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Effect of cooling rate on the solidification behavior of magnesium alloys

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ABSTRACT

Purpose: The goal of this paper is to present the thermal characteristics of magnesium alloy using the novel Universal Metallurgical Simulator and Analyzer Platform.

Design/methodology/approach: The objective of this work is determine the liquidus, solidus temperature and beginning nucleation temperature to understanding crystallization of magnesium alloys.

Findings: The research show that the thermal analysis carried out on UMSA Technology Platform is an efficient tool for collect and calculate thermal parameters. The formation temperatures of various thermal parameters and hardness are shifting with an increasing cooling rate.

Research limitations/implications: This paper presents results for one alloy – MCMgAl12Zn1 only, cooled with three different solidifications rate i.e. 0.6, 1.2 and 2,4 °C/s, for assessment for the liquidus, solidus temperatures and describe a beginning of nucleation of α(Mg)-ß(Mg-$Mg_{17}Al_{12}$) eutectic and its influence on the mechanical properties. Further investigations should be concentrating on assessment an influence of different solidification rate on microstructure.

Practical implications: The parameters described can be applied in metal casting industry for selecting magnesium ingot preheating temperature for semi solid processing to achieve requirements properties.

Originality/value: The paper contributes to better understanding and recognition an influence of different solidification condition on non-equilibrium thermal parameters of magnesium alloys.

Keywords: Casting; MCMgAl12Zn1; Thermal analysis; UMSA

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MANUFACTURING AND PROCESSING OF ENGINEERING MATERIALS

1. Introduction

The density of magnesium alloy is lower than that of aluminum alloy, titanium alloy and other metals, therefore, it is mainly applied on 3C (computer, communication and consumer-electronics), bicycle and automobile industries. The use of magnesium alloy is making a car body could practically save fuel consumption [1,2]. Magnesium alloy components are usually produced by various casting processes. The most applicable methods are high-pressure die casting and gravity casting, particularly sand and permanent mold casting. Other relevant production technologies are: squeeze casting, thixocasting and thixomolding [3-5]. The designers strive for achieve a suitable a mechanical properties and knowledge about how cooling rate influences on solidification process and mechanical properties, it is very important.

The solidification sequence is influenced to a considerable extent by the presence of iron and manganese, which elements together with aluminum and silicon start to precipitate just after formation of the dendritic network. The sequence starts with development of a dendritic network around 590°C. In a binary alloy system Mg-Al, one should expect a final eutectic reaction involving precipitation of the $Mg_{17}Al_{12}$ phase to occur at 437°C. Based on Mg-Zn phase diagram, can be noted that Zn has a high solubility in magnesium, created a different phases like Mg_2Zn_3, $MgZn_2$ or Mg_2Zn_{11} [6]. Gödecke et al. [7] have shown by differential thermal analysis and metallographic observations that on cooling of a melt with eutectic concentration at usual cooling rates crystallization of stable mixture (Zn) + Mg_2Zn_{11} does not occur. Instead, crystallization of metastable mixture (Zn) + ($MgZn_2$) takes place. During the solidification process, zinc successively goes into solution and it is therefore difficult to asses a definite termination of the process. In research no trace of such a reaction has been detected by thermal analysis.

Backerud et al. [8, 9] identify reactions in Al-Mg alloys and based on these literatures is proposed following solidification sequence (Table 1).

Table 1.
Reactions occurring during the solidification of the MCMgAl12Zn1 based on literature [8, 9]

No	Reaction
1	Development of dendritic network
2	$L \rightarrow \alpha(Mg)$
3	$L \rightarrow \alpha(Mg)+Mg_2Si+(Al+Mn)$
4	$L \rightarrow \alpha(Mg)+\beta(Mg - Mg_{17}Al_{12})$

2. Experimental procedure

2.1. Material

The MCMgAl12Zn1 magnesium alloys used in the experiment was made in cooperation with the Faculty of Metallurgy and Materials Engineering of the Technical University of Ostrava and the CKD Motory plant, Hradec Kralove in the Czech Republic. The chemical composition of the investigated materials is given in Table 2. A casting cycle of alloys has been carried out in an induction crucible furnace using a protective salt bath Flux 12 equipped with two ceramic filters at the melting temperature of 750±10ºC, suitable for the manufactured material. In order to maintain a metallurgical purity of the melting metal, a refining with a neutral gas with the industrial name of Emgesalem Flux 12 has been carried out. To improve the quality of a metal surface a protective layer Alkon M62 has been applied. The material has been cast in dies with betonite binder because of its excellent sorption properties and shaped into plates of 250x150x25mm.

Table 2.
Average chemical composition (mass%) of the MCMgAl12Zn1 alloy

Al	Zn	Mn	Cu	Si	Fe
11.894	0.55	0.22	0.0064	0.05	0.02

2.2. Test sample

The experiments were performed using a pre-machined cylindrical test sample with a diameter of ϕ=18mm and length of l=20mm taken from the ingot. In order to assure high repeatability and reproducibility of the thermal data, the test sample mass was 9.3g within a very closely controlled range of ±0,1g. Each sample had a predrilled hole to accommodate a supersensitive K type thermocouple (with extra low thermal time constants) positioned at the center of the test sample to collect the thermal data and control the processing temperatures.

2.3. Thermal analysis and hardness test

The thermal analysis during melting and solidification cycles was carried out using the Universal Metallurgical Simulator and Analyzer (UMSA) [10,11]. The melting and solidification experiments for the MCMgAl12Zn1 alloy were carried out using Argon as cover gas. The data for Thermal Analysis (TA) was collected using a high-speed National Instruments data acquisition system linked to a personal computer. Each TA trial was repeated three times.

Liquidus, solidus and nucleation of eutectic temperatures were obtained based on cooling curve and its first derivative. The methodologies of calculations of these temperatures were described at [12-15].

The procedure comprised of the following steps. First, the test sample was heated to 700±2°C and isothermally kept at this temperature for a period of 90s in order to stabilize the melt conditions. Next, the test sample was solidified at cooling rate of approximately 0.6°C/s, that was equivalent to the solidification process under natural cooling conditions, 1.2°C/s and a 2.4°C/s average solidification rate. The Argon gas at 8bars pressure was used to cool the outer surface of the test sample to accelerate the solidification process.

Hardness tests were made using Zwick ZHR 4150 TK hardness tester in the HRF scale.

3. Results and discussions

The cooling curves recorded for MCMgAl12Zn1 alloy at various cooling rates are shown in figure 1. Two visible temperatures were observed on the cooling curves. More information about the liquidus and solidus temperatures and nucleation of eutectic were characterized based on the first derivative curves. Thermal analysis of magnesium alloy revealed that the solidify process of material cooled at 0.6°C/s (Figure 1, line a) started at 583.01± 9.18°C (point 1) and was completed at 420.07±2.97°C (point 3) where fraction solid obtained a 100%. Next change on the first derivative curve, at 432.55± 0.64°C was observed and corresponded to the nucleation of the α(Mg)-β(Mg-$Mg_{17}Al_{12}$) eutectic (Figure 1, point 2). Participation of fraction solid at this point obtained 80.7%.

The cooling curve for the MCMgAl12Zn1 alloy that solidified under a 1.2°C/s solidification rate is presented in Figure 1 (line b). Alloy started solidify at 582.4±1.98°C and finished at 414.03±3.84°C. The nucleation of the α(Mg)-β(Mg-$Mg_{17}Al_{12}$) eutectic was observed at 436.05±0.83°C.

The non-equilibrium liquidus temperature of MCMgAl12Zn1 alloy that solidified under a 2.4°C/s (Figure 1, line c) was found approximately at 592.28±4.64°C. A further decrease in the temperature resulted in nucleation of the α(Mg)-β(Mg-$Mg_{17}Al_{12}$) eutectic at 441.87±2.24°C. The solidification process finished approximately at 415.42±0.93°C when the fraction solid obtained a 100%.

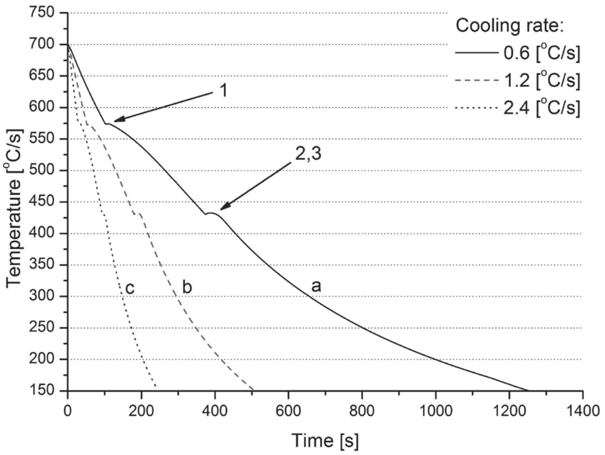

Fig. 1. Temperature vs. time curves of the MCMgAl12Zn1 alloy test samples recorded during solidification at 0.6°C/s (line a), 1.2°C/s (line b) and 2.4°C/s (line c). The numbers correspond to the various metallurgical reactions as presented in Table 3

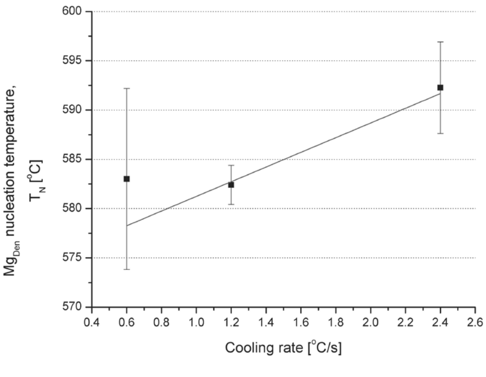

Fig. 2. Variation of the Mg_{Den} nucleation temperature as a function of cooling rate

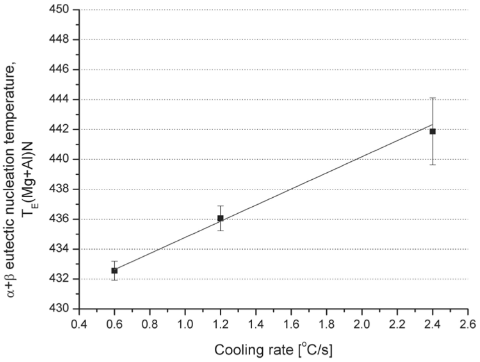

Fig. 3. Variation of the $\alpha+\beta$ eutectic nucleation temperature as a function of cooling rate

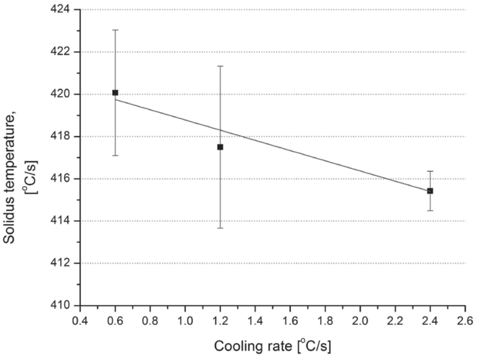

Fig. 4. Variation of the solidus temperature as a function of cooling rate

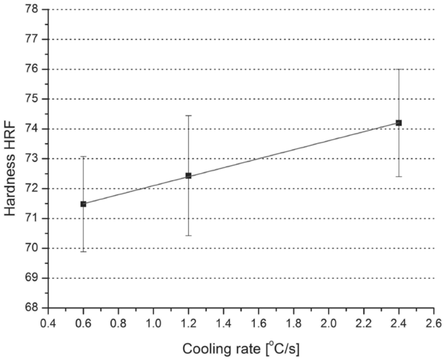

Fig. 5. Variations of the hardness as a function of the cooling rate

Figure 2-4 presents variations of the α-magnesium (Mg_{Den}) nucleation temperatures, $\alpha+\beta$ eutectic nucleation ($T_{E(Mg+Al)N}$) temperatures and solidus temperature as a function of cooling rate. (T_{Sol}). Liquidus temperature and beginning of nucleation of α(Mg)-β(Mg-$Mg_{17}Al_{12}$) eutectic increases with increase cooling rate. In opposite way is for solidus temperature. Increases a cooling rate cause's decreases of solidus temperature, results in widen the solidification range from 163°C to 177°C.

Table 3.
Non-equilibrium thermal characteristics of the MCMgAl12Zn1 alloy test samples obtained during the solidification process at 0.6°C/s, 1.2°C/s and 2.4°C/s solidification rates.

Points	Thermal characteristics	Solidification rates [°C/s]					
		0.6		1.2		2.4	
		Temp. [°C]	Fraction solid [%]	Temp. [°C]	Fraction solid [%]	Temp. [°C]	Fraction solid [%]
1	Nucleation of the α(Mg) (Liquidus temperature)	583.01± 9.18	0	582.4±1.98	0	592.28±4.64	0
2	Beginning of nucleation of α(Mg)-β(Mg-$Mg_{17}Al_{12}$) eutectic	432.55± 0.64	80.7±0.99	436.05±0.83	78.37±1.07	441.87±2.24	80.7±0.14
3	End of solidification process (Solidus temperature)	420.07±2.97	100	414.03±3.84	100	415.42±0.93	100

Mechanical properties of the magnesium alloys are strongly depended on cooling rate. The hardness grows with increment of the cooling rate. The hardness increases from 71.4±1.5HRF for lowest cooling rate to 74.5±1.8 HRF for highest cooling rate (Figure 5). Measuring errors occurred during testing did not exceed 5%.

4. Conclusions

The subject of the research is conducted with the evaluation of the influence of the crystallization cooling rate on the phase crystallization temperature and mechanical properties of MCMgAl12Zn1 alloy. The research show that the thermal analysis carried out on UMSA Technology Platform is an efficient tool for collect and calculates data about temperature and time of phase transformations, liquidus and solidus temperatures as well.

The results are summarized as follows:

1. Solidification parameters are affected by the cooling rate. The formation temperatures of various thermal parameters are shifting with an increasing cooling rate.
2. Increasing the cooling rate increases significantly the Mg nucleate temperature, α+β eutectic nucleation temperature and decreases the solidus temperature simultaneously widens a solidification range.
3. Increasing the cooling rate increases hardness of the material.

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