

## SOLIDIFICATION OF THE Al ALLOY COMPOSITE REINFORCED WITH GRAPHITE PARTICLES

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Preliminary Note – Prethodno priopćenje

The aim of the work was to analyse the solidification of the Al matrix composite reinforced with graphite particles and to determine the influence of these particles on the solidification kinetics of metal composites. The AlMg10 alloy was used as the matrix of the tested composites. The tests covered composites containing 10 %, 20 %, 30 % graphite particles, produced in a two-stage process with the method of mechanical mixing. Solidification tests were performed by the thermal derivative analysis method (ATD). The introduction of ceramic particles into the matrix changed the solidification kinetics of the alloy.

*Keywords:* AlMg10 matrix composites, solidification, graphite, ceramic, ATD method

### INTRODUCTION

The set of favourable physical properties of aluminium alloys (low density, high thermal and electrical conductivity, high corrosion resistance) and good technological properties allow them to be widely used in technology. Both foundry and wrought aluminium alloys, despite a number of favourable properties, have a number of disadvantages that cannot be eliminated by traditional manufacturing processes and their heat treatment. The disadvantages of aluminium alloys include, among others, low hardness and low abrasion resistance [1]. One of the ways to improve the mechanical properties of aluminium alloys is to reinforce them with ceramic particles [2].

Properties of metal composites reinforced with ceramic particles depend not only on the characteristics of the introduced particles, but also on their volume share and distribution in the matrix [3,4]. The distribution is largely determined by the interaction of particles with the crystallization front and the processes of wetting ceramics by liquid metal [5-8].

When the particles are wetted, it is possible to nucleate the crystalline phase on the surface of the particles, otherwise the reinforcement is most often forced out of the crystallization front. It is determined by the extreme contact angle that allows heterogeneous nucleation, which is 120°. Below this value, the particles become the site of crystal nucleation. It is also favoured by the possibility of adsorption of alloying element atoms on the ceramic surface, which in turn leads to the formation of

transition layers that retain their structure even after the composite has been remelted. This is evidenced by, among others Al particle suspension stability  $A_2O_3$  and SiC in aluminium and the possibility of remelting the composite several times. These two crystallization mechanisms are largely determined by the speed of crystallization. In the case of high crystallization speed, the particles are evenly distributed in the matrix, without any clear segregation of the reinforcement in the composite. When the solidification time is extended, regions without reinforcing phase or gradients in the distribution of particles in the matrix are formed. There is a critical crystallization rate above which the particles in the liquid matrix are absorbed by the crystallization front, while at lower crystallization rates the ceramic particles are repelled. We calculate the critical speed from the formula [1]:

$$V_k = 2(n = 1) \left[ \left( \frac{LVDa}{kT} \right) \cdot \left( \frac{1}{d^2} \right) \right] \quad (1)$$

where:

- n - constant, amounting to 4 - 5,
- L - heat of crystallization,
- a - constant equal to  $10^{-8}$  cm,
- V - atomic volume of the matrix metal,
- D - diffusion coefficient,
- k - Boltzman's constant,
- T - matrix solidification temperature,
- d - particle diameter;

The force of interaction between the particle and the crystallization front depends on the particle size, surface tensions at the interface and the molecular diameter of the matrix material. The resistance force, on the other hand, depends on the dynamic viscosity, the proportion of particles, their diameter and the distance of the particle from the crystallization front [2,9,10].

The introduction of ceramic particles into the liquid metal increases its viscosity, and thus reduces the

M. Łągiewka (lagiewka.malgorzata@wip.pcz.pl), C. Kolmasiak, Czestochowa University of Technology, Faculty of Production Engineering and Materials Technology, Czestochowa, Poland

castability. According to Surappa [11], the castability decreases with the increase of the total surface area of S particles in the unit volume of the alloy. For this reason, the introduction of ceramic particles from the liquid matrix may make it impossible to cast such a suspension, therefore the technological process covers only the production of ingots, from which then finished products are produced by means of liquid-solid pressing or rolling and hot forging [2].

The structure of the composite, as well as the distribution of particles in the matrix, are primarily shaped by the solidification process, which can be divided into:

- pouring period
- crystallization period

During the pouring period, the properties of the liquid phase (viscosity, fluidity) and the phenomena of sedimentation or particle outflow are of decisive importance, affecting both the possibility of obtaining castings and the distribution of particles in the matrix. Lowering the viscosity of the composite alloy and increasing its castability is possible only by increasing the casting temperature.

One of the most important issues in shaping the structure of composites obtained by mixing is that the suspension of ceramic particles in the liquid alloy retains its initial uniformity after the matrix has passed into the solid state.

The aim of the presented research results is to analyse the solidification of the Al matrix composite, in which the reinforcement was made of graphite particles, and to determine the influence of these particles on the solidification kinetics of metal composites.

## METHODOLOGY AND RESEARCH MATERIAL

The AlMg10 alloy was used as the matrix of the tested composites. This alloy has very good physical (low density), chemical (high corrosion resistance) and

also mechanical properties. The graphite with a carbon content of 99,5 - 99,9 % was used as reinforcement.

AlMg10 based composites containing 10 %, 20 %, 30 % graphite particles were produced in a two-stage process by mechanical mixing. The metal was melted in an induction crucible furnace and heated to a temperature of 953 K. Due to the high oxidation of the matrix alloy, the process was carried out under argon. The next stage was the introduction of C reinforcing particles  $C_{gr}$  into the liquid melt using a dosing chute. Mixing was performed with a propeller agitator, which was placed in 1/3 of the liquid level from the bottom in the crucible axis [11]. The composite manufacturing parameters were established on the basis of many previous studies. The mixing speed was 500 rpm and the mixing time was 5 minutes. After each melt, metallographic specimens were made of the cast samples. Solidification tests were performed by the thermal derivative analysis method (ATD).

## RESULTS OF RESEARCHES

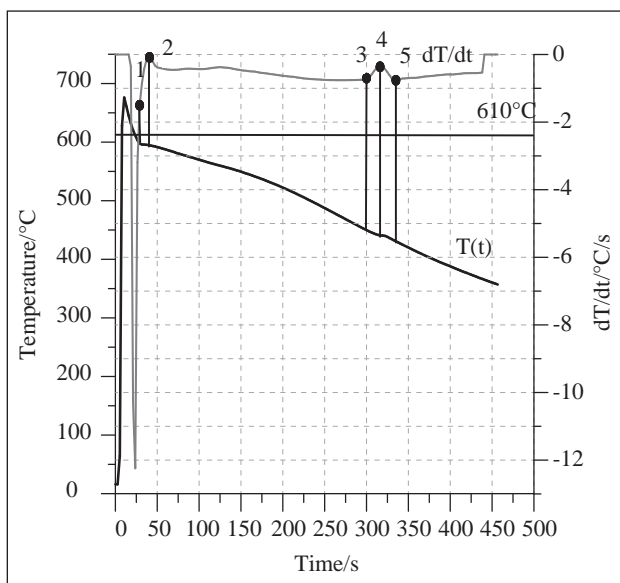
Figures 1 - 4 show exemplary cooling  $T(t)$  and solidification ( $dT/dt$ ) curves of the AlMg10 alloy.

Quantities read from the chart:

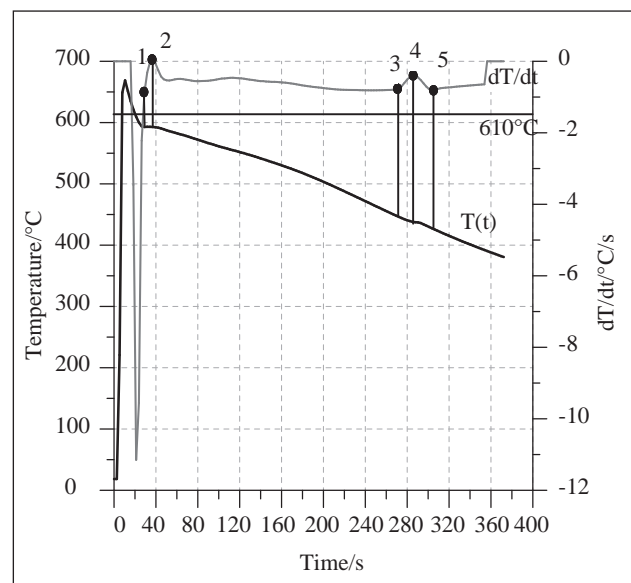
- 1 The temperature of the onset of solidification of the  $\alpha$  phase
- 2 Temperature at which maximum subcooling of the alloy occurs
- 3 Eutectic solidification begins  $\alpha + \beta$
- 4 The mean solidification point of the eutectic  $\alpha + \beta$
- 5 Solidus temperature.

Figure 1 shows the cooling and solidification curves of the composite based on the AlMg10 + 10 %  $C_{gr}$  alloy matrix.

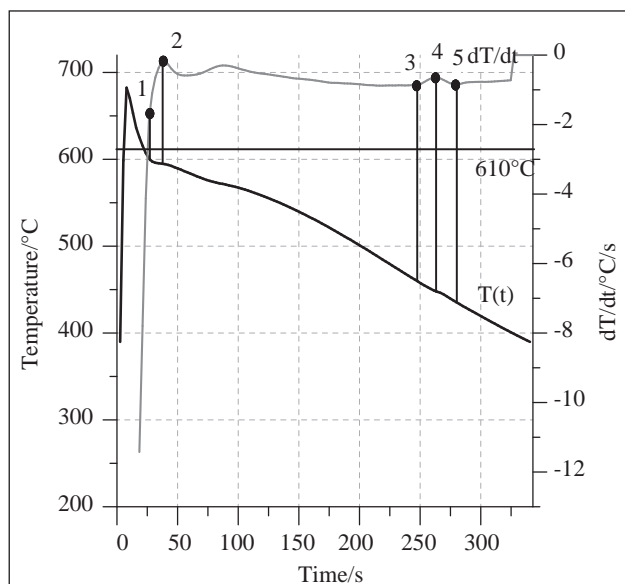
Figure 2 shows the cooling and solidification curves of the composite based on the AlMg10 + 20 %  $C_{gr}$  alloy matrix.



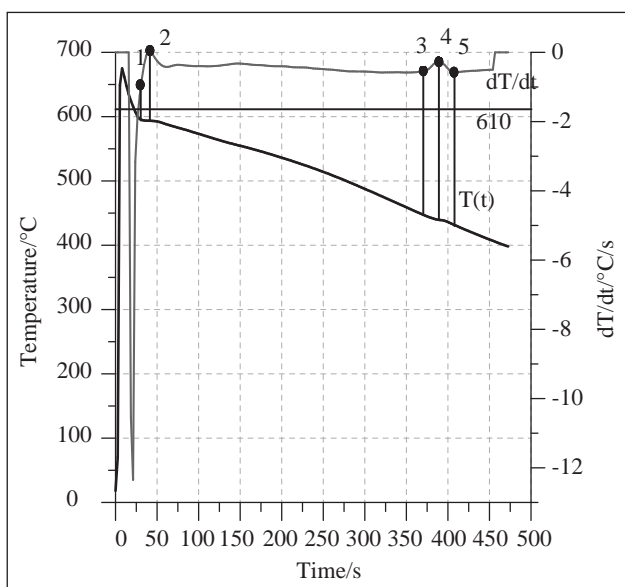
**Figure 1** The cooling and solidification curve of the AlMg10 + 10 %  $C_{gr}$  composite.



**Figure 2** The cooling and solidification curve of the AlMg10 + 20 %  $C_{gr}$  composite.



**Figure 3** The curve of cooling and solidification of the composite AlMg10 + 30 % Cgr.



**Figure 4** Composite matrix cooling and solidification curve - AlMg10 alloy.

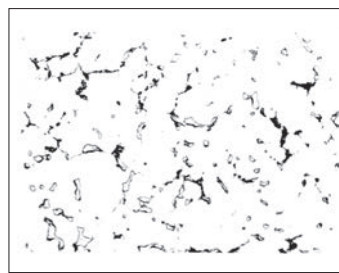
Figure 3 shows the cooling and solidification curves of the composite based on the AlMg10 + 30 %  $C_{gr}$  alloy matrix.

Figure 4 shows the cooling and solidification curves of the composite matrix - AlMg10 alloy.

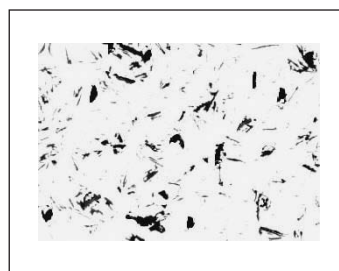
The matrix alloy microstructure and an exemplary composite microstructure are shown in Figure 5 and 6.

Fragmentation of graphite particles, which occurred during mixing of the liquid suspension, was observed on the microstructures representing the composites. The microstructures show an even distribution of graphite particles in the matrix volume, which proves their good wetting by the AlMg10 alloy under selected test conditions.

The conducted tests of the solidification process by the ATD method allowed to determine the change of temperature of individual phase transformations and kinetic



**Figure 5** AlMg10 alloy microstructure, 200 x



**Figure 6** Alloy matrix composite AlMg10 + 10 % Cgr, 100 x

parameters for the tested composites and to compare them with the data obtained from the test using the same method of a pure matrix alloy without ceramic particles (AlMg10). It was found that the presence of particles in the solidifying matrix significantly influences the solidification process. The introduction of ceramic particles into the matrix resulted in a change in the solidification kinetics as a result of the interaction of two factors:

- reduction of the mass of the solidifying metal in relation to the pure matrix due to the proportion of ceramic particles ( $C_{gr}$ ) in the volume of the composite, i.e. the total amount of the heat of solidification,
- increase in heat flow resistance to particles  $C_{gr}$  ( $\lambda_{C_{gr}} < \lambda_{AlMg}$ )

The first factor shortens the solidification time and is dominant at low solidification rates, e.g. in the ATD sampler. The second factor may play a role in very fast clotting and will then act opposite to the first. Comparing the obtained data presented in the graphs (Figure 1 - 4) a shorter time alloy solidification after the introduction of particles  $C_{gr}$  is noticed, in relation to the solidification time of the matrix itself. The value of the solidification time for individual composites was as follows:

In addition, a higher temperature was observed of the commencement of solidification of the composites in relation to the solidification temperature of the matrix alloy.

The reason for the discrepancy in the results is also the differences in the amount of released heat of solidification ( $L$ ) of the matrix and composites. The values of the heat of solidification for individual composites were calculated from the dependence (2) F. Stręka [11]. However, this dependence does not take into account the heat of accumulation that is released in the freezing temperature range.

Table 1 The solidification time of the tested materials

	AlMg10	AlMg10+10 %	AlMg10+20 %	AlMg10+30 %
Time/s	445	437	420	415

Table 2 The temperature of the beginning of solidification of the tested materials

	AlMg10	AlMg10+10 %	AlMg10+20 %	AlMg10+30 %
Temp/°C	590	594	595	599

$$L_{c(r)} = L(1 - V_{pm}) \quad (2)$$

where: L - solidification heat of the metal matrix,  $V_{pm}$  - mass fraction of particles

$$L_{AlMg10} = 380 \cdot 10^3 \text{ J/kg}$$

The calculated amount of released heat of solidification of the tested composites is:

$$\text{for AlMg10+10 \%}, L_{c(r)} = 342 \cdot 10^3 \text{ J/kg}$$

$$\text{for AlMg10+20 \%}, L_{c(r)} = 304 \cdot 10^3 \text{ J/kg}$$

$$\text{for AlMg10+30 \%}, L_{c(r)} = 266 \cdot 10^3 \text{ J/kg}$$

The above calculations show that the heat of solidification (L) of the tested composites changes depending on the number of particles present in it. The more particles, the less heat of solidification is released.

## SUMMARY

- 1 Introduction to the liquid alloy of reinforcing graphite particles  $C_{gr}$  caused significant changes in the coagulation kinetics of the tested composites. The enrichment of the AlMg10 alloy with graphite particles significantly shortened the solidification time (from 8 s with 10% share of  $C_{gr}$  - up to 30s with 30 % share of  $C_{gr}$ ).
- 2 The introduction of graphite particles into the metal matrix resulted in an increase in the composite solidification onset temperature along with the increase in the percentage of particles in the composite.
- 3 The variable percentage of graphite content in the tested composites significantly influenced the amount of released heat of solidification. As the amount of

graphite increased, the composite released less energy, reducing the amount of solidification heat released from  $342 \cdot 10^3 \text{ J/kg}$  with a 10 % share of  $C_{gr}$  - to  $266 \cdot 10^3 \text{ J/kg}$  with a 30 % share of  $C_{gr}$ .

- 4 The applied method of producing composites consisting in introducing particles into a mechanically mixed alloy had a very positive effect on the distribution of particles in the matrix of the composite.

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**Note:** The professional translator for English language is Dogadamycie Sp zo.o., Agnieszka Chmielewska, Koszalin, Poland