Influence of impurity elements on the casting properties of Al – Mg based alloys

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Increasing demand for industrial applications of aluminum alloys achieved a new aspect; nowadays the demand for corrosion-resistant alloys largely exceeds the one for other high-strength, wear-resistant and heat-resistant aluminum alloys. Moreover, the relatively low-cost of casting technology provides an increased share of demand for foundry corrosion-resistant alloys in comparison with the deformable ones. Another advantage of foundry Al alloys is their excellent recyclability. However, recycling of scrap metals causes an increase in the content of impurity elements. In this study, the influence of individual and combined addition of impurity elements, such as Si, Fe, Cu, Zn, Pb, Sn, Ni and Mn, on the casting properties of corrosion-resistant Al – Mg alloy with the Mg content ranging between 4–8% was investigated. While the microstructure of the alloys in as-cast state was characterized using optical and scanning electron microscopes, the fractured surfaces of tensile test specimens were investigated using the latter microscope.

The results of the experimental investigations of the effect of the main impurities on casting properties, such as fluidity, hot cracking, shrinkage and pre-shrinkage expansion of Al – Mg based alloys have been systematically summarized. It has been found that among various impurity elements, Si, Fe and Cu can exert much greater influence on fluidity and hot tearing. All these elements tended to improve fluidity; however, it occurred at the expense of a considerable reduction in hot tearing of Al – Mg alloys. The casting properties of die castings, castings obtained under pressure and die castings after hot isostatic pressing (HIP) have been studied and compared with each other and it has been found that isostatic pressing causes reduction of porosity in alloys, but slightly affects the mechanical properties. Casting with excess gas pressure ($P = 0.7$ atm) exerted almost no apparent influence on density (porosity) of the castings from various alloys. In general, the increased content of impurities has an insignificant effect on the casting properties of Al – Mg based alloys, so it is concluded that low-grade (secondary or recycled) aluminum can be used in the fabrication of corrosion-resistant applications.

Key words: aluminium, magnesium, Al – Mg alloys, impurities, composition, casting properties, fracture surface.

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Introduction

Among the corrosion-resistant alloys, the Al – Mg based alloys are widely used in various industrial sectors [1–4]. High demand for these alloys can be associated with their low cost [4]. In addition to Mg, which is the main alloying element in these alloys, other elements, such as Ti, Zr, B, Sc, are normally added to these alloys in small amounts to improve certain properties and most importantly, these alloys also contain some impurities, such as iron, silicon, copper, manganese, tin, lead, bismuth, nickel and zinc, in trace amounts [5–10]. Use of high-purity A95 alloy for corrosion-resistant components suppresses actions aimed at further reduction in the cost of these alloys, and hence, expansion of their application. Usage of secondary (recycled) Al – Mg based alloys, rather than the primary ones, in the fabrication of corrosion-resistant components appears to be a robust solution to this issue [11–13]. Although increased content of impurity elements has been found not to exert a significant influence on alloy mechanical properties [14–16], it can be deleterious to the casting properties of aluminum alloys. Since the casting properties of the alloys is an important parameter in obtaining high-quality shape castings, further investigations is needed to characterize the role of impurity elements on casting properties of Al – Mg alloys.

High-quality castings should be such that they are uniform in cross-section in terms of chemical composition, have no cracks and pores and possess high surface quality. The level of casting properties (fluidity, shrinkage and hot tearing) of the alloys is determined by their composition and processing conditions [1, 3–5].

Fluidity can be defined as an ability of the alloy to fill the mold cavity. This characteristic is purely technological, as it also depends on the molten metal and mold temperatures, and the level of the metallostatic pressure [5]. All these factors affect the fluidity through the physical properties of the melt, particularly the viscosity and surface tension of the melt.

The quality of castings can be significantly affected by the shrinkage, which occurs during the crystallization stage, promoting the formation of shrinkage voids and stresses. Shrinkage stresses can be credited for the formation of hot cracks. To ensure high-quality castings production route, it is important to know the quantitative relationship between shrinkage holes and shrinkage porosity. The index of shrinkage of the alloy is influenced by the index of pre-shrinkage expansion, which is an increase in the volume of the alloy during the crystallization process; this does not occur in all alloys and the causes of which are not yet clear [3, 5]. The level of porosity in alloys determines their tightness. The tightness depends on the total volume of the pores, their sizes and distribution along the ingot section and the isolation from each other.

Review of the literature indicates that although the casting properties of Al – Si based alloys are well studied, there is not sufficient data on the casting properties of Al – Mg alloys. In the literature, data on the effect of impurities on the casting properties of Al – Mg alloys are practically not given. It is known that Si tends to improve alloy castability [5–6], while the influence of other impurities is not well understood. Therefore, the present work is aimed at investigating the casting properties of Al – Mg alloys containing various levels of impurity elements.

This study is thus aimed at investigating the effect of the increased content of impurities on the casting properties of corrosion-resistant Al – Mg alloys and the following tasks have been completed:

– the effect of individual and combined addition of impurities on the casting properties of Al – Mg alloys has been studied;

– the structure of cast Al – Mg alloy with an increased content of impurities has been investigated;

– fractographic analysis of the fractured surfaces of tensile test specimens from Al – Mg alloys with an increased content of impurities has been performed;

– the results of experimental investigations of the influence of the main impurities on the fluidity, hot tearing, shrinkage and pre-shrinkage expansion index of Al – Mg based alloy are summarized.

Materials and methods

In this study, the alloys of the Al – Mg system in the range of 4–8% Mg with various contents of impurities, such as Si, Fe, Cu, Zn, Sn, Pb, Ni and Mn, were investigated. The experimental alloys were prepared using commercially pure Al, master alloys: Al – 10Fe, Al – 5Cu, Al – 10Zn, Al – 5Ni, Al – 7.5Mn, pure Mg, Sn and Pb master alloys (in wt.%). The pre-calculated amount of master alloys was added to molten Al (~ 2kg) to reach the chemical composition (shown in Table 1). In addition to the alloys (shown in Table 1), Al – Mg alloys with the addition of 1.5% Si or 0.8% Cu were investigated. The materials were melted in an electric resistance furnace with the excess P = 0.7 atm at a temperature range of 720–740 ^{o}C since too high melting temperature can result in the removal of some impurities and most importantly the reduction of Mg content via oxidation. Prior to pouring, the molten alloy was treated with the addition of C_2Cl_6 and then the dross from the surface of melt was removed. After that the molten alloy was kept quiet for about 10 min and then poured into the die cavity at 700–710 ^{o}C. Isostatic pressing of the alloys was performed at 400 ^{o}C, with the holding time of 2h and pressure of 1700 atm.

Table 1

The chemical composition of experimental alloys (wt.%)

Alloys	Concentration, %								
	Mg	Si	Fe	Cu	Zn	Sn	Pb	Ni	Mn
1	4	–	–	–	–	–	–	–	–
2	4	0.3	0.3	0.3	0.3	0.1	0.1	0.2	0.3
3	4	0.6	0.6	0.6	0.6	0.3	0.3	0.5	0.6
4	8	–	–	–	–	–	–	–	–
5	8	0.3	0.3	0.3	0.3	0.1	0.1	0.2	0.3
6	8	0.6	0.6	0.6	0.6	0.3	0.3	0.5	0.6
7	6	–	–	–	–	–	–	–	–
8	6	0.3	0.3	0.3	0.3	0.1	0.1	0.2	0.3
9	6	0.6	0.6	0.6	0.6	0.3	0.3	0.5	0.6
10	6	0.3	–	–	–	–	–	–	–
11	6	0.6	–	–	–	–	–	–	–
12	6	1.0	–	–	–	–	–	–	–
13	6	–	0.3	–	–	–	–	–	–
14	6	–	0.6	–	–	–	–	–	–
15	6	1.0	–	–	–	–	–	–	–
16	6	–	–	0.3	–	–	–	–	–
17	6	–	–	0.6	–	–	–	–	–
18	6	–	–	–	0.3	–	–	–	–
19	6	–	–	–	0.6	–	–	–	–
20	6	–	–	–	1.0	–	–	–	–
21	6	–	–	–	–	0.1	–	–	–
22	6	–	–	–	–	0.3	–	–	–
23	6	–	–	–	–	–	0.1	–	–
24	6	–	–	–	–	–	0.3	–	–
25	6	–	–	–	–	–	–	0.2	–
26	6	–	–	–	–	–	–	0.5	–
27	6	–	–	–	–	–	–	–	0.3
28	6	–	–	–	–	–	–	–	0.6

Fluidity was evaluated using ball test. Hot tearing was investigated using pencil probe test. Shrinkage and pre-shrinkage expansion indexes were determined using graphite device with moveable fillet. Porosity level in castings was determined by the method of hydrostatic weighing of tensile test specimens. The tightness of alloys depends on the total volume of pores, their size and distribution over the cross section of casting and the distance between them. Detailed explanation of the methods used to characterize the casting properties, microstructure and mechanical properties of the experimental alloys can be found elsewhere [1, 5–6].

Optical and scanning electron microscopes were used for microstructural characterization and the latter tool was employed to analyze the fractured surfaces of the specimens.

Results and discussion

Typical as-cast microstructure of the alloys (shown in Table 1) consists of primary α-Al, eutectic Mg_2Si, $FeAl_3$, $CuAl_2$ and other phases. The Fe-rich $FeAl_3$ compounds appear in the microstructure with mainly acicular morphology and the trace elements, such as Mn, Cu, and Ni were found to partially dissolve into this phase. Other impurity elements, such as Sn, Pb accumulated into Mg_2Si, while Zn tended to dissolve into $CuAl_2$. Mainly Zn, Cu and negligible amount of Si got dissolved into the solid solution of α-Al; in contrast, both Pb and Sn caused the formation of interdendritic particles.

Changes occurred in the casting properties (hot tearing, fluidity, linear shrinkage and pre-shrinkage expansion) of binary Al – Mg alloys with the variation of Mg content (can be observed in Fig. 1); results obtained are consistent with the literature [5–6, 17–19]. Increasing the Mg content from 4% to 6% in binary alloys substantially increased fluidity index to about 40%; however, further increase of Mg content to 8% did not exert any further influence. The HTI of binary alloys, on the contrary, was decreased with increasing the Mg content.

In the presence of impurities in both Al – 4Mg and Al – 6Mg alloys, the hot-tearing index (HTI) tended to decrease as the impurity content went upward (see Fig. 1, *b*); this may be due to the increase in the volume fraction of eutectic phases. The HTI of Al-8Mg alloy with different content of impurities (alloys 5, 6 according to Table 1) turned out to be slightly higher in comparison with Al – 4Mg and Al – 6Mg alloys, which is probably associated with the cracking of a large number of brittle excess phases below the solidus.

A slight improvement in the fluidity of alloys with an increase in the total content of impurities may be due to an increase in the number of eutectic compounds (see Fig. 1, *a*).

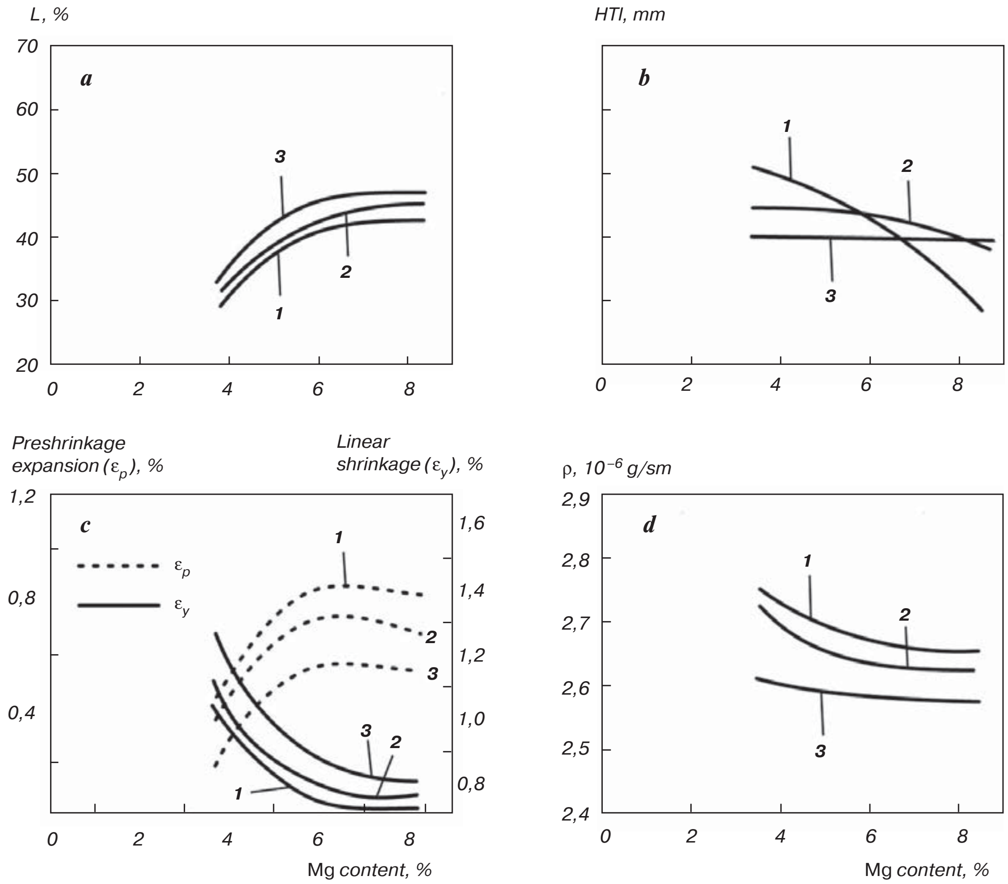

Fig. 1. Influence of compositional variations on the casting properties of Al-Mg alloy:
1 — Binary alloys; *2* — Alloys with low levels of impurities; *3* — Alloys with high levels of impurities

The data on the influence of impurities, such as Si in the amount of 0.3–1.5%, Zn and Fe in the amount of 0.3–1% each, Cu in the amount of 0.3–0.8%, Sn and Pb in the amount of 0.1–3% each, Ni in the amount of 0.2–0.5% and Mn in the amount of 0.3–0.6% (Fig. 2) on the casting properties indicates that, in general, the nature of the change in properties can be explained by analogy with a change in these properties for alloys of binary and ternary systems.

At the same time, it should be noted that Si, Fe and Cu have the strongest effect on fluidity and hot tearing (Fig. 2). These elements increase fluidity, while at the same time they slightly reduce the hot-tearing index. Thus, for example, with the introduction of silicon into the Al – 6Mg alloy in an amount of up to 1.5%, the fluidity index of the alloy rises to ~45%, while the HTI decreases to ~10 mm. This suggests that an admixture of silicon (as well as iron and copper) is useful from the point of view of increasing the casting properties of the alloys.

Since an increase in the concentration of impurities, as shown above, increases the volume fraction of excess phases of eutectic origin, the share of eutectic porosity should also increase. This in turn can cause the reduction of the mechanical properties of the Al – Mg alloys containing high impurity levels.

To clarify this, alloys 1, 4, 7–9 (Table 1) were cast with excess pressure. In addition, a sample with a diameter of ~55 mm was sectioned from the castings produced in metallic mold to apply comprehensive gas isostatic pressing. The porosity was determined experimentally by the hydrostatic weighing method on tensile test specimens.

Table 2 shows the mechanical properties, the calculated (ρ_T) and the experimental (ρ_E) values of the density of binary Al – Mg alloy with 4, 6 and 8% Mg, and the Al – 6Mg alloy containing various impurity levels (alloys 1, 4, 7–9 according to Table 1). According to the results of mechanical tests, analysis of the density and porosity of binary alloys (Table 2), the isostatic pressing contributed to an increase in mechanical properties and a decrease in the porosity of alloys.

Analysis of the fracture surfaces of the tensile-tested specimens (Fig. 3) confirms this conclusion. While the sections corresponding to the pores were observed in the fracture surfaces of the Al – 6Mg alloy before isostatic pressing (see Fig. 3, *a*), applying isostatic pressing led to complete removal of porosity from the fractured surfaces (Fig. 3, *b*). The fracture surfaces of the Al – 6Mg alloy with the highest impurity content (Fig. 4, *a*) before and after isostatic pressing differ from each other in the presence of small dispersed dimples in the latter case (Fig. 4, *b*).

This difference is, apparently, the result of a reduction in the size of the inclusions of the excess phases due to their dissolution into the α-Al solid solution under isostatic pressuring. Moreover, fracture of alloys corresponds to brittle fracture. The increase in the density (and, hence, the decrease in the porosity) of alloys with impurities observed after isostatic compaction does not affect the mechanical properties of the alloys.

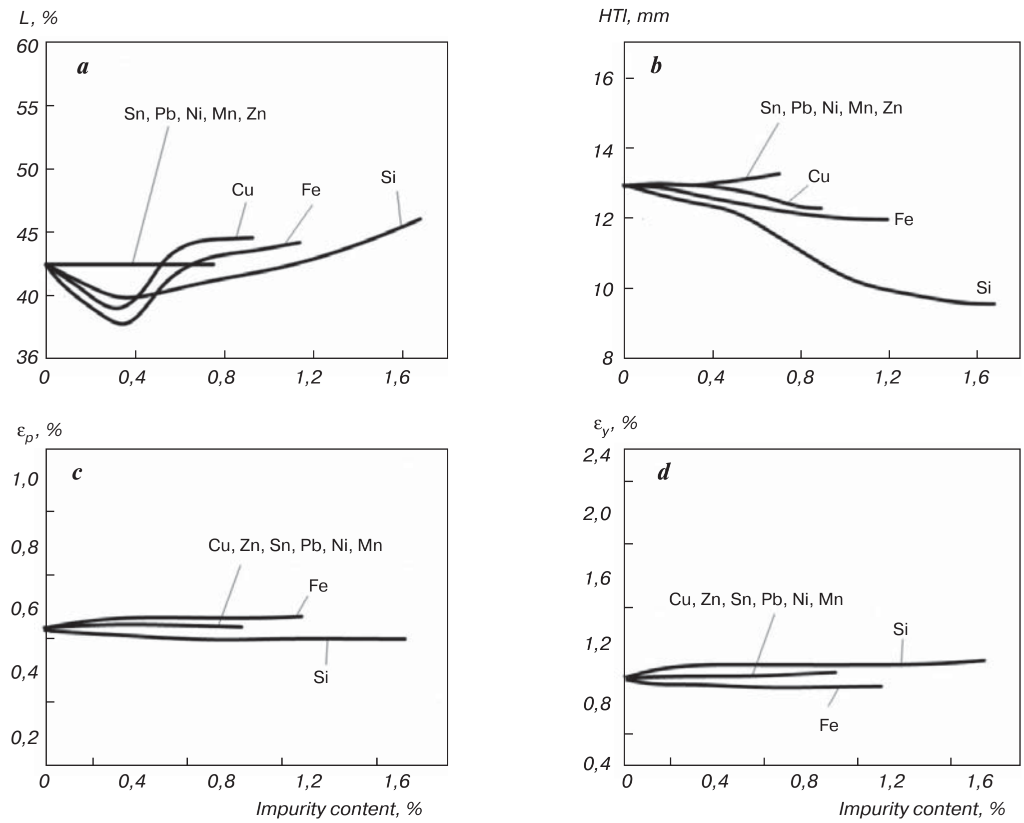

Fig. 2. Influence of impurity elements on the casting properties of Al – 6Mg alloys

Thus, casting under excess gas pressure (P = 0.7 atm) practically did not affect the density (porosity) of the castings of all alloys. Probably, to increase the density of castings and thus improve the mechanical properties, it is necessary to apply casting with crystallization under pressure or to apply a greater excess external gas pressure ($P > 2$–5 atm).

For comparison, Table 3 presents the casting properties of some industrial silumins used by enterprises in large volumes and Al – Mg based alloys. This data can be used as a reference.

Experimental investigations conducted within this study allowed to establish the influence of individual and

Table 2
Density and mechanical properties of Al – Mg based cast alloys containing various levels of impurity elements

Alloy No	Density, porosity and mechanical properties															
	ρ_T, g/sm^3	Die casting					High-pressure die casting					Gas isostatic pressing				
		ρ_E, g/sm^3	Pores, %	σ, MPa	$\sigma_{0.2}$, MPa	δ, %	ρ_E, g/sm^3	Pores, %	σ, MPa	$\sigma_{0.2}$, MPa	δ, %	ρ_E, g/sm^3	Pores, %	σ, MPa	$\sigma_{0.2}$, MPa	δ, %
1	2.653	2.631	0.81	204	88	28	2.638	0.56	193	100	28	2.651	0.05	209	102	29
4	2.609	2.580	1.07	286	115	13	2.590	0.88	232	144	14	2.600	0	238	147	26
7	2.628	2.600	0.92	263	110	27	2.605	0.55	233	123	26	2.618	0	299	128	29
8	–	2.645	–	226	134	5	2.648	–	223	129	5	2.671	–	264	138	5
9	–	2.653	–	226	156	2	2.658	–	186	155	2	2.689	–	249	146	2

Table 3
Casting properties of industrial silumins and Al – 5Mg – Si alloys

Alloy	Fluidity, mm		Linear shrinkage, %	Hot tearing, mm	Tightness		
	rod	spiral			Heat treatment	Air pressure, MPa	Water pressure, MPa
AK7	340	760	1.0 – 1.2	3	–	3	5, fracture
AK5M2	330	730	1.2 – 1.3	8	–	3	5, fracture
AK5M7	–	–	0.9 – 1.1	10	–	2	–
AM5K	250	–	1.0 – 1.2	12	–	4	6, fracture

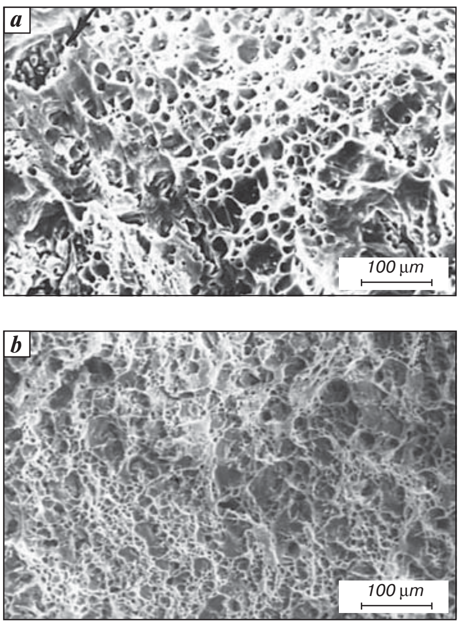

Fig. 3. SEM micrographs showing fractured surfaces of Al – Mg based alloy (a) before and (b) after isostatic pressing

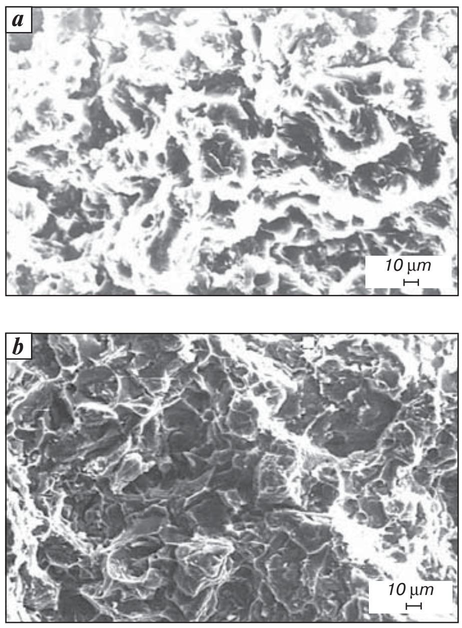

Fig. 4. SEM micrographs showing fractured surfaces of Al – Mg based a lloy with the highest impurity content (a) before and (b) after isostatic pressing

combined addition of impurities on the casting properties (fluidity, hot tearing, shrinkage and pre-shrinkage expansion), microstructural evolution and fracture behaviour of Al – Mg based alloys.

In recent years, adding Ca to Al – Mg alloys showed interesting results [17–19]. Calcium, like silicon, is a eutectic-forming element. It reduces weight, improves corrosion resistance, and also significantly increases the casting properties of Al – Mg alloys. In addition, it has been found that calcium binds iron and silicon to ternary interdendritic intermetallics, reducing their negative effect on the mechanical properties of alloys, as well as the negative effect of iron on corrosion resistance. This suggests the possibility of adding calcium in the process of melting secondary alloys in order to increase their casting properties, without a noticeable decrease in alloy mechanical properties.

Conclusions

The influence of impurity elements introduced separately and together on the casting properties and the structure of Al – Mg alloys has been investigated. The increased content of impurities in secondary (recycled) Al – Mg alloys is not an obstacle to their widespread use for industrial production. Although Si is the most harmful element in terms of alloy mechanical properties, it has the most favourable effect on the casting properties of secondary alloys. Negative influence of Si and Fe on mechanical properties and corrosion resistance of Al – Mg based alloys can be neutralized by the addition of Ca.

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