful in saving the environment and the money. Magnesium use for front side of the vehicle not only reduces the weight of the body but helps in shifting the center of gravity of the vehicle to the rear side, which in result improves the handling and stability of the vehicle and increases the flexibility.

Aerospace sector

Aerospace industry has been using metals for different military and civil structural works from long back time. Earlier alloys of aluminum, laminates of glare, fiber reinforced composites. This material has been replaced by magnesium which is light material and proves itself as an excellent aerospace material which provides reduction in consumption of fuel, reduction in cost and increased efficiency. Magnesium have been used by one of the aircraft manufacturing company Boeing in 737,747,757,767 planes with this magnesium use has also been done in engines of aircraft and transmission casing and housings of the helicopters. A lot of work is being done on improving the properties of magnesium and its alloys for higher temperature applications and lot of work can be done in future recent study shoes the application of magnesium and its alloys is increasing in missile system and aircrafts, where weight plays a significant role in design to get the desired results.

Reduction in weight leads to less storage and less consumption of fuel and is helpful for sending aircraft outside the atmosphere and to set the satellite in its orbit. The demand of magnesium is increasing in the field missile system and in presently being used in intercontinental ballistic missile and the other missile such as Titan, Agena and Atlas. Some of the magnesium alloys used in aerospace industry is shown in the table with the passing years. With all these good factors there is a loop hole of magnesium as it is flammable in its pure form and powdered form, but lot of work is being done to improve this property. Some other properties which are being worked are increase in strength at elevated temperatures, fatigue resistance, corrosion resistance and erosion of the material. Use of magnesium for aerospace applications such as aircraft engine housing shown in **Fig. 5.**

Fig. 5. Aircraft engine housing made of magnesium.

Fig. 6. Application of magnesium for electronic equipment.

Electronic application of magnesium and its alloys

In today's world the demand of compact devices is increasing day by day which can be carried easily and is easy to use with minor completion magnesium is playing an important role in replacing the heavy metals in the field of electronics which is bring change in the conventional designs to compact and complex devices and providing flexibility to the product. Reduction in weight of electronic applications has reduced the cost of the part with good metallic surface finish and durable life span. It is observed that magnesium has the capability of releasing heat easily and keep the system working without malfunctioning at high temperatures which is an important feature as compared to plastics which used to melt at high temperatures or created problems at elevated temperatures. Magnesium has special characteristics of shielding electromagnetic radio frequency infiltration so because of which it becomes good electronic equipment. Magnesium component can easily be replacing plastic as Mg can easily be recycled by simple process with low cost and the material can be reused for different uses which would save the resources. Many different complex shapes can be obtained from Mg as it can be casted easily with very good surface finish. Some of the items used for as electronic equipment's are mobile casing, laptop top casing and cover, digital camera casings **(**as shown in **Fig. 6)**.

Recycling of magnesium

In today's world the optimum use of resources is the main concern of the world as the demand of the products are increasing and the resources are available in limited quantity, so recycling and reuse of resources becomes an important measure to fulfills the current need of the people **[68]**. There are various methods of recycling of magnesium such as process scrap during fabrication and ELV scrap. Harbin university of science and technology of china have found that the solid state recycling of magnesium and its alloy chips is best as compared to melting as lots of energy in melting and then again casting and to perform the melting operation special protection measures are need to reduce the effect of oxidation and melting could also lead to oxidation of Mg **[69]** MC-HPDC (melt conditioned high pressure die casting) was developed by Brunel Centre for Advance Solidification Technologies for recycling cast components of magnesium of high quality recycled produced magnesium was found with nearly same tensile strength and similar elongation as compared to the parent material. Despite of present methods being used there is lots of scope for development of new methods of recycling and the process presently being used needs lots of hard work and improvement for better utilization of resources without harming the environment **[70]**.

Conclusions and future scope

This article overviews the different atomic and physical properties, various methods of Processing, applications in different walks of life followed by good factors and limitations of magnesium alloys along with various applications automotive, aerospace, electronics and others. It has been revealed by many researchers that the adaption of Mg and its alloys as substitution to iron, silicon, zinc and aluminum alloys has more advantages. Cast magnesium alloys have a good usage enough to show excellent mechanical properties while the research work on usage of wrought magnesium is continued and is in progress. Mg-Al-Zn alloys offers strength and ductility at room temperature with excellent flexibility in various applications. Magnesium and its alloys provide an opportunity to the researchers to work in a broad area and a lot of scope is being watched for further research. Increase in global awareness for environmental protection, Magnesium alloys are seen as a shining star which can reduce the usage of fuel and bring reduction in the exhaust gases by the vehicles, weight reduction is another factor of the vehicles which reduces the consumption of fuel hence increase the fuel economy. Weight reduction by magnesium in transportation is interesting and has proven with good results. However, lot of hard work is being done by the researchers further to make it cost effective and simple methods for the processing of magnesium, development of alloys, improvement in mechanical and corrosion resistance properties to meet the future set goals for reduction of weight and overall mass of the object to enhance the efficiency and the reduction in amount of greenhouse gasses to save the environment and the beautiful planet earth.

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