Magnesium Alloy Casting Technology for Automotive Applications- A Review

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Abstract: *Magnesium and its alloys have excellent use for automotive application. An overview of different casting process and their effects in the different Mg alloys are discussed. Addition of different of materials at different composition and the effects of those materials on Mg alloys are also conversed. Some materials addition with different Mg alloys also improves corrosion resistance behavior. Overall changes in the mechanical, microstructure and elongation properties of different Mg alloys are conferred at different temperature and pressure zones.*

Keywords: Magnesium alloys, casting process, corrosion, purification, effects of materials

1. Introduction:

Magnesium alloys are made with combination of magnesium along with other metals such as aluminium, zinc, silicon, manganese, zirconium, copper and rare earths. It has hexagonal crystal structure and it is the lightest metal for structural applications .In the recent years, application of the magnesium alloys has been extended due to combination of high strength and light weight. The usage has been increased in the structural applications, automotive sector as well as in non-automotive applications such as aerospace, electronics, and computer and so on. Density of the magnesium (1.8 g/cm^3) is two third that of the aluminium (2.7 g/cm^3) and also it exhibits greater mechanical properties. The advantages of the magnesium alloy lies in light weight, greater damping capacity, good dimensional stability, better impact and dent resistance.

2. Literature Review on Magnesium alloy

Qiyang Tana et al. (1) (2017) evaluated the combined influence of Be and Ca on the high temperature oxidation resistance of Mg-9Al-1Zn alloy. The alloy is fabricated, microstructure is characterized and the oxidation behavior is evaluated through thermo-gravity metric analysis at 400 °C - 450 °C for 5 h in air. The improved oxidation resistance was attributed to the formation of a Be-reinforced compact CaO-MgO composite layer on the alloy surface and suppressing the grain boundary evaporation of Mg by the elimination of Mg-Al eutectic micro-constituent and the increase in thermal stability of the β-$Mg_{17}Al_{12}$ due to the Ca alloying.

Ming Liu and Guang-Ling Song (2) (2013) investigated the corrosion behavior of AXJ530 magnesium alloy with different iron and manganese contents in 3.5 wt% sodium chloride solution in order to tailor the tolerance limit of Fe impurity in the magnesium alloy. The tolerance limit of Fe impurity in a magnesium alloy is determined by the precipitation of the Fe rich phase. The Mn content and casting temperature can influence the precipitation of the Fe rich phase and thus the corrosion performance of a magnesium alloy is improved.

Dan Luo et al. (3) (2013) evaluated the microstructural characteristics and mechanical properties of Mg-5Sn alloy produced through horizontal centrifugal casting method and compared it with the alloy produced through gravity casting. In case of centrifugal casting, columnar fine equaled grains are developed and dendritic crystal structure in obtained in case of gravity casting. The fine equated grains obtained through centrifugal casting has improved the compression strength, yield strength and elongation compared to the gravity casting.

Robert Fritzsch et al. (4) (2014) investigated the microstructure, mechanical properties and fracture behavior of high vacuum die cast Mg-8Gd-3Y-0.4Zr alloy. The heat treatment process on the Mg alloy increases cuboidal particles which in turn results in good mechanical properties. The ductility of the solution treated alloy is improved significantly compared with that of as-cast alloy. The fracture mode of solution treated is improved as trans-granular quasi-cleavage fracture from trans-granular cleavage fracture.

Fuyong Caoa et al. (5) (2016) investigated the production of a passive magnesium (Mg) alloy through metallurgical approaches, such as purification, alloying, heat-treatment, mechanical processing and non-equilibrium sputter deposition. Passivity in Mg alloy might be produced through a non-equilibrium technique with a sufficiently-high concentration of a strong passivating element supersaturated in the matrix phase. High-purity or ultra-high-purity Mg does not exhibit passivity in a concentrated chloride solution. Hot rolling can improve the corrosion resistance of an Mg alloy through modifying the crystallographic orientation.

M. Wang et al. (6) (2017) evaluated the effects of Si addition on microstructural characterization, mechanical properties and degradable behavior of Mg-17Al-5Zn alloy. With the increase of Si content, the yield strength of the alloys initially increases and reaches to the maximum of 309 MPa in alloy containing 0.5 wt % Si. Increasing Si contents, the volume fraction of Mg_2Si phase increases and the morphology gradually changes from fine spherical shape to coarse polygonal type and eventually to dendrite crystal.

Zhenming Li et al. (7) (2015) investigated the fatigue behavior of magnesium castings with NZK (Mg–Nd–Zn–Zr) alloys and other magnesium alloys including AZ91D, GW103, and AM-SC. In the absence of casting defects or when the casting defects are smaller than a critical size, fatigue failure of cast magnesium alloys is dominated by crack initiation and propagation from either twin grain boundaries in the T4 heat treatment condition. The fatigue life of cast magnesium alloys can be well predicted using multi-scale fatigue (MSF) models together with characteristic microstructure constituent – grain sizes.

Feifan Wanga et al. (8) (2017) evaluated the heat transfer and contact pressure at the casting-die interface in squeeze casting process. Experiments were conducted and a "plate shape" was used to cast aluminum alloy A356 in H13 steel die. The pressures at the casting-die interface rose to the maximum as soon as the pressure was applied by the press. The interfacial heat transfer coefficient profiles of the cases with the pressures 23 MPa and 46 MPa applied did not make much difference. However, there are still great challenges remained. In the future study, more efforts need to be made to establish a comprehensive function of the IHTC and process parameters including pressure.

Hassan Jafari et al. (9) (2012) explored the reaction between ceramic shell investment mold and AZ91D magnesium alloy as well as the related mechanism involved during investment casting process using in-situ melting technique. AZ91D granules were melted in a ceramic shell investment casting mold at 750° C in an argon protected environment and a melting flux. At high process temperature and high affinity of magnesium with oxygen developed cracks in the ceramic shell investment mold. The results showed that the black residue with a granular morphology has the same microstructure as that of AZ91D alloy and also comprises of MgO and Mg_2Si on its surface. The use of flux in contact with the mold can effectively inhibit the investment mold adhesion to in-situ melted cast AZ91D.

Yanlei Li et al. (10) (2017) investigated the effects of processing parameters (such as pouring temperature and mold pre-heating temperature) and flame-retardant content on the microstructure and fluidity of sand-cast magnesium (Mg) alloy Mg-10Gd-3Y-0.5Zr (GW103K). Increase of pouring temperature from (720 ◦C to 780 ◦C) leads to coarsened microstructure and decreased fluidity of sand-cast GW103K alloy. Fluidity of the alloy initially increases and then decreases due to increase of flame retardant content. The improvement of fluidity of sand-cast Mg-10Gd-3Y-0.5Zr alloy with flame retardant into molding sand mainly relies on the formation of protective atmosphere, which hinders oxygen diffusion and prevents the propagation of exothermic combustion.

Yang Zhang et al. (11) (2014) proved that rheo-squeeze casting combined with gas bubbling process is effective to improve the mechanical properties of AZ91-2 wt% Ca (AZX912) alloy. Commercial AZ91D ingots and pure metal Ca (99.9%) were used to prepare AZX912 alloy. Increase of gas flow promoted the refinement and spheroidization of primary a-Mg particles in semi-solid slurry of AZX912 alloy prepared by gas bubbling. The mechanical properties of rheo-squeeze casting AZX912 alloy samples were also improved continuously with the increase of applied pressure. Heat treatment at 410°C improved the ductility of rheo-squeeze casting AZX912 alloy and the tensile strength also increased slightly. Compared with conventional squeeze casting, the mechanical properties of rheo-squeeze casting AZX912 alloy were improved by more than 20%. The improvement is mainly attributed to the refinement in microstructure.

Jae-Hyung Cho et al. (12) (2016) carried out deep drawing on two different ZK60 (Mg-Zn-Zr) magnesium sheets fabricated via ingot and twin-roll casting methods and also examined the effects of the microstructure and texture on the deep draw ability and the associated microstructural evolution of ZK60 alloy sheets. During the deep drawing process, the ingot-casted sheets with large grains experienced more tensile twinning than the twin-roll casted sheets, and shear bands. Thickness variations of the drawn cups showed that the twin-roll casted sheets resisted wall thinning more effectively than the ingot-casted sheets.

H.S. Jiang et al. (13) (2016) investigation on high quality WE43 magnesium alloy ingots with diameter of 500 mm by direct-chill (DC) casting was successfully fabricated. With the average grain size decreasing from the center to the edge of the ingot, the mechanical properties are improved gradually. The DC casting WE43 alloy shows an excellent age-hardening effect. The hardness increases from 85 HV to 117 HV after peak-ageing at 250 °C for 16 h. The treated WE43 alloy exhibits yield strength of 215 MPa, ultimate YS of 274 MPa, and elongation to failure of 3.4%, which is higher than the WE43 alloy processed by sand casting and permanent mold casting.

B. Kondori and R. Mahmudi (14) (2017) investigated the microstructure and creep properties of cast Mg–6Al–0.3Mn (AM60) alloys containing 0.5, 1.2, and 2.0 wt% Ca by impression creep testing method. Calcium addition can substantially improve creep properties, withstands deformation at high temperatures, and thus, improves creep resistance. Two different mechanisms are proposed for creep deformation of AM60–xCa. At low stresses and temperatures, stress exponent of $n \approx 5$ and activation energy of pipe diffusion advocate dislocation climb controlled by pipe diffusion creep mechanism. At higher stresses and temperatures, power-low breakdown leads to stress exponent and activation energy of slightly higher than that of self-diffusion of magnesium atoms.

Apratim Khandelwal et al. (15) (2017) studied the effect of ultrasound-assisted solidification processing on the mechanical behavior of $AZ31/Al_2O_3$ magnesium metal matrix nanocomposites (MMNCs). The addition of nanoparticles and introduction of UST resulted in significant improvements in mechanical properties of both types of composites. The strengthening contribution due to the particles is significantly high and increases with an increase in the concentration of the nano-alumina particles. AC-UST type of processing conditions showed superior tensile properties, improved ductility and lower porosity whereas, ISO-UST type of processing showed superior hardness, reduced ductility and higher porosity.

Katarzyna Kus´nierczyk and Michał Basista (16) (2017) discussed the corrosion mechanisms along with corrosion protection methods in magnesium alloys and also development of magnesium alloys in biomedical applications. Special attention is given to metal matrix composites composed of Mg alloys and calcium phosphates with emphasis on the biodegradation behavior, microstructure and mechanical properties in view of potential application of these materials in bone implants.

Sravya Tekumalla et al. (17) (2016) developed a new magnesium alloy with 0.4% cerium using the technique of disintegrated melt deposition followed by hot extrusion. Tensile and compressive properties of Mg-0.4Ce were investigated and it was found that addition of cerium has enhanced the strength and elongation to failure of Mg. After heat treatment, under compression, the Mg–0.4Ce(S) alloy exhibited extensive plastic deformation which was 80% higher than that of the as-extruded condition. Both as-extruded and heat treated alloys were investigated with the aid of microstructural characterization techniques.

Jufu Jiang et al. (18) (2014) discussed the complex motorcycle wheel components of AM50A magnesium alloy had been formed by double control forming and die casting. The surface quality of components was much improved in double control forming than die casting as the tensile strength increased from 149.4MPa to 207.0MPa and the elongation increased from 5.6% to 10%. The fracture mode of die casting components was brittle fracture and the fracture mode of double control forming components was ductile fracture. The second phase of double control forming components was needlelike or rod-like which was distributed at the grain boundaries.

Wenbo Yu et al. (19) (2016) investigated the interfacial heat transfer behavior at the metal/shot sleeve interface in the high pressure die casting (HPDC) process of AZ91D alloy. Under static condition the interfacial heat transfer coefficient peak values will be 11.9, 7.3, 8.33kWm−2K−1 at pouring zone (S2), middle zone (S5), and end zone (S10), respectively. At slow speed the IHTC curve shows a second peak of 6.1kWm−2K−1 at middle zone and when high speed started the IHTC curve reached a second peak of 12.9kWm−2K−1 at end zone. Under different slow speeds the calculated initial temperature and short sleeve surface temperature decreases from 0.1 ms−1 to 0.3 ms−1and then increases from 0.3 ms−1 to 0.6 ms−1. Finally the defect bands appear at 0.4 ms−1.

Xiaogang Fang et al. (20) (2015) investigated the microstructure evolution and mechanical properties of the rheo-squeeze casting (RSC) alloy with different pressures where the semi-solid slurry used in the process was treated by direct ultrasonic vibration (DUV) and then casted with squeeze casting. After analysis the increase in pressure results in increasing solid solubility in the matrix and uniform distribution along the grain boundary. The yield strength (YS), ultimate tensile strength (UTS) and elongation of RSC sample are improved by 17.0%, 19.2% and 81.7% than the corresponding values of the samples without pressure.

FU Yu et al. (21) (2016) investigated the influence of Ca addition on the as-cast microstructure, casting fluidity and mechanical properties of Mg-Zn-Ce-Zr alloy. When adding Ca content of 0.2 wt. %–0.6 wt. % it led to effective grain refinement and enhanced the fluidity of the alloys. At Ca 0.2 wt. % exhibited the finest grain size of 35.9 μm, and filling length was increased approximately by 55.4%. The yield strength increased accordingly while increasing the Ca content, but the ultimate strength and elongation decreased. The fracture mode was quasi-cleavage fracture.

Hua Qian Ang et al. (22) (2008) investigated the strain rate sensitivity of die casting Mg-Al based alloys. The strain rate effect ranges from 10^{-6} s^{-1} to 10^{-1} s^{-1}. The strain rate sensitivity decreases with increasing solute level in the matrix. This is due to strain ageing from the interaction between aluminium solute and dislocations. Under microstructural examination it is found that the deformation twinning is more active in the alloys with lower strain-rate sensitivity. The high strain-rate sensitivity shows that increase in work hardening rate, suggests difficulty in dislocation motion at higher strain rates and reducing the ductility.

Preciado Mónica et al. (23) (2016) examined the microstructural behavior of a high pressure die-casting (HPDC) AZ91 magnesium alloy with deep cryogenic treatment (DCT) prior to aging. The phase precipitation of $Mg_{17}Al_{12}$ are analysed by TEM, SEM and mechanical behavior is explained by optical microscopy following each heat treatment processes (T6). The mechanical properties were improved and yield strength was higher. Elongation was also higher with deep cryogenic treatment process. Thus continuous precipitation is promoted by cryogenic treatment, resulting in an improvement of elongation by 20%.

K.N. Braszczynska Malik (24) (2016) presented the microstructure and mechanical property investigations of high-pressure die-cast AME501, AME503 and AME505 experimental alloys. Fabrication of investigated materials were done on the basis of AM50 commercial magnesium alloy with 1, 3, 5 wt % cerium rich misch metal. The experimental alloys were mainly composed of a-Mg, $Al_{11}RE_3$and $Al_{10}RE_2Mn_7$ intermetallic phases. Due to non-equilibrium solidification conditions, small amounts of α+γ divorced eutectic and Al_2RE intermetallic phase were revealed. Significant influence of rare earth elements on the tensile properties was shown. Suppression of the α+γ eutectic caused a decrease in the α-Mg crystals and an increase in the tensile properties of the alloys.

K Ponappa et al. (25) (2012) investigated the influence of Y_2O_3 particles on magnesium and magnesium alloy (AZ91D). Magnesium and magnesium alloys are well suited for structural and automotive applications owing to their lightweight but the reduced hardness and strength of these alloys cause problems in exploiting their usage. These lightweight metal matrix problems can be solved by reinforcing hard phase particles. Different percentages of Y_2O_3 particles are added to magnesium and magnesium alloy (AZ91D) and it is processed through two step stir casting method. Under as-cast and heat treatment process mechanical and metallurgical characteristics of Mg alloy were carried out. Under certain experiments through hardness tests it is observed that increased yttrium particles increased the hardness of Mg alloy.

Fusheng Pan et al. (26) (2016) developed a novel based on low-cost method for melt purification of magnesium alloys, the melt self-purifying technology based on a low temperature melt treatment without adding any fluxes. The solubility rate of iron and its velocity of particles in the molten magnesium and its alloys were calculated. After doing certain experiments it is found that Low temperature melt treatment is an effective method to decrease the impurity of Fe content in Mg and its alloys. For different Mg alloys AZ31 and AZ61 it if observed that Fe content is reduced to 15 ppm from the initial 65 ppm, and 20 ppm from the initial 150 ppm. Similarly for Mg alloys like AM60, AM50 and ZK60 the Fe content value is decreased after LTMT process. The Si content in all above alloys is decreased too.

YANG Mingbo et al. (27) (2008) investigated the as-cast microstructure, mechanical properties and casting fluidity of ZA84 alloy containing TiC. On adding 0.5wt%TiC to ZA84 alloy can refine the as-cast microstructure but do not form of any new phase. Changes occur from coarse in the grain boundaries from coarse to fine set. The tensile properties of ZA84+0.5TiC alloy at room temperature were comparable to those of AZ91D alloy, and were higher than those of ZA84 alloy. It is found that at 150 ℃, the tensile and creep properties of of ZA84+0.5TiC alloy was higher than that of AZ91D and ZA84 alloys. The casting fluidity of ZA84＋0.5TiC alloy was slightly poor than AZ91D alloy but was higher when compared to ZA84 alloy. This is because of effect of TiC on the solidification temperature range of ZA84 alloy.

A.V. Koltygin et al. (28) (2013) proposed the application of Calcium on Mg alloys. data. Mg-7% Al-4% Ca-0.5% Mn casting alloy possessed the low propensity to the hot brittleness and good castability. The alloy had moderate strength and satisfactory percentage elongation. Calcium-containing alloys smelting of Mg-Al-Ca-Mn system was preferable with the application of low-chloride flux FL10. The alloy smelting in argon and SF_6 mixture resulted in increased shelling and wastage of calcium content. The heat treatment offered for the developed alloy was directed to the Al_2Ca phase spheroidizing.

Li-feng Hou et al. (29) (2013) investigated the erosion of die materials during die casting mechanism. Numerous microholes, microcavities and cracks were observed on the die surface of the insert close to the moveable mould. Continuous impact of high-temperature and high-velocity molten metal on the insert with a tilt angle relative to the die surface caused surface defects on the molten metal. The results shows that erosion of the die insert occurs through depression, plastic deformation and tearing actions.

3. Processing roots for casting of Mg alloy:

3.1. Die Casting Process:

The mechanical properties and microstructure of alloys such as Mg-8Gd-3Y-0.4Zr, Mg-5Al-0.4Mn-RE, AZ91D, and AM50A were experimented under die casting methods. In this process the alloys were tested at various temperature and pressures. The mechanical and microstructure properties were found to be improved at certain temperatures. Mg-8Gd-3Y-0.4Zr alloy was prepared by high vacuum die casting process showed improved ductility properties of the solution. Then it undergone heat treatment process and showed increase in mechanical properties of the alloy and its fracture mode (1). Mg-5Al-0.4Mn-RE alloy has shown changes in the intermetallic phases by high pressure die casting process. Significant influence of rare earth elements on the tensile properties of the solution was also discussed (24). AZ91D alloy has shown interfacial heat transfer behavior at various temperatures by high pressure die casting process. The heat transfer behavior of the alloy varies by varying speeds at different zones of the process (20). AM50A alloy showed improvement in its surface quality by double forming process, tensile strength and elongation properties were improved by die casting process. The fracture mode was improved in the die casting process (19).

3.2. Centrifugal Casting Process- Gravity Casting Process:

Mg-5Sn alloy under horizontal centrifugal casting process evaluated the microstructure and mechanical properties of the solution and it is compared with the alloy produced by gravity casting process. Centrifugal casting showed improvement in its compression strength, yield strength and elongation compared to the gravity casting (3).

3.3. Investment Casting Process:

AZ91D Magnesium alloy with ceramic shell mold by investment casting process developed cracks at high temperatures and produced oxides of magnesium under argon protected environment. This resulted to provide and interfacial reaction between AZ91D alloy and ceramic shell mold and the oxides produced effectively inhibit the investment mold adhesion to in-situ melted cast AZ91D (9).

3.4. Squeeze Casting Process:

AZ91-Ca prepared by rheo-squeeze casting combined with gas bubbling process showed improvement in its mechanical properties. Increased pressure and flow of gas had increased the mechanical properties of AZ91-Ca alloy about 20% more. Also under heat treatment process the tensile strength also increased slightly (11).
Mg–RE–Zn–Y alloy under different temperatures was prepared by squeeze casting process after its treatment with UV radiations has shown improvement in microstructure and mechanical properties of the solution. The yield strength, ultimate strength and elongation also improved due to increase of pressure (21).

3.5. Stir Casting:

AZ31/Al2O3 alloy prepared by ultrasound stir casting process has shown improvement in mechanical behavior of magnesium metal matrix nano composites (MMNCs). The strength of alloy increased with increased concentration of the nano-alumina particles (16).

3.6. Direct Chill Casting:

WE43 alloy prepared by direct chill casting method showed improvement in its mechanical behavior. Age-hardening effect of the WE43 alloy was also been shown. The tensile strength, ultimate strength and elongation were more when compared to sand casting and permanent mold casting processes (13).

3.7. Twin Roll Casting:

ZK60 alloy prepared by twin roll casting method showed effects in the mechanical and microstructural properties of deep drawing sheets made from the alloy. Thickness variations of deep drawing sheets showed wall thinning more effectively compared to ingot-casted sheets (12).

4.1. Effects of other materials on Mg alloy:

Be and Ca on Mg-9Al-1Zn showed improvement to oxidation resistance at high temperatures. The improved oxidation resistance attributed to the formation Be-reinforced compact CaO-MgO composite layer which suppressed the grain boundary evaporation of Mg (1). Iron and Manganese on AXJ530 magnesium alloy-Different composition of Fe and Mn on the AXJ530 alloy showed impurity control and corrosion resistance behavior. The Mn content and casting temperature influence the Fe rich phase which results in improvement of corrosion resistance of the Mg alloy (2). Si addition on Mg-17Al-5Zn alloy showed varying microstructural behavior, mechanical properties and degradation behavior. With increasing Si content the yield strength of the alloys initially increases and reaches to the maximum of 309 MPa in the alloy (6). Ca additions on cast Mg–Al–Mn magnesium alloy showed improvement in creep resistance properties of the alloy. At different stresses and pressure different creep resistance was showed which varies at low and high pressure and stress (15). Cerium on Magnesium alloy has shown improvement of strength and elongation properties. Also cerium addition influenced the corrosion resistance behavior. After heat treatment process under compression the solution exhibited extensive plastic deformation (18). Ca addition on Mg-Zn-Ce-Zr magnesium alloy influenced the microstructural and mechanical properties and it also influenced the casting fluidity of the alloy. Addition of of 0.2 wt % Ca to the solution content lead to effective grain refinement and enhanced fluidity of the alloy. The yield strength increased with increasing Ca content but the ultimate strength had decreased (22). Y_2O_3 particles on AZ91D magnesium alloy influenced hardness of the AZ91D alloy. Different percentages of Y_2O_3 particles are added to Mg alloy and it is carried out under stir casting process. Under heat treatment it is found that the hardness of the alloy increased with increased yttrium particles (26). TiC addition on ZA84 alloy showed improvement in mechanical, microstructure and elongation properties. . It is found that at 150 ℃, the tensile and creep properties of of ZA84+0.5TiC alloy was higher than that of AZ91D and ZA84 alloys. The casting fluidity of ZA84＋0.5TiC alloy was slightly poor than AZ91D alloy but was higher when compared to ZA84 alloy (28).

4.2 Corrosion resistance behavior of Mg alloys:

Hot rolling process can remove corrosion resistance property in Mg alloys (5). Addition of Fe and Mn element in sodium chloride solution at casting temperature can improve corrosion resistance behavior of AXJ530 Mg alloy (2). Ce addition on Mg alloys can also prevent corrosion after heat treatment process of the alloy (18).

4.3. Purification of Mg alloy:

Low temperature melt treatment (LTMT) process rjeduced impurity of Fe content in Mg alloys. In alloys such as AZ31 and AZ61 the impurity Fe content decreased from 65ppm to 15ppm and 150ppm to 20ppm. Also in alloys like AM60, AM50 and ZK60 the LTMT purification process showed good results. It was also found that Si content in Mg alloys was also reduced (27).

5. Conclusion:

In recent years there is increase in growth of Mg alloy usages for various applications. Different methodologies of casting process carried out for improvement of strength and tensile properties are studied. Mg alloys showed improvement in corrosion properties with addition of Fe ad Mn materials. Also impurity control process of few alloys is discussed too. Although the casting process and various process provides study on mechanical, microstructure and strength properties, life extension and creep properties of Mg alloys are need to be undergone in further studies.

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