

# Thermal and mechanical characteristics of cast Mg-Al-Zn alloy

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## Abstract

This work presents effect of cooling rate on the grain size, mechanical properties and thermal characteristic results of MCMgAl9Zn1 cast alloy. The solidification process was studied using the cooling curve and crystallization curve at solidification rate ranging from 0.6°C/s up to 2.4°C/s. It was determined that the higher solidification rate increases the magnesium dendrite nucleation temperature. In addition, it was observed that the non-equilibrium solidus temperature and the grain size constituent decreases when the solidification rate increases.

**Keywords:** Magnesium alloy; UMSA; thermal analysis

## 1. Introduction

Magnesium is the lightest of all the engineering metals. It is 35% lighter than aluminum and over four times lighter than steel. Magnesium is the eighth most common element. It is produced through either the metallothermic reduction of magnesium oxide with silicon or the electrolysis of magnesium chloride melts from seawater. Each cubic metre of the sea water contains approximately 1.3 kg (0.3%) magnesium. Magnesium has a good ductility, better noise and vibration dampening characteristics than aluminum and excellent cast ability. Alloying magnesium with aluminum, manganese, rare earths, thorium, zinc or zirconium increases the strength to weight ratio making them important materials for applications where weight reduction is important, and where it is imperative to reduce inertial forces. Because of this property, denser material, not only steels, cast iron and copper base alloys, but even aluminum alloys are replaced by magnesium alloys. The requirement to reduce the weight of car components as a result of legislation limiting emission has created renewed interest in magnesium [1-7].

Generally near net shape parts can be produced by die-casting techniques. As a result of the high cooling rate experienced by the material that solidifies in a steel-die, the microstructure is characterized by the presence of non-equilibrium structures.

When the principal alloying element is aluminum, the main phases encountered are magnesium solid solution ( $\alpha$ -phase) both as homogeneous grains and separated by a divorced eutectic structure, formed together with the brittle  $Mg_{17}Al_{12}$  intermetallic phase. Thermal treatments are sometimes performed in order to modify this microstructure, and to achieve increased stability to medium service temperature. It is useful to remind that maximum service temperature for such magnesium alloys is of about 120°C, that correspond to about 0.4-0.5T<sub>m</sub>, a rather high homologous temperature. In order to predict adequately the effect of thermal treating or of maintenance at high temperature on the alloy properties, a better understanding of the kinetic aspects of the transformations occurring is needed.

Thermal analyses are widely used for several thermodynamic evaluations of chemical and physical reactions, mainly of inorganic and organic materials. In the field of metallurgy, several authors have used thermal techniques for the evaluation of

precipitation processes, recrystallization, phase transformation, and even for deriving CCT diagrams [8-11].

Thermal analysis comprises a group of techniques in which a physical property of a substance is measured as a function of temperature, while the substance is subjected to a controlled temperature programme [12-15].

This work presents a methodology to determine the thermal characteristics of magnesium alloy based on customized UMSA computer controlled rapid solidification experiments [16].

## 2. Experimental procedure

### 2.1. Material

The investigations have been carried out on MCMgAl9Zn1 experimental magnesium alloys in as-cast 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 1. 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  $750\pm 10^\circ\text{C}$ , 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  $250\times 150\times 25$ .

Table 1.

Average chemical composition (wt%) of the MCMgAl9Zn1 alloy

Al	Zn	Mn	Cu	Si	Fe
9.399	0.84	0.24	0.0018	0.035	0.007

### 2.2. Test sample

The experiments were performed using a pre-machined cylindrical test sample with a diameter of  $\phi=18\text{mm}$  and length of  $l=20\text{mm}$  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  $\pm 0.1\text{g}$ . 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 (Figure 1).

### 2.3. Thermal analysis

The thermal analysis during melting and solidification cycles was carried out using the Universal Metallurgical Simulator and Analyzer (UMSA) [16]. The melting and solidification experiments for magnesium 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.

The procedure comprised of the following steps. First, the test sample was heated to  $700\pm 2^\circ\text{C}$  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  $0.6^\circ\text{C/s}$ , that was equivalent to the solidification process under natural cooling conditions, and a  $2.4^\circ\text{C/s}$  average solidification rate. The Argon gas at 8bars pressure and at a flow rate of up to 125LPM (Liters Per Minute) was used to cool the outer surface of the test sample to accelerate the solidification process.

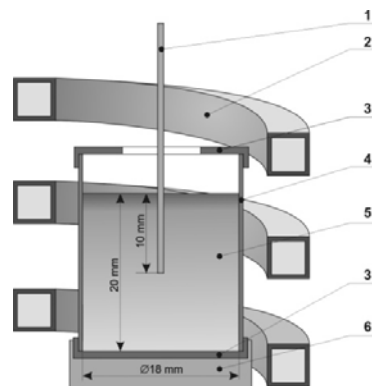


Fig. 1. Scheme of the UMSA Thermal Analysis Platform experimental set-up: 1 – low thermal mass thermocouple, 2 – heating and cooling coil, 3 – thermal insulation, 4 – steel foil, 5 – test sample, 6 – ceramic base.

## 3. Results and discussions

Figure 2 shows the variation of the magnesium nucleation temperature as a function of cooling rate and the variation of the Mg nucleation undercooling temperature. Standard errors calculated for each measured data point have also been included in the graph. It is evidence from the plot, that the Mg nucleation temperature increase with increase cooling rate from 0.6 to  $2.4^\circ\text{C/s}$ , the Mg nucleation temperature increases from  $597.97\pm 5.1^\circ\text{C}$  to  $600.89\pm 3.36^\circ\text{C}$ . Increasing the cooling rate increases the heat extraction. Due to the increase the cooling rate the nucleation undercooling increase.

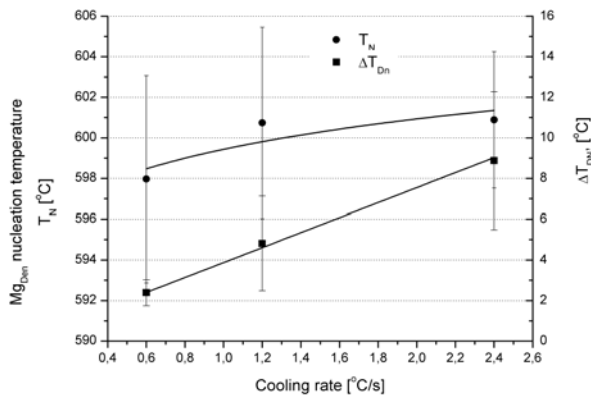


Fig. 2. Variation of the Mg nucleate temperature as a function of cooling rate and variation of the Mg nucleate undercooling temperature as a function of cooling rate

The variation of grain size has been showed graphically in Figure 3. Grain size is strictly depending on the cooling rate. For the sample that was cooled with lowest cooling rate, the grain size is approximately  $143.53 \pm 23.12 \mu\text{m}$ . In the highest cooling rate, the grain size is approximately  $66.73 \pm 11.22 \mu\text{m}$ .

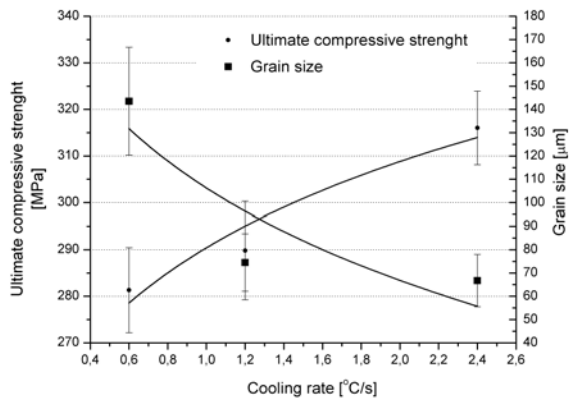


Fig. 3. Variation of the grain size and ultimate compressive strength as a function of cooling rate

Mechanical properties of the magnesium alloy are strongly dependent on the effect of grain size. Ultimate compressive strength increases with a decrease the grain size. Investigations results shows, the increase the cooling rate from  $0.6^\circ\text{C/s}$  to  $2.4^\circ\text{C/s}$  influence on the reduction of the grain size, what have influence on the ultimate compressive strength. The ultimate compressive strength increase from  $281.31 \pm 9.12 \text{ MPa}$  for lowest cooling rate to  $316.04 \pm 7.89 \text{ MPa}$  for highest cooling rate (Figure 3).

Figure 4 presents a variation of the solidus temperature as a function of cooling rate and variation of the  $\alpha+\beta$  eutectic nucleation temperature as a function of cooling rate

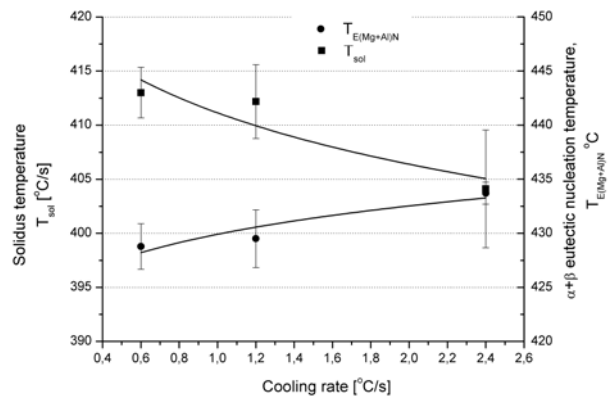


Fig. 4. Variation of the solidus temperature as a function of cooling rate and variation of the  $\alpha+\beta$  eutectic nucleation temperature as a function of cooling rate

The  $\alpha+\beta$  eutectic nucleation temperature increase with increase cooling rate from  $0.6$  to  $2.4^\circ\text{C/s}$ , the  $\alpha+\beta$  eutectic nucleation temperature increases from approximately  $428.78 \pm 2.1$  to  $433.71 \pm 1.2^\circ\text{C}$ . Due to the increase of the cooling rate the solidus temperatures decrease. When the cooling rate is increased, the solidification temperature is decreased from  $413.01 \pm 2.34^\circ\text{C}$  for the  $0.6^\circ\text{C/s}$  cooling rate to  $404.11 \pm 5.43^\circ\text{C}$  for  $2.4^\circ\text{C/s}$  cooling rate.

The temperatures of metallurgical reactions are presented in Table 2.

Figure 5 presents a variation of the hardness as a function of cooling rate. The hardness grows with increment of the cooling rate. The hardness increases from  $57.29 \pm 0.83 \text{ HRF}$  for lowest cooling rate to  $64.94 \pm 1.58 \text{ HRF}$  for highest cooling rate. Measuring errors occurred during testing did not exceed 5%.

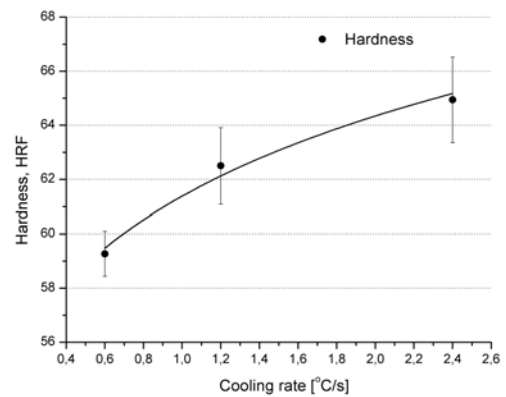


Fig. 5. Variation of the hardness as a function of cooling rate

## 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 in  $\text{MCMgAl9Zn1}$  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 phases are changed with an increasing cooling rate.

2. Increasing the cooling rate increases significantly the Mg nucleate temperature, nucleation undercooling temperature, solidification range.
3. Mechanical properties of the magnesium alloy are strongly dependent on the effect of grain size. Ultimate compressive strength and hardness increases with a decrease the grain size.

Table 2.

Non-equilibrium thermal characteristics of the MC MgAl9Zn1 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 $\alpha$ (Mg) (Liquidus temperature)	597.97±5.1	0	600.74±4.72	0	600.89±3.36	0
2	Beginning of nucleation of $\alpha$ (Mg)- $\beta$ (Mg-Mg <sub>17</sub> Al <sub>12</sub> ) eutectic	428.78±2.1	89.25±0.55	429.5±2.67	88,12±0.57	433.71±1.02	87.04±0.33
3	End of solidification process	413.01±2.34	100	412.19±3.41	100	404.11±5.43	100

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