Temperature interval determination for the performing local squeezing casting process on the AlSi10Mg alloy castings

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Abstract

The temperature interval for the performing local squeezing casting process has been established with the aim of the hot spot elimination, i.e. potential place of the shrinkage cavity occuring in the AlSi10Mg alloy casting. The local squeezing process temperature has been determined on the base of preliminary examinations of the AlSi10Mg alloy, whereby the temperature intervals and the relevant temperature of the significant phase precipitations have been established, as well as prediction of the place of shrinkage cavity occurrence based on the numerical simulation of the pouring and casting solidification. The influence of variation of process temperature on the density, i.e. soundness (compactness) of AlSi10Mg alloy castings has resulted in temperature interval determination.

Key words: AlSi10Mg, thermal analysis, numerical simulation, local squeezing process, density

1. Introduction

The tendency of secondary raw materials application, which beneath the low price has wide tolerances for the impurity elements, occurs. An alloy composition will influence the relative quantities of each of the solidification reaction products in Al-Si alloys, as well as the reaction temperatures. During solidification of here-investigated commercial hypoeutectic AlSi10Mg alloy, the following reactions may occur (see in Table 1) [1].

The sequence of the solidification process can be recorded through thermal analysis. The corresponding phases precipitation and their feeding restriction can induce defect occurrence [2]. The defects can be predicted and analysed using the first derivative of the obtained cooling curve and confirmed through the microstructure observation [3].

However, technologies of die and gravity casting increase the number of highly functional castings, which have been characterized with the very complex geometry. Due to the different wall thickness in these castings, as well as the high solidification rates, premature interruption of feeding occurs. Impossibility of adequate feeding results in occurring of stand-alone solidification areas. These areas are characterized with the smallest cooling and solidification rate and with the volume defects such as shrinkage, micro- and macro porosity appearance.

Tendency of volume defects removal, as well as the high requirements for the quality and low product price led to the new production processes develop-

Table 1. Reactions occurring during the AlSi10Mg alloy solidification [1]

Reaction	Temperature (°C)
L → development of the dendrite network + $Al_{15}(MnFe)_3Si_2$	568
L → $\alpha_{Al} + \beta_{Si} + Al_5FeSi$	575
L → $\alpha_{Al} + \beta_{Si} + Mg_2Si + Al_8Mg_3FeSi_6$	554
L + $Mg_2Si + \beta_{Si}$ → Al + $Al_5Mg_8Si_6Cu_2$	529
L → $\alpha_{Al} + Al_2Cu + Al_5FeSi + \beta_{Si}$	525
L → $\alpha_{Al} + \beta_{Si} + Al_5Mg_8Si_6Cu_2$	507

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Table 2. Analysis of the chemical composition in mass.%, of test samples of an AlSi10Mg alloy cooled in different thermal analysis cups

Cooling	Element											
Sand mould	Al	Cr	Mg	Mn	Cu	Zn	Ti	Ni	Fe	Si	Ca	Pb
	88.7863	0.0512	0.3096	0.1273	0.0896	0.0416	0.0090	0.0274	0.7193	9.8236	0.0038	0.0080
Steel mould $d = 30$ mm	Al	Cr	Mg	Mn	Cu	Zn	Ti	Ni	Fe	Si	Ca	Pb
	88.7779	0.0483	0.3128	0.1177	0.0867	0.0417	0.0090	0.0259	0.6310	9.9339	0.0044	0.0075
Steel mould $d = 15$ mm	Al	Cr	Mg	Mn	Cu	Zn	Ti	Ni	Fe	Si	Ca	Pb
	88.7610	0.0448	0.2855	0.1130	0.0861	0.0422	0.0088	0.0254	0.6632	9.9459	0.0146	0.0067

ment. A new processes group has been developed, such as semi solid casting processes that indicate the high integrity die casting and squeeze casting processes [4]. One of the subtypes is local squeeze casting process, which was applied in this work for the volume defects removal. Local squeeze casting process enfolded the local squeezing of hot spot, e.g. potential place of shrinkage cavity forming.

2. Experimental

Preliminary investigations of chemical composition, with the simple thermal analysis, simultaneous thermal analysis of an AlSi10Mg alloy have been performed on the test samples poured in three cups with the different geometry and materials (sand mould, steel mould with $d = 30$ mm and steel mould with $d = 15$ mm) to achieve the different cooling rates.

Test sample was a casting in the form of two joined cubes with different dimensions. Mould was preheated on the work temperature, close to that in real casting terms ($\sim$ 350 ℃). Casting charge (m $\sim$ 0.5 kg) was melted in the corundum cup until the achieved temperature of $\sim$740 ℃. Briefly after melting, local squeezing casting process has been performed.

Local squeezing casting process experiment was obtained toward scheme illustrated on Fig. 1.

Temperature has been measured with the thermocouples NiCr-Ni (K type) and recorded during mould preheating and melt pouring, as well as during local squeezing process with the pin.

Local squeezing process has been obtained in the mushy state of an alloy. Applied force projects corresponding pressure within the casting that results in filling in the formed shrinkage cavity. The moment of performing the local squeezing process has been determined by monitoring of the temperature decrease with the thermocouple. Local squeezing process examinations have been performed in the temperature interval of 550–575 ℃.

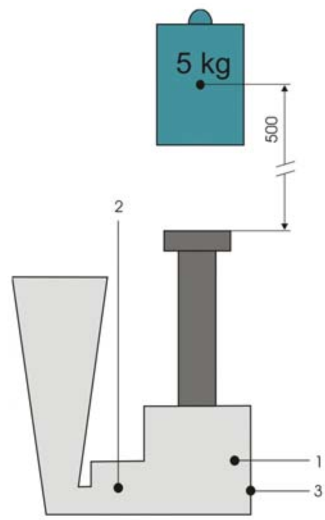

Fig. 1. Scheme of the experiment with marked positions of thermocouples. Thermocouples Nr: 1 – on the 7.5 mm distance from the edge of big cube, 2 – in the centre of the small cube, 3 – on the edge of the mould.

During local squeezing casting process the following parameters were variable: temperature and the time of the local squeezing process. Test samples density has been obtained on the base of the Archimedes law to establish the correlation between the local squeezing process and casting density.

3. Results and discussion

3.1. Chemical analysis

Chemical composition analysis has been performed on the test samples from the simple thermal analysis of an AlSi10Mg alloy. Average values of the chemical composition are shown in Table 2.

Results of chemical composition analysis do not differ from reference values.

Table 3. Significant temperatures obtained with the various thermal analysis methods

Cooling	Cooling rate ($K\,s^{-1}$)	T_N (℃)	$T_{L/max}$ (℃)	$T_{L/min}$ (℃)	dT_L (℃)	$T_{E/min}$ (℃)	$T_{E/max}$ (℃)	dT_E (℃)	T_S (℃)
Thermo-Calc	0.00	–	596.0	–	–	–	–	–	561.0
STA	0.17	–	586.0	–	–	560.0	–	–	557.0
Sand mould	4.40	640.5	586.5	582.3	4.2	563.5	566.3	2.8	542.8
Steel mould $d = 30$ mm	32.40	633.0	584.0	581.8	2.2	556.8	559.4	2.6	550.2
Steel mould $d = 15$ mm	↓ 96.00	–	582.5	580.3	2.2	554.2	556.7	1.8	531.0

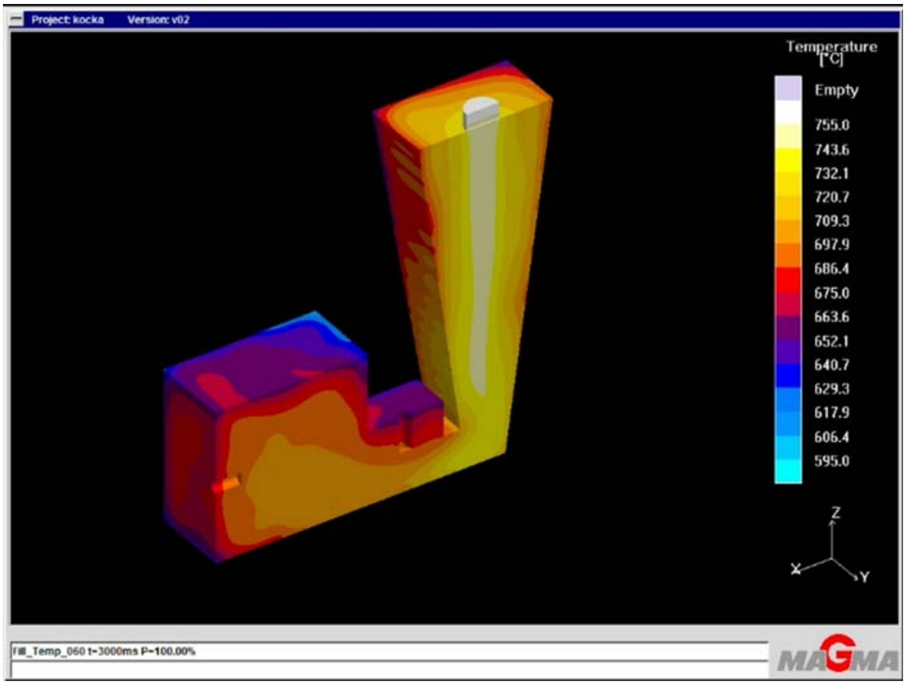

Fig. 2. Numerical simulation of solidification, casting intersection [5].

3.2. Thermal analysis

Average values of the nucleation temperature, maximum and minimum liquidus temperature, maximum and minimum eutectic temperature, as well as the solidification end temperature are shown in Table 3.

Equilibrium solidification with the cooling rate of $0\,K\,s^{-1}$ has been obtained with the Thermo-Calc software. Only liquidus temperature, T_L, and solidus temperature, T_S, were established at this cooling rate. Cooling with the rate of $0.17\,K\,s^{-1}$ has been obtained by the simultaneous thermal analysis (STA). Cooling with the rates of $4.4\,K\,s^{-1}$, $36.4\,K\,s^{-1}$ and $96\,K\,s^{-1}$ represented the simple thermal analysis examinations results.

Significant temperatures overview obtained by the various thermal analysis methods provided the decreasing trend of the liquidus temperature, T_L, solidus, T_S, and eutectic temperature, T_E, with the cooling rate increase. Temperatures overview shown in Table 3 indicates the temperature interval in which the squeezing process must be obtained. Temperature interval of the local squeezing process performing was 565–570 ℃. The lower temperature was determined above the average eutectic temperature in Table 3, and the upper temperature was chosen as a temperature below which the dendrite network was developed [1].

3.3. Numerical simulation of the pouring and solidification – MAGMASoft

Numerical simulation was performed with the MAGMASoft software [5].

Temperature area points out the hottest zone, by the colour scale on the predicted place of the shrinkage cavity occurrence, as it is shown on Fig. 2. Numerical simulation results show that the hottest zone freezes last, because of the premature feeding interruption, which brought to the shrinkage cavity occur-

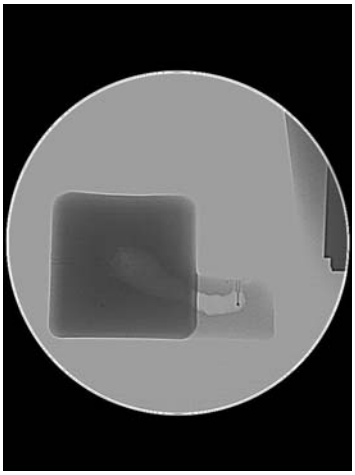

Fig. 3. X-ray examination of the casting.

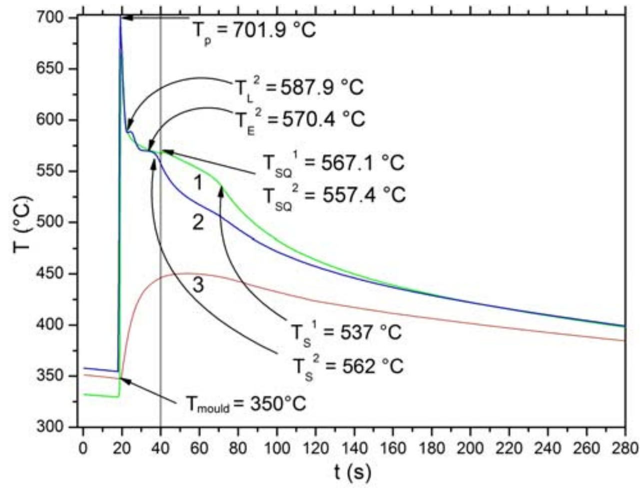

Fig. 4. Diagram of the cooling curves obtained in both cubes, with indicated moment of the local squeezing process performing. Diagram legend: 1 – big cube temperature, 2 – small cube temperature, 3 – mould temperature, 4 – moment of the local squeezing process performing.

rence. The local squeezing process performing should allow the slurry pressing into the shrinkage cavity occurred during the solidification process. Casting of the test sample has been technologically prepared without extra feeders. The brief neck of the gating system does not allow the melt to chill. This is the reason why the feeding has not been interrupted because the gating system has undertaken the role of the feeder. This brought to the withdrawal of the hottest zone toward the feeder.

Solidification simulation has shown that the latest solidificated area is placed inside the big cube (Fig. 2). It has been predicted that position of the hot spot moved due to the high metallostatic pressure, which pushed that area toward the opposite side of the casting in relation to the gating system. Experimental results indicate elongation of the hot spot through both cubes. Irregularity of the experimental results and results obtained by the numerical simulation has occurred due to directed solidification. Numerical simulation results indicate the temperature interval 565 ℃ $< T_{\mathrm{SQ}} <$ 570 ℃ in which the local squeezing process should be obtained.

3.4. X-ray examination

X-ray examination of the sample without performed local squeezing process indicated shrinkage cavity occurring, which had been elongated through the both cubes, shown on Fig. 3. This was imputed to the shrinkage solidification.

3.5. Local squeezing process

During local squeezing process the temperature decrease during cooling has been established after the pouring and local squeezing process performance. The example of the local squeezing process performance is shown on Fig. 4. The melt temperature measured in the furnace was ∼ 740 ℃. The maximum registered temperature in the mould cavity at the beginning of pouring was T_{p} = 701.9 ℃. Significant temperature decrease of ∼ 100 ℃ occurred during casting, due to the heat extraction toward mould, preheated on the 350 ℃.

During cooling and solidification between the mould and the casting an empty space has occurred and the separation of the formed casting shell from the mould has been obtained, which resulted in cooling rate decrease. The pin impact during local squeezing process has been evolved; the casting shell again lies on the mould surface, after which the thermal flux has been established again, and the cooling rate increased rapidly, as shown on the cooling curve. Temperature measured inside the big cube was T_{SQ}^1 = 567.1 ℃. On the small cube this impact had the insignificant influence, which was reflected as a smaller temperature decrease. Temperature registered in the central part of the small cube was T_{SQ}^2 = 557.4 ℃. At the mould edge no changes were noticed in the moment of the local squeezing process performing.

The slot depth that occurred by the pin impact during the local squeezing process performing varied from $1 < h < 15$ (mm).

Correlation between the slot depth from the pin indent, h, and the temperature of the local squeezing process, T_{SQ}, has been examined, and graphically presented on Fig. 5.

Equation (1) shows expected good correlation between the slot depth, h, and local squeezing temperature, T_{SQ}:

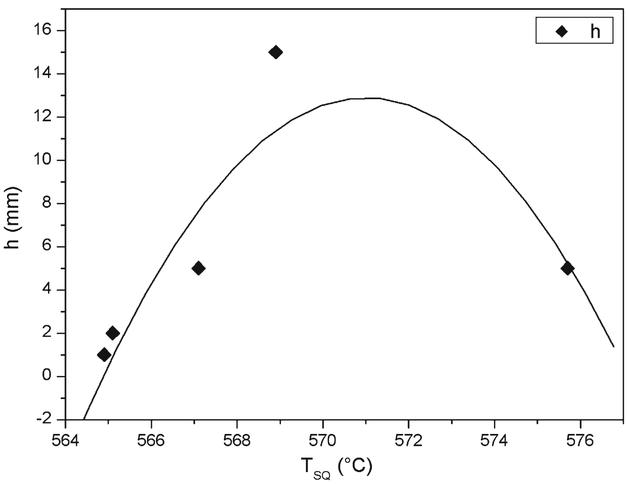

Fig. 5. Diagram of the slot depth, h, versus local squeezing process temperature, T_{SQ}.

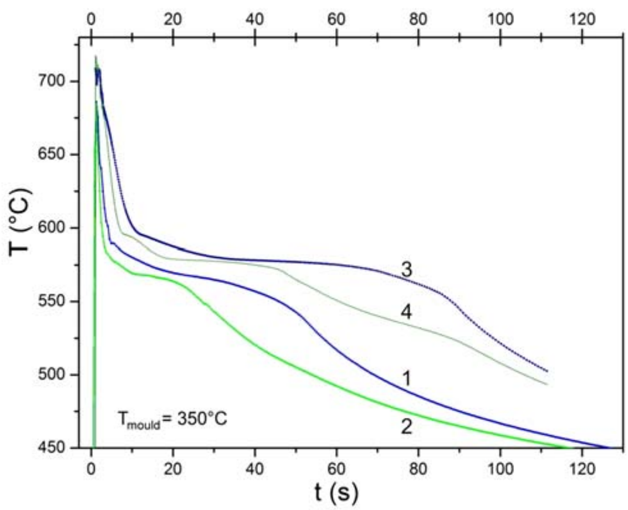

Fig. 6. Cooling curves obtained by the numerical simulation and by the experiment. Diagram legend: 1 – cooling curve of the big cube obtained by the numerical simulation, 2 – cooling curve of the small cube obtained by the numerical simulation, 3 – cooling curve of the big cube obtained by the experiment, 4 – cooling curve of the small cube obtained by the experiment.

$$h = -11219.81 + 393.11 \cdot T_{SQ} - 0.34 \cdot T_{SQ}^2,$$
$$R^2 = 0.76, \tag{1}$$

where R is a correlation coefficient.

Higher local squeezing temperature implicates less developed dendrite network, which allows inmost penetration of pin.

Comparison of the cooling curves obtained by the numerical simulation of pouring and solidification of both cubes and real cooling curves without the performed local squeezing process is shown on Fig. 6. Due to those curves it was possible to establish the time interval in which the local squeezing process should be obtained. The local squeezing process should be performed within the 60 s from the end of pouring. This time implicates solidification time before eutectic reaction.

Table 4. Data obtained by the local squeezing process: temperature registered during local squeezing process performing on the determined places in the casting, slot depth occurred by the pin impact and the casting density

Sample	T_{SQ}^1 (°C)	h (mm)	ρ_o (g cm^{-3})	$\Delta\rho$ (g cm^{-3})
1	575.7	5	2.636	0.064
2	565.1	2	2.645	0.055
3	564.9	1	2.666	0.034
4	568.9	15	2.664	0.036
5	567.1	5	2.654	0.046

An irregularity occurred between the experimentally obtained curves and those obtained by the numerical simulation. Curve shapes were similar as well as the relation between the significant temperatures. Experimentally obtained curves moved toward lower temperature values. Consequently, the solidification times for the curves obtained by the numerical simulation were longer. The cause of those temperature changes in absolute values (liquidus, eutectic and solidus temperature) was in different cooling rates, which were related to the heat transfer coefficient between the mould and the casting, as well as to the heat conduction of the mould materials.

3.6. Density determination

Density determination was provided to establish the correlation between the local squeezing process and the density as a measure of the casting soundness (compactness) (Table 4). The density of the sample without local squeezing process was $\rho_o = 2.599\,\mathrm{g\,cm^{-3}}$. Difference between theoretical density ($\rho_t = 2.700\,\mathrm{g\,cm^{-3}}$, [6]) and real density of the sample without local squeezing process was $\Delta\rho = 0.101\,\mathrm{g\,cm^{-3}}$.

Exponential dependence of the difference between the theoretical density and real obtained casting density, $\Delta\rho$, and local squeezing temperature, T_{SQ}, and the slot depth from the pin indent, h, are shown on Fig. 7.

Specified correlation can be presented with the following Eqs. (2) and (3), respectively:

$$\Delta\rho - T_{SQ}, \quad \Delta\rho = 122.31 - 0.43 \cdot T_{SQ} + 3.79 \cdot e^{-4T_{SQ}^2},$$
$$R^2 = 0.54, \tag{2}$$

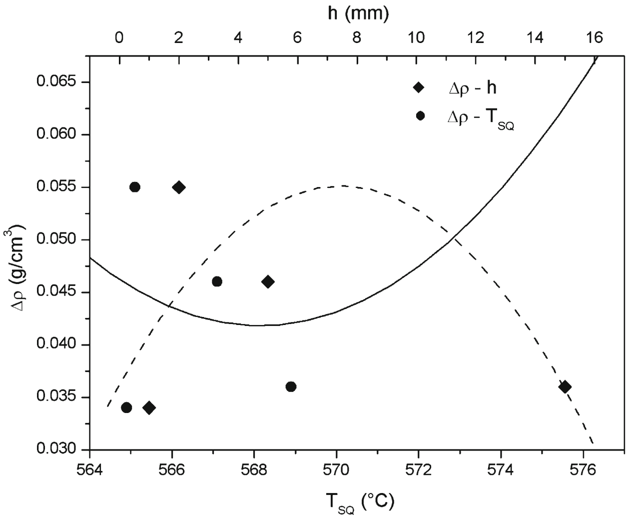

Fig. 7. Parallel overview of the difference between the theoretical density and real obtained casting density, $\Delta\rho$, versus local squeezing process temperature, T_{SQ}, and the slot depth, h.

$$\Delta\rho - h, \quad \Delta\rho = 0.036 + 0.0051 \cdot h - 3.4005 \cdot \mathrm{e}^{-4h^2}, \quad R^2 = 0.43. \tag{3}$$

An alloy should be in the mushy state during local squeezing casting in predicted temperature interval towards simple thermal analysis results. The best approach to the theoretical density value was provided in the temperature interval 565 ℃ $< T_{\mathrm{SQ}} <$ 570 ℃, in which the local squeezing process should be performed. This temperature interval falls in the area of dendrite network development [1], where the influence of the several intermetallic phases, which appear, can be excluded [2]. Outside this temperature interval the difference between the theoretical density and real casting acquires higher, not favourable values. Smaller density difference can indicate less present volume defects. Data dissipation was observed because of the central shrinkage movement toward the riser, whereby the local squeezing shrinkage filling became indirect, and caused smaller correlation factor obtained through the statistical modelling.

There is no significant correlation between the difference of the theoretical density and real obtained casting density, $\Delta\rho$, and the slot depth from the pin indent, h. Also bigger slot depth from the pin indent does not implicate smaller density difference due to other influenced variables.

Bigger correlation should be expected in the further examination with the greater data quantity.

4. Conclusion

The temperature interval of the performed local squeezing casting process has been established with the aim of the hot spot elimination, i.e. potential place of the shrinkage cavity in the AlSi10Mg alloy casting. The influence of variation of process temperature on the density, i.e. soundness (compactness) of AlSi10Mg alloy castings was obtained by the local squeezing process with the pin during gravity casting in the special permanent mould.

From the results obtained by the experimental examinations the following was established:

– As the cooling rate increases (4.4 K s^{-1}, 32.4 K s^{-1}, 96 K s^{-1}), temperatures of the phase transformations (liquidus, eutectic and solidus temperature) move toward the lower values.

– A hot spot, i.e. the place on which the shrinkage cavity occurs, as well as the porosity are established by the numerical simulation of the pouring and casting solidification in the central part of the casting.

– X-ray examination confirms the shrinkage cavity occurrence.

– Experimentally obtained shrinkage cavity position within the test sample is moved from the place predicted by the numerical simulation. This is a result of the complex way of heat extraction, as well as the lateral pouring, i.e. feeding of the casting.

– Experimentally obtained cooling curves are moved related to those obtained by the numerical simulation toward lower temperature values. Also, solidification times for the cooling curves obtained by the numerical simulation are longer.

– The local squeezing process of the AlSi10Mg alloy test samples should be performed in the temperature interval from the 565–570 ℃, in which the casting is in the mushy state.

– The smallest difference between the theoretical and real obtained density is determined in this temperature interval. Correlation of these parameters is rather small probably because of the central shrinkage cavity movement toward riser while the indirect filling of the cavity occurs.

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