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Investment Castings of Magnesium Alloys: A Road Map and Challenges

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Abstract

In the manufacturing sector, the processing of magnesium alloys through the liquid casting route is one of the promising methods to manufacture automotive and aircraft components, for their excellent mechanical properties at the lower weight. Investment casting process has the great cabaility to produce near net shape complex castings for automotive and aircraft applications. The distinct and attractive engineering properties of magnesium alloys have shown to be promising in terms of its potential to replace materials such as cast iron, steel, and aluminum In this regard, the efforts to develop processing technology for these alloys for their wide range of applications in industries have been reported by the scientific and engineering community. For successful production of magnesium alloy castings, it requires specialized foundry techniques because of the particular chemical and physical properties of magnesium; especially the reactive and oxidative nature of these alloys. The industry is young enough, to tap the potential.

Keywords: Magnesium, Investment casting, Reactions, Melting

1. Introduction

Automotive industries are focusing on the potential applications of light metals. Aluminum alloys are far ahead in terms of applications as compared to magnesium alloys, though, magnesium alloys have good castability, machining characteristics, damping capacity, corrosion resistance, higher strength to weight ratio, elevated temperature performance and great recycling potential [1]. As per the annual casting census published by AFS (American Foundry Society), in the last five years, the vast difference in aluminum and magnesium castings production can be observed worldwide. This is presented in Fig. 1 (a). The contribution of aluminum castings production is 15% of the total casting production worldwide. Whereas, magnesium casting production is only 0.35% of aluminum as per the casting census of 2020 as presented in Fig. 1 (b).

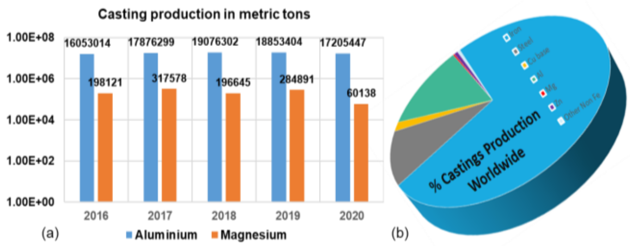

Fig. 1. Worldwide casting production in metric tons (a) year-wise comparison for aluminum and magnesium, (b) contribution of various metals in a year 2020

The future of magnesium in the automotive industry has been proposed by Miller in 1999 (shown in Fig. 2), where it was predicted that aluminum or magnesium would lead in the next two or three decades [2]. The decline in magnesium casting production may be due to process complications or missing actual know-how. However, it is a fact that Volkswagen was using magnesium castings in "Beetle" even before World War 2 [3].

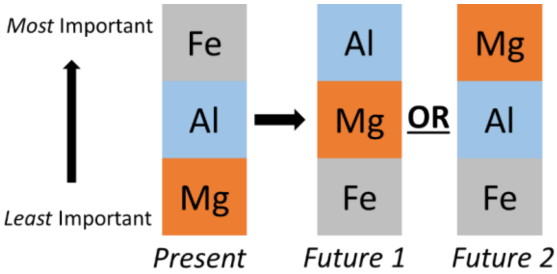

Fig. 2. Current and future scenario of magnesium and aluminum in the automotive industry

2. Road Map for Magnesium Foundry Development

The prime concerns needed to be addressed by any present Fe/Al foundry to convert into Mg foundry are indicated in a schematic of "Road map" presented in Fig. 3. The prime countries producing magnesium are the USA, Italy, Germany, UK, Russia, and Canada (AFS World Casting Census). India needs to rely on these countries for magnesium either as a virgin metal or as an ingot form. In addition, the availability of metal ingots with inherent quality is also important. The presence of oxides in the magnesium ingots increases dross formation during melting, leading to the formation of defects.

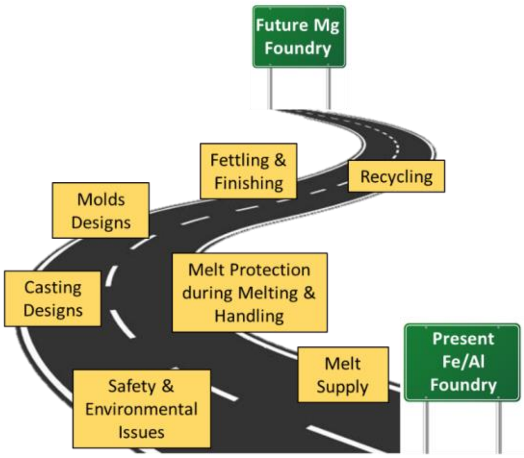

Fig. 3. A Road map for future magnesium foundry journey

The processing of magnesium is hazardous due to its reactive and explosive nature. It is important to be aware of the hazard and adopt safe practices for magnesium melting, handling, and pouring to eliminate the hazard or any accident. From the environmental point of view, greenhouse emissions of the gases and fluxes used during melting and handling of magnesium should be less. The geometrical aspect such as a thin wall or thick wall casting as well as a selection of face-coat materials, mold surface finish, mold permeability, and strength during mold development should be considered [4-6]. During fettling and finishing, care should be taken to prevent the burning of chips and fins. Adequate recycling techniques should be developed as the increase in oxide level during melting/ remelting leads to degradation of quality.

3. Challenges to Magnesium Alloy Investment Casting Development

The traditional sand-casting process produces poor surface quality and dimensional accuracy which mainly caters to economical production of low volume. While the issues concerning the formation of porosity during high pressure die casting and its high cost limit the broader use. There appears to be a clear need for the development of the investment casting process for reactive magnesium alloys to meet the current demand for the economic production of low volume and high precision complex parts. Investment casting industries face several problems during the melting and casting of magnesium alloys. The prime reason is the greater affinity of magnesium for oxygen. Unlike aluminum, during melting, the molten magnesium must be prevented from contact with oxygen in the air. It reacts spontaneously with oxygen, which rapidly oxidizes the melt and produces hazardous flames. Apart from this, in the case of investment casting, interfacial mold-metal reactions are the barriers to the successful production of quality castings. Therefore, the melting and casting of magnesium alloys needed to be carried out under protective gas or with the application of flux.

3.1. Protection during Melting Practice

In general, magnesium and its alloys melt in a range of around 650°C to 700°C. However, the burning and oxidation of these alloys are observed at higher temperatures. The high vapor pressure of magnesium at the higher temperature initiates the ignition. Thus, a protective environment during melting and casting is mandatory to prevent ignition and thereby burning and oxidation [7]. Though many flux-less melting techniques are developed to create a protective environment nowadays, many foundries still use traditional fluxes during melting. The flux composition is prepared in such a way that it melts before the metal gets melted and floats on the melt surface to protect the metal from the atmosphere. In addition, the molten flux should be thick and viscous enough so that it can be easily separated from the melt prior to the pouring. This phenomenon of thickening and increasing viscosity is termed as 'inspissation' of flux [8]. Initially, the flux with the combination of $MgCl_2$ and KCl was used to prevent oxidation and burning. Later, the application of fluorine containing compounds in flux mixture was proven as good resistant to melt burning and oxidation. The addition of compounds such as magnesium fluoride (MgF_2), sodium fluoride (NaF), or potassium fluoride (KF) reduces the surface tension and increase the wettability between melt and flux, facilitating the formation of a dense oxide cover film, preventing further oxidation of the melt [9-11].

The application of gas mixture during melting and casting was considered as a flux-less melting technique. The mixture of sulfur dioxide with air was the most commonly used flux-less technique in earlier times. The toxic and corrosive nature of this gas limited its application in foundries and the necessity on the application of some other gases was built. The application of inert gases such as carbon dioxide, argon, nitrogen as a carrier gas with a small proportion of sulfur hexafluoride has been reported by many researchers. It was concluded that mixture of 2% to 4% of SF_6 with CO_2 act as an effective flux-less technique for magnesium melting [12]. The protective function of the fluxes can be explained by the Pilling and Bedworth factor. It is the ratio of the volume of the elementary cell of a metal oxide to the volume of the elementary cell of the corresponding metal (from which the oxide is created). The value of this ratio of more than 1 indicates the formation of the dense and continuous film on the melt. Pilling and Bedworth factors for various films are presented in Table 1. From the table, it can be concluded that fluorine-contained films offer the best protection to the melt from oxidation.

Table 1
Pilling and Bedworth factor for various films [13]

Surface film formed	Pilling and Bedworth factor
$Mg + S = MgS$	1.26
$3Mg + 2BF_3 = 3MgF_2 + 2B$	1.32
$Mg + 2HF = MgF_2 + H_2$	1.32
$3Mg + N_2 = Mg_3N_2$	0.79
$2Mg + CO_2 = 2MgO + C$	0.9

3.2. Interfacial Mold-metal Reactions during Investment Casting

The molds in investment casting are primarily prepared with ceramic refractory oxide materials. During solidification, the reactions occur at the mold-metal interface due to the strong affinity of magnesium metal to oxygen as the molds are of oxide material. These reactions produce burn marks on produced casting and deteriorate the surface finish due to the formation of oxide layers (MgO) on the casting surface. During the process, mold oxygen may get decomposed and dissolve into the melt. This dissolved oxygen into the melt increases the surface hardness of the solidified casting causing premature failure of the casting. The interfacial reactions, during investment casting of reactive metal and alloys, can be categorized in general as: [14]

1. The dissolution of mold material in the presence of highly reactive liquid metal and reaction of melt with dissolved mold elements.
2. A formation of the thin layer of reaction compound on casting surface by reaction between mold and metal at the interface.
3. The reaction of melt with the atmosphere of the mold cavity or with any gases present in the mold cavity.
4. The penetration of metal into a mold that results in a poor finish on the surface of castings.
5. The reaction of liquid metal with atmosphere during solidification.

3.3. Stability of Face-coat Oxides against Reactions

The ceramic oxides are used as a face-coat primary slurry material in investment casting molds. Zirconium silicate (ZrSiO4) is a traditional face-coat material used in foundries. This face-coat is proven successful for producing near net details for intricate and complex castings [15]. However, during casting of reactive alloys such as magnesium or titanium, this face-coat was observed to decline to meet its performance regarding surface quality due to reactions of the face-coat with reactive alloy at the interface. The introduction of some newer ceramic oxides as a face-coat material is needed for the casting of reactive alloys. There are many other ceramic oxides such as Al_2O_3, ZrO_2, MgO, Y_2O_3, and CaO, etc. that can be used as a face-coat slurry material. These oxides should be thermally and chemically stable enough at elevated temperature. Therefore, the reactions that occur with liquid metal from mold decomposition can be suppressed or eliminated.

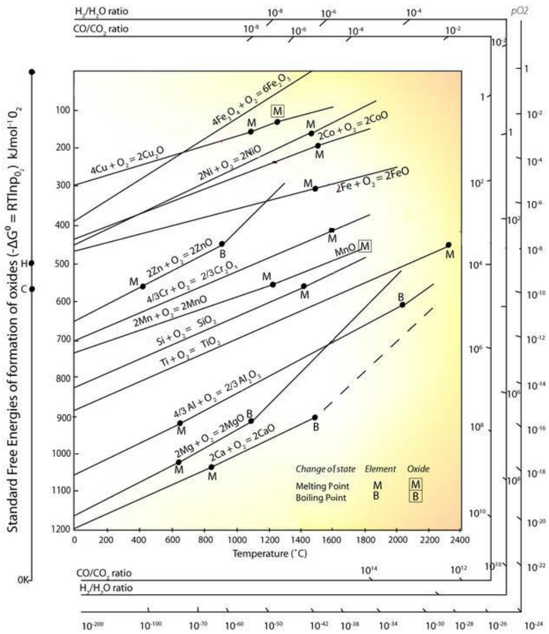

Fig. 4. Ellingham diagram [16]

The theoretical stability of oxides can be judged by Gibbs free energy of compound formation. The Gibbs free energy change for compound formation at various temperatures for various oxides is shown in the Ellingham diagram presented in Fig. 4. The compounds such as CaO and MgO can be considered most stable as having the larger negative values of Gibbs free energy change for compound formation. The work was carried out by many researchers to asses the effectiveness of various ceramic oxides to suppress the reactions during investment casting of reactive magnesium alloys. The various unconventional oxides Al_2O_3, CaO, $CaZrO_3$, MgO, ZrO_2, Y_2O_3 etc. were used as a face-coats in place of conventional face-coat $ZrSiO_4$ where, some oxides were observed effective to suppress the mold-metal reactions. However, the results were not in agreement with the theoretical stability of face-coats in some cases [17-20].

4. Magnesium Alloys and their Applications

In general, it is difficult to use magnesium in pure form for commercial applications, as it is too weak and has lower ultimate tensile strength. As per ASTM, magnesium alloys can be categorized into three major groups viz, magnesium-aluminum alloys, magnesium-zinc alloys, and magnesium-rare earth alloys. In the first group, AZ and AM series are widely used for automotive and aerospace applications, where, Zn and Mn are used as secondary elements, respectively. These alloys contain mainly 8 to 10% aluminum as a primary alloying element. ZK series is the most popular for the second group of magnesium alloys where zinc is added up to 8% as a primary alloying element. EK, EZ, QE, WE (Electron) are the popular series of a third group where various rare earth elements such as cerium, thorium, zirconium, yttrium, etc. are being used as alloying elements. AZ series alloys are widely used for their optimum combination of strength and ductility. These alloys have good corrosion resistance because of the formation of Al_2O_3 in the surface film of these alloys. The increase in Al and Zn content increases the fluidity, and thereby castability [21]. Therefore, magnesium AZ91 is considered as a castable alloy with 9% of Al and 1% of Zn. The addition of Si in a small amount improves the creep resistance of this alloy along with castability [22].

Major applications of magnesium alloys have been observed in automobile, aircraft, and biomedical sectors [23]. Few examples of magnesium castings used in automobile vehicles by various manufacturers are listed in Table 2 [24-26]. The higher temperature creep resistance and galvanic corrosion resistance make magnesium alloys also suitable for aircraft applications. The magnesium casting parts used in various aircraft are listed in Table 3 [27].

Table 2.
Automobile manufacturers using Mg alloy cast parts

Company	Parts
General Motors	Valve cover, air cleaner, clutch housing, induction cover, clutch pedal, brake pedal, steering column brackets, cylinder block, intake manifold, instrument panel
Ford	Clutch housing, oil pan, steering column, four-wheel-drive transfer case housing, manual transmission case housing
Chrysler	Drive brackets, oil pan, steering column brackets, drive brackets, oil pan
Porsche	Chassis, magnesium alloy wheel, camshaft drive chain case
Daimler-Benz	Seat frames
BMW	Engine block, air intake system, steering wheel frame
Volkswagen	Brackets for air comfort system compressor, steering booster pump, and generator
Volvo Motors	Cylinder head, clutch case, transmission case
Toyota	Wheel rims, instrument panel
Honda Motor	Cylinder head

Table 3.
Magnesium alloy cast parts used in aircrafts

Aircraft	Parts
Boeing 737, 747, 757, 767	Thrust reverser, cascade casting
Rolls Royce	RB211 gearbox
General Dynamics F16	Accessory drive gearbox
Boeing AH-64D Apache	Main transmission casing plus six other drive train components
Bell Augusta 609	Tilt-axis gearbox, quill, cover
Sikorsky S92	Main transmission casing

Nowadays, the demand for magnesium alloy castings in biomedical applications is also increasing. The similar density and elastic modulus of magnesium alloys to that of the human bone tissues enable it to avoid the stress shielding effect (reduction in bone density) caused by usual implants. The biodegradable load-bearing magnesium orthopedic implants would remain in the body and maintain mechanical integrity over a time scale of 12–18 weeks while the bone tissue heals, eventually being replaced by natural tissue [28-29].

5. Conclusions and Future Scope

The review of literature unfolded the scope of improvement for the production of quality investment castings of reactive magnesium alloys. Foundry engineers dealing with the investment casting of magnesium alloys faced problems regarding interfacial mold-metal reactions. There is a clear need to:

- Identify and develop low-cost non-global-warming cover gas for melting/casting procedures.
- Investigate the effect of cast part geometry on interfacial reactions.
- Explore the feasible application of different un-conventional face-coat ceramic oxides to suppress the reactions.

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