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LOCAL SQUEEZING CASTING INFLUENCE ON THE COMPACTNESS OF AlSi10Mg ALLOY CASTINGS

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The aim of the local squeezing casting process examination has been to eliminate the hot spot i.e. the place of potential formation of shrinkage porosity. The influence of variation of process parameters on the density i.e. soundness (compactness) of AlSi10Mg alloy castings has been obtained by the local squeezing process with the pin during gravity casting in the special permanent mould. Local squeezing parameters have been determined on the basis of preliminary investigations of AlSi10Mg alloy: temperature intervals and relevant temperature of singular phases precipitation and the microstructure development at different cooling rates. The temperature interval of performing the local squeezing casting process have been established in which the density values approaching to the theoretic ones have been determined.

Key words: *Al-Si alloy, thermal analysis, microstructure development, local squeezing process, density, compactness*

Utjecaj postupka lokalnog tiskanja na kompaktnost odljevka od AlSi10Mg legure. U radu se ispitivao postupak lijevanja lokalnim tiskanjem s ciljem eliminiranja toplog čvorišta odnosno mjesta potencijalnog nastanka usahline. Postupkom lokalnog lijevanja trnom pri gravitacijskom lijevanju odljevka u specijalno izrađene kokile ispitan je utjecaj varijacije procesnih parametara na gustoću odnosno ispravnost (kompaktnost) odljevka od legure AlSi10Mg. Parametri lokalnog tiskanja određeni su na osnovi preliminarnih ispitivanja legure AlSi10Mg pri čemu su utvrđeni temperaturni intervali i relevantne temperature izlučivanja pojedinih faza, te razvoj mikrostrukture pri različitim brzinama hlađenja. Utvrđen je temperaturni interval izvođenja postupka lokalnog tiskanja u kojem je uočeno približavanje vrijednosti gustoće ispitnih uzoraka teorijskim vrijednostima.

Ključne riječi: *Al-Si legura, tolinska analiza, razvoj mikrostrukture, postupak lokalnog tiskanja, gustoća, kompaktnost*

INTRODUCTION

Casting solidification brings to the shrinkage in the liquid state, solidification shrinkage and shrinkage in the solid state. Recently, technologies of die and gravity casting have increased 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 have been characterized with the smallest cooling and solidification rate and with the volume defects such as shrinkage, micro- and macro porosity appearance.

AlSi10Mg alloy has been used for the acquiring thin wall castings of complex geometry production for the airplane, automotive, chemical and nutritional industry. During solidification of commercial hypoeutectic AlSi10Mg alloy, the following reactions would roll on as shown in Table 1. [1].

Also, the chemical composition can also, due to the corresponding phases precipitations and by restricting of feeding, induce defect occurring. There has been the tendency of the secondary raw materials application, which beneath the low price has wide tolerances for the impurity elements.

Since the mass iron concentration has been influenced the microstructure development, it can also influence the porosity share which appears in the castings due to the cooling rate. Cooling rate influences the time required for the ferrous intermetallic phases forming, which bring the kinetic of the reactions on the first place. At the gravity sand mould castings low cooling rates contributes the Al_5FeSi

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phase forming. High cooling rates, such as those from the high pressure die casting, suppresses (restricts) iron segregation in the Al_5FeSi form, while the $Al_{15}(Mn,Fe)_3Si_2$ form is favorable [2].

Table 1. **Reactions occurring during the AlSi10Mg alloy solidification [1]**
Tablica 1. **Reakcije koje se odvijaju tijekom skrućivanja legure AlSi10Mg [1]**

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

It has been claimed that Al_5FeSi plates physical blocks melt flow for interdenritic feeding, which results with increased porosity, [2]. It has been made and hypothesis that those phase serves as an efficient place for the pore nucleation as well as for the restricting of the pore growth, [2].

The quantifying method for casting porosity has been developed. Porosity has been represented by formulae:

$$\%P = (\text{solidification shrinkage porosity}) + (\text{gas porosity}) \qquad (1)$$

Which can be determined as, [3]:

$$\%P = \frac{\beta \cdot V^*}{V_C} + \left(\Phi \frac{T \cdot \rho \cdot L}{(237K) \cdot p}\right)(v - v^*). \qquad (2)$$

Tendency of volume defects removal, as well as the high requirements for the quality and low product price brought to the new production processes development. A new processes group is made of semi solid casting processes which enable the high integrity die casting and squeeze casting processes, [4]. One of the subtypes is the local squeeze casting process, which has been applied in this work for the volume defects removing. Local squeeze casting process enfolds the local squeezing of hot spot i.e. potential place of shrinkage forming.

EXPERIMENTAL

Researches were obtained in Foundry laboratory, Laboratory for heat treatment of Faculty of Natural Sciences and Engineering, University of Ljubljana. Preliminary examinations of chemical composition, with simple thermal analysis, simultaneous thermal analysis and optical microscopy of an AlSi10Mg alloy were performed on the test samples poured in three cups of different geometry and materials to achieve the different cooling rates and its influence on the microstructure.

Test sample was a casting in the form of two joined cubes of different dimensions. Mold was preheated on the work temperature, close to those in real casting terms (~350°C). Casting charge (m ~ 0,5 kg) were melted in the corundum cup until the temperature of ~740 °C achieving. After the melting, local squeezing casting process were obtained.

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

Temperature has been registered with the thermocouples NiCr-Ni (K typ), as shown on the Figure 1. Their works were monitored during mould preheating and melt pouring, as well as during local squeezing process with the pin.

Local squeezing process was performed on the center of the big cube upper surface by the pin impact. Applied force was obtained by the 5 kg weight falling from the 0,5m height.

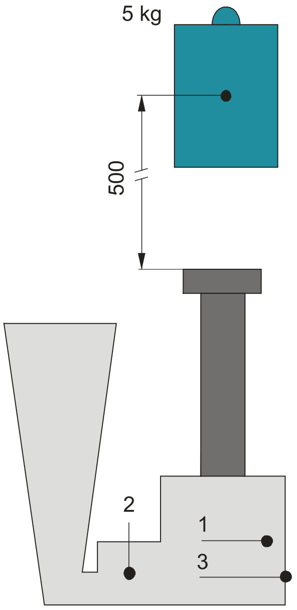

Figure 1. **Examination performing scheme with the determined, marked position of thermocouples. Thermocouples Nr.: 1 - on the 7,5 mm distance from the edge of big cube. 2 - in the centre of the small cube. 3 - on the edge of the mould**
Slika 1. **Shema izvođenja ispitivanja s označenim pozicijama termoelemenata. Termoelement broj: 1 - na udaljenosti od 7,5 mm od ruba velike kocke, 2 - u središtu male kocke, 3 - na rubu kokile**

The force measuring method with the strain gauge was applied “in situ”. Strain gauge was embedded on the pin, as shown on Figure 2.a, from which the registered impact has been transferred to the device and personal computer where the registered applied force curve has been obtained, as shown on Figure 2.b.

Strain gauge was preliminary calibrated on the force: weight with the mass of 5 kg corresponding the voltage of 0,145 V. Diagram on the Figure 3. illustrates measured force of 2339 N applied on the pin during weight falling at the local squeezing process.

Local squeezing process was obtained in the mushy state of an alloy. Applied force projects corresponding pressure within the casting which results in filling in of the formed shrinkage. The applying moment of the local

Figure 2. **Force measured with the strain gauge during weight falling on the pin. a) Strain gauge embedded on the pin. b) Device and the personal computer**

Slika 2. **Mjerenje sile kojom uteg padom djeluje na trn pomoću mjernog listića. a) Trn s ugrađenim mjernim listićem. b) Uređaj i osobno računalo**

squeezing process was determined by the monitoring of the temperature decreasing with the thermocouple Nr. 1.

Local squeezing process examinations were performed in the temperature interval from the 550 - 570 °C.

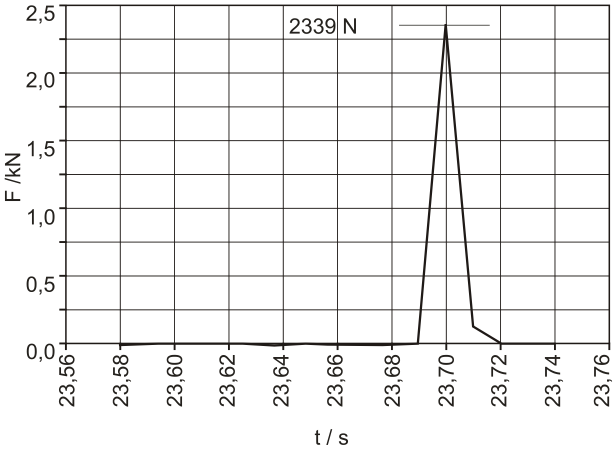

Figure 3. **Applied force value in the moment of pin impacting**

Slika 3. **Vrijednost sile primijenjene u trenutku udara utega u trn**

During local squeezing casting process the following parameters were examined: temperature and the time of the local squeezing process. Test samples density were obtained based on the Archimed's low to establish the correlation between the local squeezing process and density relatively casting soundness i.e. compactness.

RESULTS AND DISCUSSION

Chemical composition analysis was performed on the test samples from the simple thermal analysis of an AlSi10Mg alloy from the AMAG charge supplier. Average values of the chemical composition could be seen in the Table 2.:

Table 2. **Chemical composition analysis in mass % of the AlSi10Mg alloy test samples**

Tablica 2. **Kemijska analiza uzoraka AlSi10Mg legure u mas. %**

COOLING	ELEMENT						
Sand mould	Al	Cr	Mg	Mn	Sn	Cu	Zn
	88,7863	0,0512	0,3096	0,1273	0,0032	0,0896	0,0416
Steel mould d = 30 mm	Al	Cr	Mg	Mn	Sn	Cu	Zn
	88,7779	0,0483	0,3128	0,1177	0,0033	0,0867	0,0417
Steel mould d = 15 mm	Al	Cr	Mg	Mn	Sn	Cu	Zn
	88,7610	0,0448	0,2855	0,1130	0,0029	0,0861	0,0422
Sand mould	Ti	Ni	Fe	Si	Ca	Pb	
	0,0090	0,0274	0,7193	9,8236	0,0038	0,0080	
Steel mould d = 30 mm	Ti	Ni	Fe	Si	Ca	Pb	
	0,0090	0,0259	0,6310	9,9339	0,0044	0,0075	
Steel mould d = 15 mm	Ti	Ni	Fe	Si	Ca	Pb	
	0,0088	0,0254	0, 6632	9,9459	0,0146	0,0067	

Results of the chemical composition analysis were within the referent values.

Temperature changes with time at the different cooling rate are shown on the Figure 4. Thermo-Calc software provides equilibrium solidification with the cooling rate of 0 K/s. At the equilibrium cooling rate liquidus T_L and solidus temperature T_S were determined. Simultaneous thermal analysis provides the cooling rate of 0,17 K/s. Results from the cooling rate of approximately 5 K/s, 40 K/s and 100 K/s represents the simple thermal analysis examinations.

The decreasing trend of the liquidus temperature $T_{L,}$ solidus T_S and eutectic temperature T_E with the increasing of the cooling rate could be seen.

Depending on the cooling rate different microstructure types can be obtained. At the cooling rate of 4,4 K/s the big dendrites could be seen. At the higher cooling rate of 32,4 K/s the grains of the primary crystals are smaller and the microstructure is directed. At the highest cooling rate of 96 K/s the grains are the smallest and equally distributed.

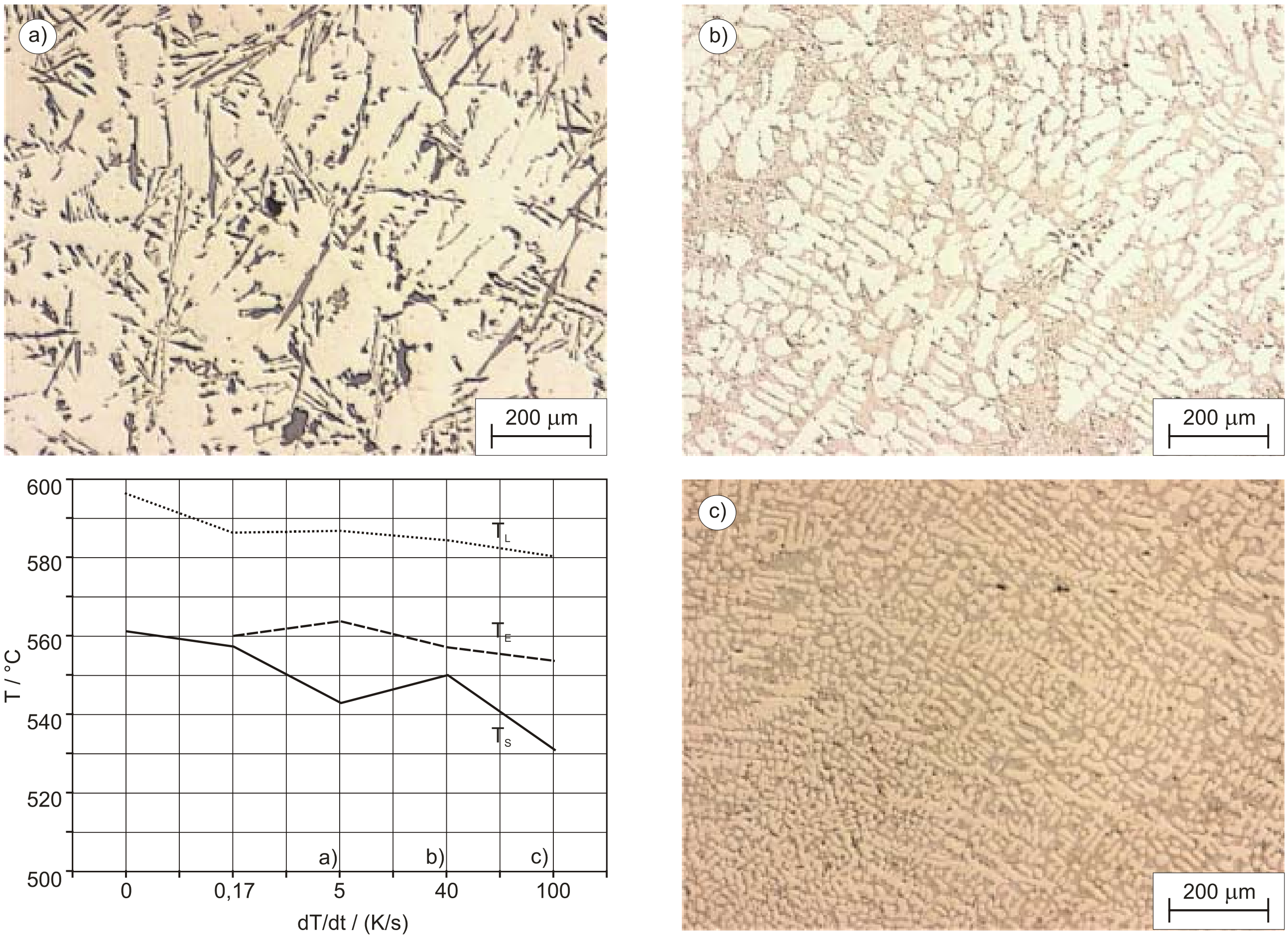

Figure 4. **Graphical illustration of the main temperatures at the alloy solidification obtained with the simple thermal analysis, software Thermo-Calc and the corresponding microstructures**

Slika 4. **Grafički prikaz osnovnih temperatura pri skrućivanju legure dobiven jednostavnom toplinskom analizom, te programskom podrškom Thermo-Calc i odgovarajućih mikrostruktura**

Metallographic examinations are performed on the test samples from the simple thermal analysis. The samples were recorded under the different magnifications. In common, microstructure should be consisting of primary crystals α_{Al} and eutectic which consists of α_{Al} and β_{Si}. Regarding chemical composition insoluble intermetallic Fe rich phases can be expected, which are responsible for the strength increasing, the decreasing fluidity as well as the decreasing of the feeding capacity, [5]. Due those reasons the bigger tendency to the porosity forming can be expected while the physical blocking of the Al_5FeSi plates and the melt flow for the feeding of the interdendritic spaces, [2]. Manganese presence also refers on the forming intermetallic Fe phases such as $Al_{15}(MnFe)_3Si_2$, [5].

The decreasing of the cooling rate results in the share and the size increase of the characteristic phases, established in the microstructure such as: Al_5FeSi, $Al_{15}(Mn,Fe)_3Si_2$ and Mg_2Si. Characteristic microstructure constituent are shown on the Figure 5.

Experimental process of the local squeezing was performed by the several pouring temperatures (701,9 °C, 667,8 °C and 687,1 °C) which have not influenced the squeezing parameters as well as the casting densities.

During local squeezing process the temperature decrease was established during cooling after the pouring and during local squeezing process performing. The example of the local squeezing process performing was shown on Figure 6. The melt temperature measured in the furnace was ~740 °C. The maximum registered temperature was T_p = 701,9 °C in the mould cavity at the beginning of casting. During casting the markedly temperature decrease of ~100 °C occurs due to taking the heat off toward mould, preheated on the 350 °C.

During cooling and solidification between the mould and the casting an empty space occurs while the separation of the formed casting shell from the mould is taking place. That results the cooling rate decreasing. The pin impact during local squeezing process evolves the casting shell again lie on the mould surface after which the thermal flux is again established, and the cooling rate is rapidly increased as shown on the cooling curve. Temperature measured inside the big cube was T_{SQ}^{1} = 567,1 °C. On the small cube those impact had the insignificant influence which has been reflected as a smaller temperature decrease. Temperature registered in the central part of the small cube was T_{SQ}^{2} = 557,4 °C. At the mould edge no changes have been noticed in the moment of the local squeezing process performing.

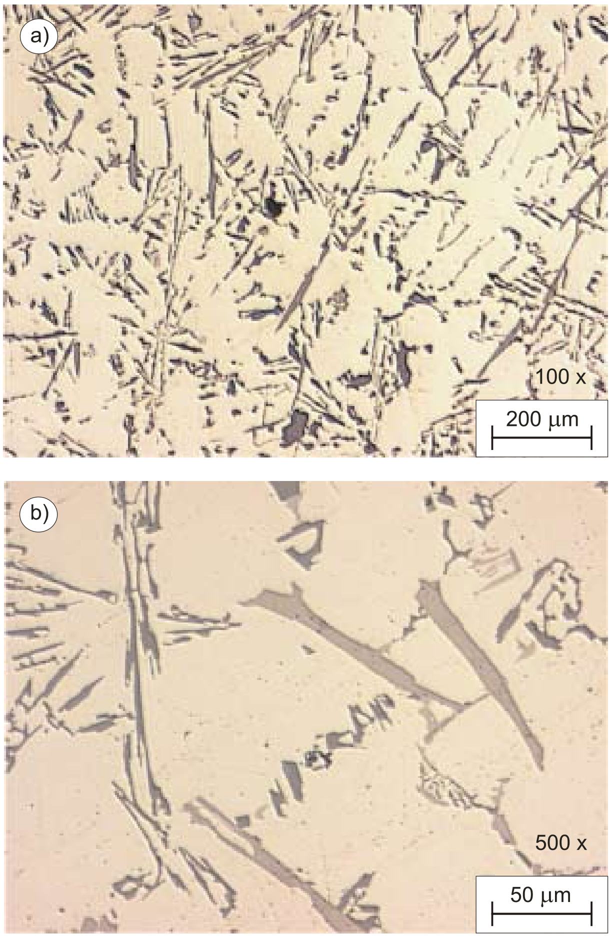

Figure 5. **Microstructure of the AlSi10Mg alloy cooled in the sand mould with the cooling rate of 4,4 K/s**
Slika 5. **Mikrostruktura legure AlSi10Mg ohlađene u većoj pješčanoj kokili brzinom od 4,4 K/s**

The slot depth occurred by the pin impact during the local squeezing process performing in this example was *h* = 5 /mm.

Density determinations were obtained to establish the correlation between the local squeezing process and the density as a measure for the casting soundness (compactness).

The casting produced without the local squeezing process had the markedly bigger difference between the theoretical and real obtained casting density. The biggest approach to the theoretical value was obtained in the temperature interval ΔT_{SQ} = 565 - 575 °C in which the local squeezing process should be performed. The local squeezing temperature increases in those temperature interval because

Table 3. **Density determination based on the Archimed's low**
Tablica 3. **Određivanje gustoće temeljeno na Arhimedovom zakonu**

Sample	*h*	*V*	ρ_0	$\Delta\rho$
kp 2	5	3919,35	2,636	0,064
kp 3	3	2351,61	2,657	0,043
kp 4	2	1567,74	2,645	0,055
kp 5	1	783,87	2,666	0,034
kp 6	15	11758,05	2,664	0,036
kp 7	5	3919,35	2,654	0,046
kp 8	20	15677,40	2,651	0,049
kp 9	0	-	2,599	0,101

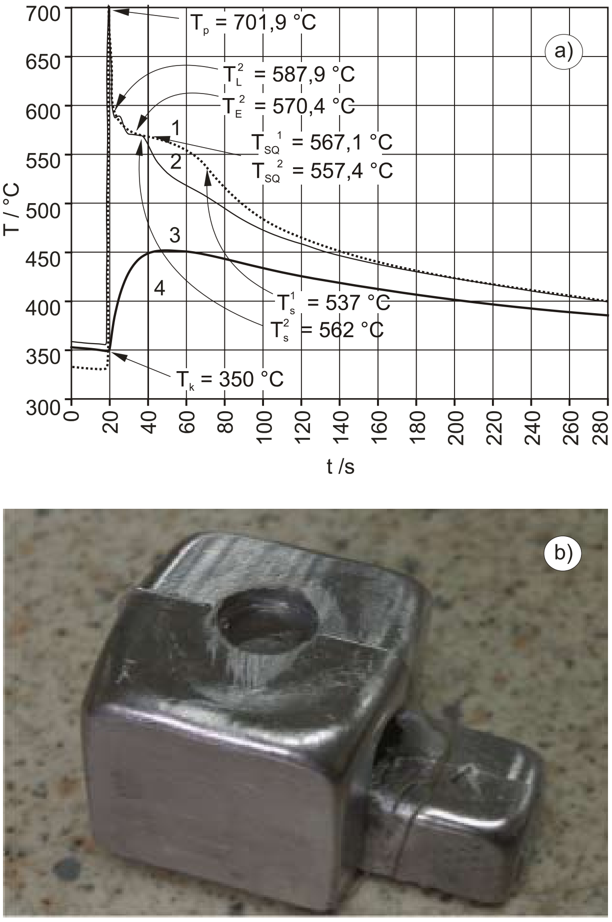

Figure 6. **The local squeezing process performing. a) Dependence diagram of the temperature versus time of casting pouring and solidification, and time of the local squeezing process performance. b) Photography of the obtained test sample**
Slika 6. **Izvođenje postupka lokalnog tiskanja. a) Dijagram ovisnosti temperature od vremena pri lijevanju i skrućivanju odljevka, te tijekom izvođenja postupka lokalnog tiskanja (kp 7). b) Fotografija dobivenog ispitnog uzorka**

of the casting density i.e. compactness decrease. Correlation dependence of those parameters is rather small which could be consequence of the central shrinkage movement toward the riser, whereby the local squeezing shrinkage filling became indirectly.

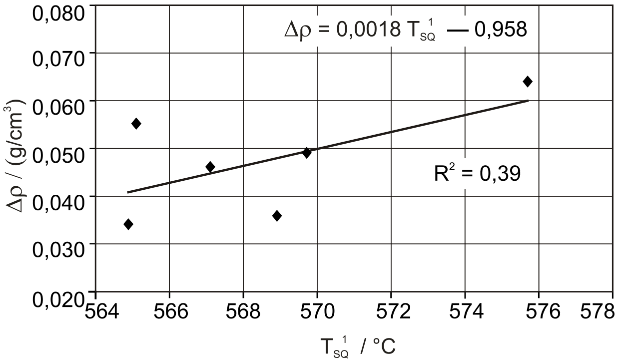

Figure 7. **Dependence of the difference between theoretical and real obtained casting density and the local squeezing temperature T_{SQ}^1**

Slika 7. **Ovisnost razlike teorijske i stvarne gustoće odljevka od temperature lokalnog tiskanja T_{SQ}^1**

The density increase trend was noticed with the slot depth (from the pin indent) increase, as shown on Figure 8.

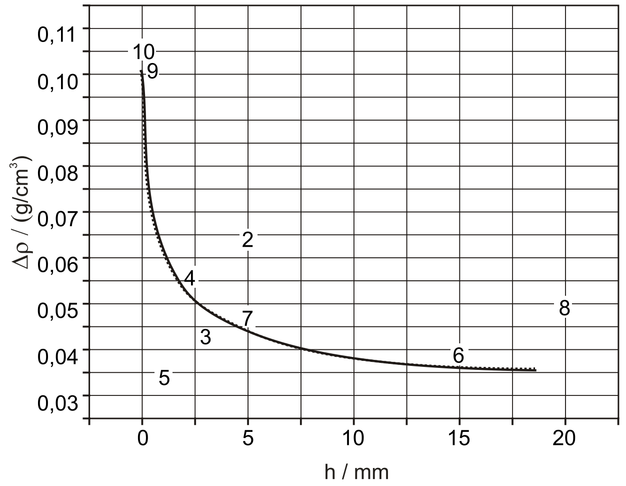

Figure 8. **Diagram of the theoretical and real obtained casting density difference and the slot depth from the pin indent**

Slika 8. **Dijagram ovisnosti razlike teorijske i realne vrijednosti gustoće odljevaka od dubine utora trna**

Exponential curve of the correlation between the theoretical and the real obtained casting density difference ($\Delta\rho$) and the slot depth (h):

$$\Delta\rho = 0{,}02514\cdot e^{-\frac{h}{4{,}60219}} + 0{,}02351\cdot e^{-\frac{h}{0{,}70997}} + 0{,}01195\cdot e^{-\frac{h}{0{,}21263}} + 0{,}03503.$$

Correlation factor between assumed and the software obtained curve was: $R^2 = 0{,}99$. This correlation refers on the casting compacting during local squeezing process.

CONCLUSIONS

The influence of the composition of the process parameters variations on the casting density e.g. soundness (compactness) was examined by the local squeezing process with the pin at the gravity AlSi10Mg alloy casting.

The local squeezing parameters were determined on the base of preliminary examinations of the AlSi10Mg alloy whereby the temperature intervals and the relevant temperature of the single phases precipitations were established, as well as the microstructure development by the different cooling rate.

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

1. The simple and simultaneous thermal analysis examinations in combinations with the metallographic analysis, and the AlSi10Mg alloy solidification was monitored and the followed microstructure constituents were established: primary crystals α_{Al}, eutectic consists of the α_{Al} and β_{Si}, needles of the Al_5FeSi phase, phase $Al_{15}(Mn,Fe)_3Si_2$ in the Chinese script form, and the Mg_2Si phase.
2. As the cooling rate increases (4,4 K/s, 32,4 K/s, 96 K/s), single temperatures of the phases transformations (liquidus, eutectic and solidus temperature) are moving toward the lower values.
3. The cooling rate increase significantly influences the microstructure development. The increase of the characteristics phases size and share, determined in the microstructure such as: Al_5FeSi, $Al_{15}(Mn,Fe)_3Si_2$ and Mg_2Si can influence on the feeding with the cooling rate decrease.
4. The local squeezing process of the AlSi10Mg alloy test samples must be obtained in the temperature interval from the 565 - 570 °C when the casting is in the mushy state. The smallest difference between the theoretical and real obtained density was determined in those temperature interval.
5. The local squeezing temperature increases in the temperature interval from the 565 - 575 °C because of the decrease of the density i.e. compactivity. 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.
6. The increase density trend with the slot depth is present. Correlation curve of the difference between the theoretical and real obtained casting density value and the sloth depth from the pin indent is presented by the following equitation:

$$\Delta\rho = 0{,}02514\cdot \mathrm{e}^{-\frac{h}{4{,}60219}} + 0{,}02351\cdot \mathrm{e}^{-\frac{h}{0{,}70997}} + 0{,}01195\cdot \mathrm{e}^{-\frac{h}{0{,}21263}} + 0{,}03503.$$

Correlation factor of the assumed and the software calculated curve is: $R^2 = 0{,}99$.

For the industrial application of the local squeezing process with the pin at the serial gravity die and the high pressure die casting, a series of the additional examinations on the real tool i.e. casting must be obtained. The acquainting of the local squeezing process with an alloy parameters, numerical simulation of the pouring and the casting solidification would provide the high integrity casting production.

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List of symbols

$\%P$ - percent porosity /%
β - solidification shrinkage factor /%
V^* - volume of liquid in casting cavity that is not supplied liquid during solidification /cm^3
V_C - volume of the casting cavity /cm^3
T - temperature of the gas in the casting cavity /K
p - pressure applied to the gas during solidification /MPa
Φ - fraction of the gas that does not report to the solidification shrinkage pores
ρ - liquid alloy density at the melting temperature /(g/cm^3)
v - quantity of the gas contained in the casting at standard temperature and pressure condition (273 K and 10^5 Pa) /(cm^3/100 g alloy)
v^* - solubility limit of gas in the solid at the solidus temperature at standard temperature and pressure conditions /(cm^3/100 g alloy)
T_{SQ}^1 - temperature in the big cube cavity at the local squeezing process applying /T
T_{SQ}^2 - temperature in the small cube cavity at the local squeezing process applying /T
ΔT_{SQ} - temperature interval of the local squeezing aplication /T
$\Delta\rho$ - theoretical and real obtained density difference of the test samples /(g/cm^3)
h - slot depth of the pin obtained by the local squeezing process /mm
R^2 - correlation factor
V - volume of the indent part of the pin /mm^3 ($V = r^2\pi h$)
ρ_o - casting density /(g/cm^3)
ρ_t - theoretical casting density /(g/cm^3) ($\rho_t = 2700$ /(g/cm^3), [11])
ρ_v - relative water density at the 293 K /(g/cm^3) ($\rho_v = 1$ /(g/cm^3), [25])
$\Delta\rho$ - theoretical and real obtained density difference /(g/cm^3)