Study on Shrinkage Development Inside an Al-Si Alloy Casting by Computer Solidification Simulation

VARGA Bela
Transylvania University of Brasov, Romania, varga.b@unitbv.ro
MUSTEAȚĂ Florin
Transylvania University of Brasov, Romania, fmusteata01@yahoo.com
CIOBANU Ioan
Transylvania University of Brasov, Romania, ciobanu_i_bv@yahoo.com
BEDO Tibor
Transylvania University of Brasov, Romania, bedo.tibor@unitbv.ro
MUNTEANU Ion Sorin
Transylvania University of Brasov, Romania, muntean.s@unitbv.ro
CRIȘAN Aurel
Transylvania University of Brasov, Romania, crisan.a@unitbv.ro

Abstract
We show that the position and shrinkage volume results given by software using casting solidification simulation doesn`t always correspond with the experimental results. This can be explained due to the simulation analysis the flow of liquid alloy inside casting (from casting-mould). For a better determination about position and shrinkage volume from casting, the numeric results and graphics given by software must be processed and interpreted by user at the end of simulation. In order to determine the position and shrinkage volume from casting one must analysed the time when feeding channel is interrupted, volume of liquid alloy from casting at that time and the position of the hot spot. We show this example to be verified as experimental in. In the end, we show the numeric results given by software and the steps to follow.

Keywords
casting, shrinkage, casting solidification, solidification simulation, aluminium - silicon alloy

1. Introduction

The emergence and appearance of software for casting simulation made possible the study of shrinkage into casting using computer modelling, without experimental casting. We can analyse the influence of different agent constructive and technological about the position and volume of shrinkage [1, 4, 8, 9, 10, 11]. As a result, we can study the possibility to eliminate this defect from casting and to optimize the technology. Using software for simulation solidification casting keeping in mind projection and optimization the casting technology presents the following advantages:

- Is not necessary to cast experimental probes to verify and the homologation of technological solution;
- Remove labour and material expenses;
- Reduce the expenses for launch time into production;
- Reduce the time of production
- The study using simulation needs fewer human resources;
- Simulation allows to do a systematic study since it is possible to modify the progressive parameter of influence, whereas it is not possible in the experimental mode;
- Remove the difficulty about control and measure different parameters;
- Remove the difficulty about associated with casting analysis, highlight the defects and dependence between factors.

To ensure the correct solution based on simulation, it is necessary to verify experimentally the results obtained with simulation [1, 3, 11].

The solidification of casting is a complex process affected by many influencing factors, some that are hard to measure and control. Therefore, the use of solidification simulation software in the industry for the design and optimization technological casting became very popular. Currently all major companies are using this type of software. Software developers have continued to produce software complete with module to study processes and effect of solidification. In the beginning, software for simulation was created to cast only in sand, giving information about temperature field, solidification front and the position of the hot spot. After that software was completed to supply information about filling forms, the position and volume of shrinkage, tendency of appear micro shrinkage, size of internal tension and the tendencies of the cracking, appearance of adherence, microstructure and mechanical proprieties and structural defects, etc. It was also used with specific software module for another casting process such as:

- pressure casting;
- metal mould casting ;
- continued casting.
- investment casting.

As a results this type of complex software there is a need for qualified, trained specialists. The accuracy of results given by this software depends on the hypotheses considered at the beginning of the development program. Most of the time this hypotheses is based of mathematical models they are development secret. Another factor to consider in determining the accuracy of results would be the database used for simulation. For this reason, sometimes software is not used in appropriate conditions. There are cases when the data provided does not correspond with reality or is not interpreted and used correctly.

We introduce a case where software programs do not lead to the same results from the stand point of shrinkage formation [1]. The results are different between software and different between experimental results. This can be explained based on mathematic model and the different assumption is into software base. One cause is that the differences in the thermo-physical characteristics material and the different module is analysed shrinkage formation. Choosing the correct solution for technology projection is influenced by the engineer ability to interpret results. This affirmation is demonstrated in the following example and in figures 1÷4. This study is realized by a few people from S.C. Saturn S.A. Company Alba Iulia [1]. In these figure are represented simulation results and experimental results about casting and solidification to a simple piece (called sample H). The probe is formed by two paralellipipedic parts with dimensions of 120×120×150mm. Two pieces are casted in a mould. This pieces are supplied from the same supplying network and is formed by funnel, vertical channel, distribution channel and two supplying channel. The supplying channel has a section of 30×120 mm and is positioned between pieces. Name "sample H" (figures 1÷4) came from piece appearance. Piece has module M = 22.2 mm. A casted piece has a direct riser with solidification module M = 22.2 mm. The riser provided with core bottleneck into lower junction with casting. A second piece has into the upper part a ventilation channel with diameter d = 20 mm. Both pieces have been casted from ductile gray iron with eutectic composition [1].

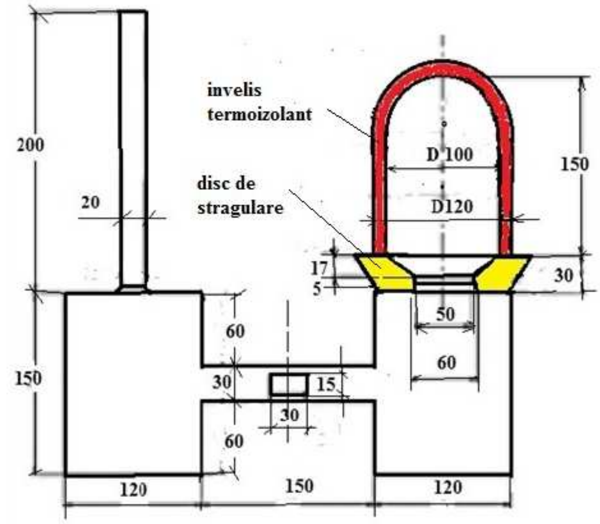

Fig. 1. The geometry and the size of H sample [1]

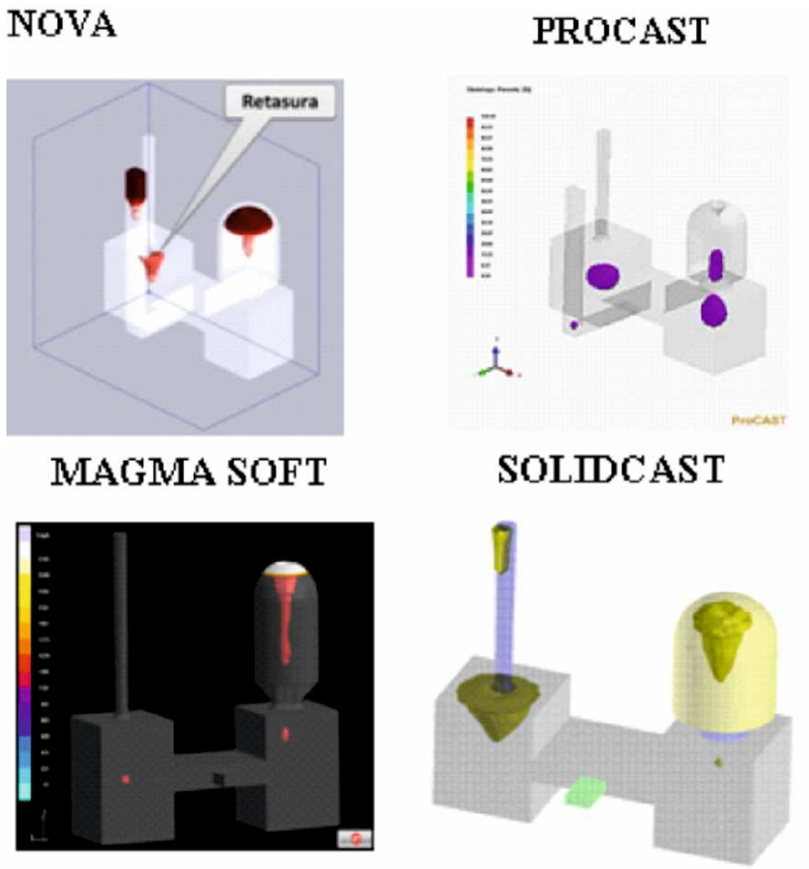

Fig. 2. The simulation results on shrinkage size and location with any software [1]

Fig. 3. Experimental casting, 3 H-Sample [1]

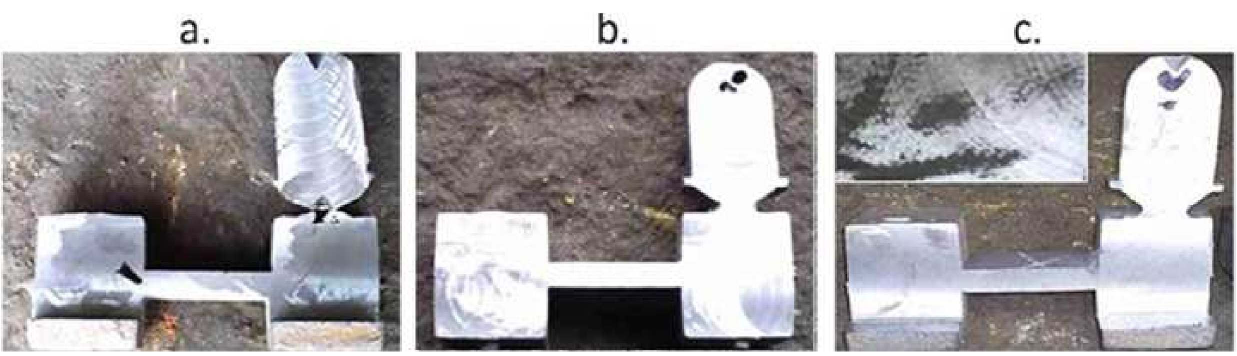

Fig. 4. The shrinkage emplacement in section H- samples

In the example below was simulated system solidification (piece- supplying network-riser) with software used in foundry (SolidCast, ProCast, Magmasoft and Nova Flow&Solid) [1]. The results regarding about shrinkage formation obtained by simulation are showed in figure 2. According to the simulation in both pieces, a shrinkage is formed including casting with riser and in riser appears a principal shrinkage with a big volume. We observe that simulation results show volume and a different position of shrinkage.

For the practical verification in S.C. Saturn S.A. company Alba Iulia were casted 44 pieces (figure 3) [1]. The pieces were sectioned to highlight the position and shrinkage dimensions (figure 4). The experimental results show that over 50% of pieces were not affected by shrinkage. In addition, the pieces that showed shrinkage, showed a different position and shrinkage dimension from that of the simulation results [1].As a results we obtained pieces without shrinkage even when pieces casted without riser. The authors from S.C. Saturn S.A. considered that the difference between experimental results and simulation is caused by “self-feeding” determined by graphite precipitation in case of current alloy (self-feeding= compensation contraction at solidification with growth volume caused by graphite precipitation) which is not taken in consideration by software [1].

We consider that the difference from simulation and practical results have two causes:

- The value of contraction coefficient at solidification used by software for ductile gray iron was higher than the real value (solidification growing volume is caused by graphite precipitation and determine a significant decrease of contraction coefficient to this iron; process called by some authors “self-feeding”);
- The simulation forming shrinkage does not take into account about self-feeding of casting in the solidification time with liquid alloy from gating system, self-feeding is possible until feeding channel is solidified.

A closer results obtained with simulation are with MAGMASOFT (figure 2). The results obtained with SolidCast and Nova Flow&Solid are more similar. This can be explained because both program use closer mathematic module and similar hypotheses.

2. Paper Aim

At department Material Science from Transylvania University Brasov was realized many software module for simulation solidification casting [3, 4, 5]. Was realized software for simulation solidification casting with eutectic alloy constant temperature solidification) and software for simulation solidification casting from alloy type solid solution which can be applied with enough precision to alloy hypo and hyper eutectic or with peritectic transformation. This program realized in Transylvania University uses a mathematic module with finite differences into Cartesian coordinate. This has the advantage to map the results (temperature maps, movement map of the solidification front, temperature gradient, etc.) are showed level line, and numeric results. This allows to obtain information more detailed about solidification parameter and temperature field at any point of casting piece or to mould.

Figures 2 and 4 shows that software used in industry doesn’t always show anytime correctly the position and the shrinkage volume [1]. We consider that an analysis must be conducted in order to verify information about the position and shrinkage volume. The shrinkage formation is influenced by solidification succession and flow liquid, which appear into casting form during the solidification time. Shrinkage formation is different from case to case and is influenced by the piece geometry and the position of casting, supplying position, height gating, and the position of the shrinkage. The process of flow and solidification (flow from funnel, and solidification supplying) cannot be contained in a mathematic model and into a general soft and is hard to obtain precise results about the position and shrinkage volume from a simple simulation. To obtain precise information about the position and shrinkage volume the numeric results about solidification alloy must be individually processed from case to case after simulation is completed, keeping in mind the geometric particularity from casting, gating system and riser. Therefore, this hypotheses propose the following.

To verify the results given by the software realized in Transylvania University, about temperature field from casting - gating - mould system and the shrinkage size.

3. Working Mode

We had done the simulation of alloy solidification into casting with hot spot that favours the appearance a concentrated shrinkage. We chose an alloy with eutectic composition. The eutectic composition (absence of a solidification interval) favours the macro-shrinkage. The studied piece is showed in figure 5. This is a corbel support casted with alloy ATSi12. We simulated solidification part with program SIM-3D-EUT realized at Transylvania University from Brasov. Figure 6 shows the position and size of ensemble casting-gating system-mould studied by simulation. First, we determined the volume and shrinkage position. Second, we studied a part that was realized experimentally and the experimental results were close to the simulation results.

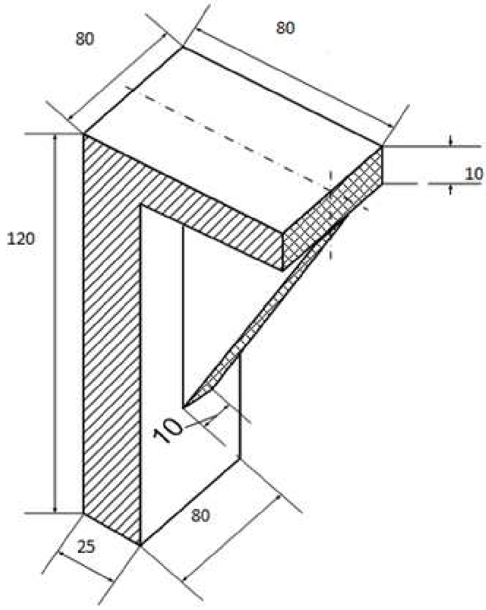

Fig. 5. Casting object of study

4. The Results Obtained by Simulation

During simulation, we took into account principals of kinetic and dynamic solidification alloy in shrinkage formation:

- Temperature map at the time when solidification is completed;
- Movement map of the solidification front;
- Solidification duration complete of casting;
- The solidification of supplying and other element from gating system;
- The time when supplying channel is interrupted;
- The position of the hot spot in casting;
- Cooling curve in different point into casting and mould;
- Evolution of the cooling speed in different point;
- Evolution quantity of liquid alloy from system;
- Evolution quantity of liquid alloy from casting;
- Temperature gradient from casting into solidification time and area where micro shrinkage appear;
- Total shrinkage volume, micro shrinkage and macro shrinkage;
- The shrinkage position.

We show at same time the condition and work mode for this study. Where is necessary and possible the results are represented with a graph. The results are analysed and interpreted keeping in mind shrinkage formation (micro and macro shrinkage). Table 1 show the values used into simulation. The results obtained from simulation are showed in the following maps and table.

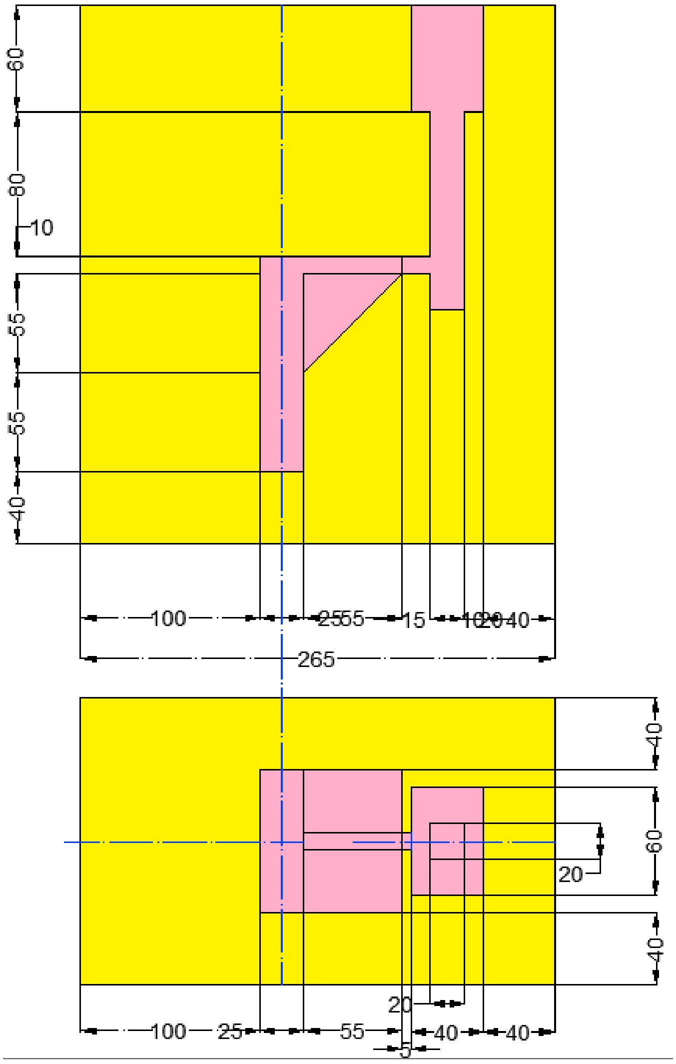

Fig. 6. Design and size of casting - mould assembly studied by simulation

Table 1. Thermo-physical and geometrical characteristics used for simulation (casting in ATSi 12 alloy)

No.	The characteristic	Symbol	Meas. unit.	Value
1	Step of mould mesh	Δ	m	0.005
2	Time step	τ	s	0.05
3	Temperature of the environment	Tex	^0C	20
4	Heat transfer coefficient mould - environment	αex	$W/m^2/K$	20
5	The solidification temperature of the cast alloy	Tsme	^0C	570
6	Thermal conductivity coefficient of the mould	λsfo	W/m/K	0.6
7	Thermal conductivity coefficient of the solid alloy	λsme	W/m/K	200
8	Thermal conductivity coefficient of the liquid alloy	λlme	W/m/K	100
9	Specific heat of the mould	Csfo	J/kg/K	1170
10	Specific heat of the liquid alloy	Clme	J/kg/K	1200
11	Specific heat of the solid alloy	Csme	J/kg/K	1000
12	Mould density	ρfo	kg/m^3	1550
13	Density of liquid alloy	ρme	kg/m^3	2600
14	Latent heat of cast alloy solidification	Lme	J/kg	545000
15	Initial temperature of the mould	T0fo	^0C	20
16	Initial temperature of the liquid alloy	T0me	^0C	720

Figure 7 shows solidification movement front into casting. Area with dark green shows that part from piece is solidified first and yellow is solidified last. This figure demonstrates a fast solidification of supplying channel and the time when supplying channel is interrupted. The time when supplying channel is solidified corresponds with the time when shrinkage is forming into casting because from this time solidification contraction from casting is not compensated anymore from gating system. Figure 8 shows two hot spots, one appears into casting and one into funnel. Hot spot from casting corresponds with the time when solidification is completed. It corresponds with lower top of shrinkage from casting and is placed on the vertical wall axis in the middle (at junction vertical wall-rib). The colour from rib area shows that solidification accurse fast. This is the reason why in the rib does not appear shrinkage. Figure 9 shows the expected position of the shrinkage in the casting and gating system.

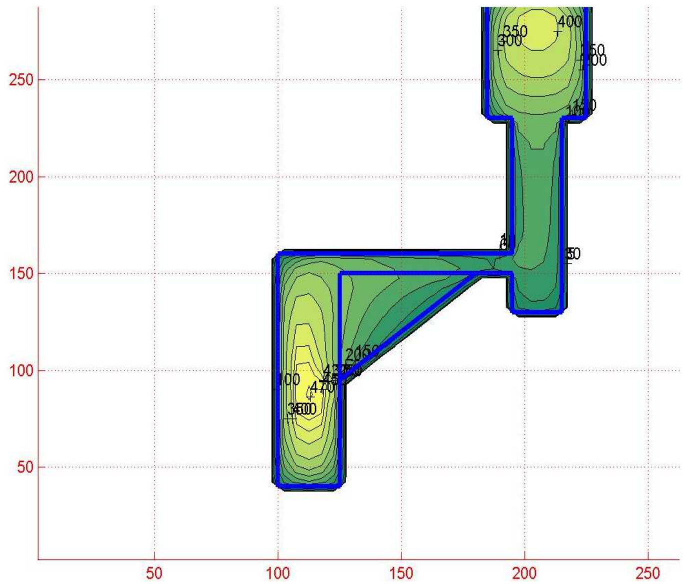

Fig. 7. Map of the solidification movement front in the of symmetry plane of the piece

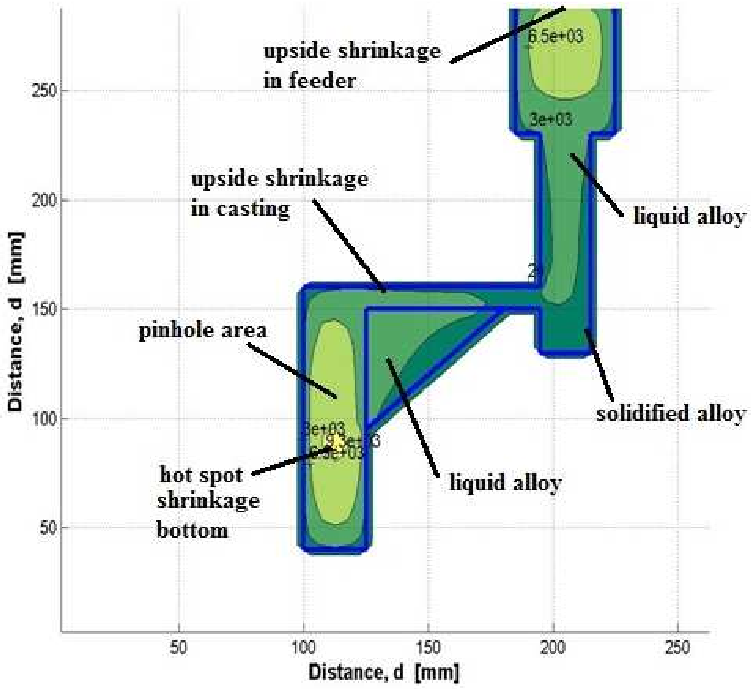

Fig. 8. Liquid alloy map inside the system at beginning time of shrinkage making and pinhole making

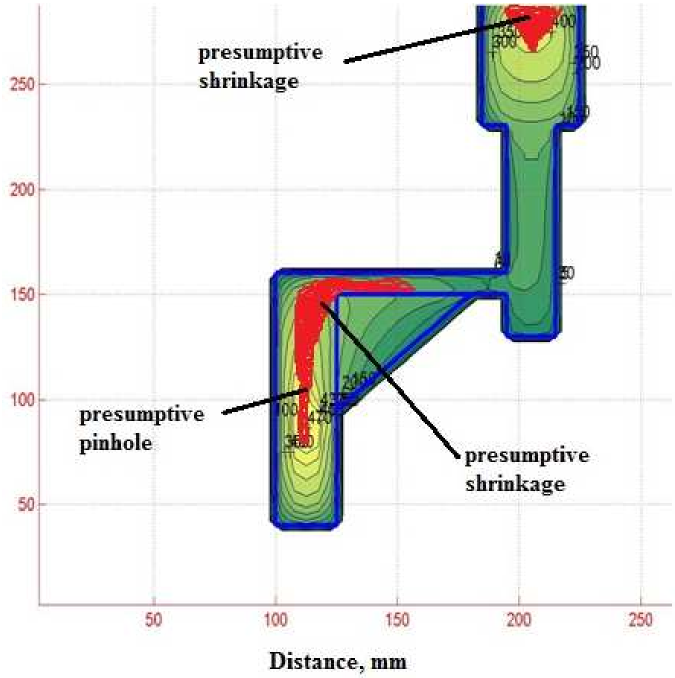

Fig. 9. Presumptive shrinkage location

Based on data from figure 8 the table with numeric results we obtain information about quantity of liquid alloy, which is solidified isolated into casting after solidification supplying channel and rib. The solidification contraction to this volume of alloy is 4% and corresponds with total volume of shrinkage from casting. Yellow and dark yellow area from vertical wall corresponds with area where temperature gradient in the axial-vertical direction from liquid alloy is very small, causing a micro shrinkage. Solidification contraction of alloy in this area gives micro shrinkage volume. The upper edge of white green area corresponds with upper edge of macro shrinkage. The upper outline of dark green area corresponds with the upper edge of micro shrinkage. The smaller yellow area shows the position of the hot spot. This corresponds with lower tip of micro shrinkage area.

Figure 10 shows temperature repartition in the ensemble casting gating system at the time when casting is solidified. We observe that the isothermal lines from this map are different from the movement map of the solidification front. This is explained because into solidified layers, after solidification appear a heat redistribution with terminal conduction. This figure shows that isothermal map cannot be used for highlight shrinkage area and hot spot how some user with less experience into simulation solidification does.

Figure 11 shows temperature repartition on the vertical axis with thickness 25 mm at the time when solidification start. We observe that on that time on this axis, the temperature is almost constant and equal with 570 °C. This temperature repartition corresponds with a temperature gradient very small into vertical direction, which shows a tendency to form axial shrinkage spread in this area.

Figure 12 shows temperature repartition in the vertical wall at the time 471.55 s when solidification is done. The top temperature (maximum curves) highlight the position of the hot spot. This figure shows also a lower temperature gradient on the vertical axis and the tendency to appear spread shrinkage on the wall axis.

Figure 13 shows temperature repartition on the studied line in the symmetry plane at the time t =325 s which correspond with the time when solidification is completed on this wall. We observe that the temperature grow from right to left, that mean from supplying channel to vertical wall. Temperature gradient in this wall is pronounced and highlight that in this area is formed micro shrinkage.

Figure 14 shows temperature variation in time in the hot spot, which is situated in the middle plan of pieces and on the vertical wall axis at the level lower rib. Figure 15 show solid fraction variation (kinetic solidification) in the hot spot. This figure highlights best the time when solidification starts and ends into this cell. Comparing figure 14 with 15 we observe that the horizontal bearing of temperature curve it extend with much time before solidification start. This show that before solidification starts the alloy cools slowly. Near the solidification is over appear a time interval when alloy cools fast. This is explained because of height temperature difference, which is created, from the layer that is solidifying and the near layers and the solidifying layer temperature became constant. This observation about dynamic cooling and solidification are highlight in figure 16, which shows cooling speed of hot spot.

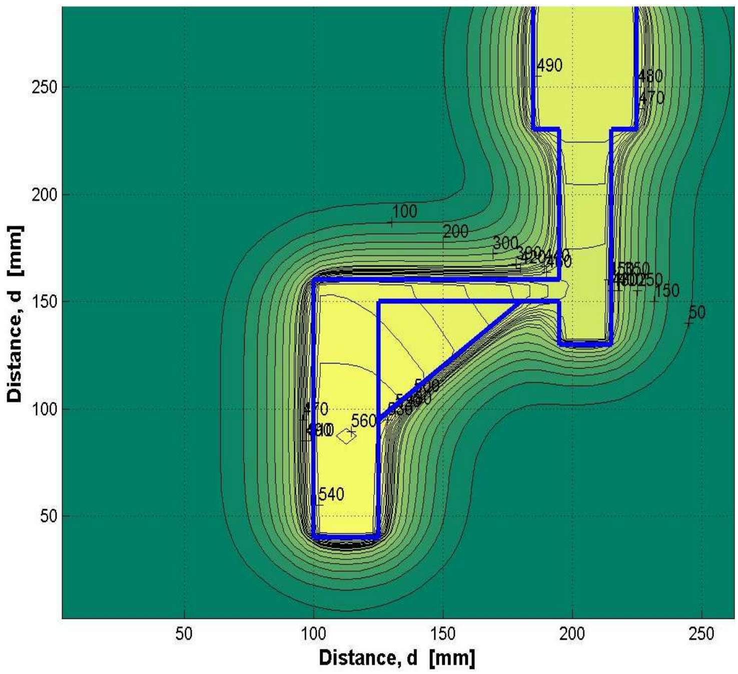

Fig. 10. Isothermal map at the solidification end of casting

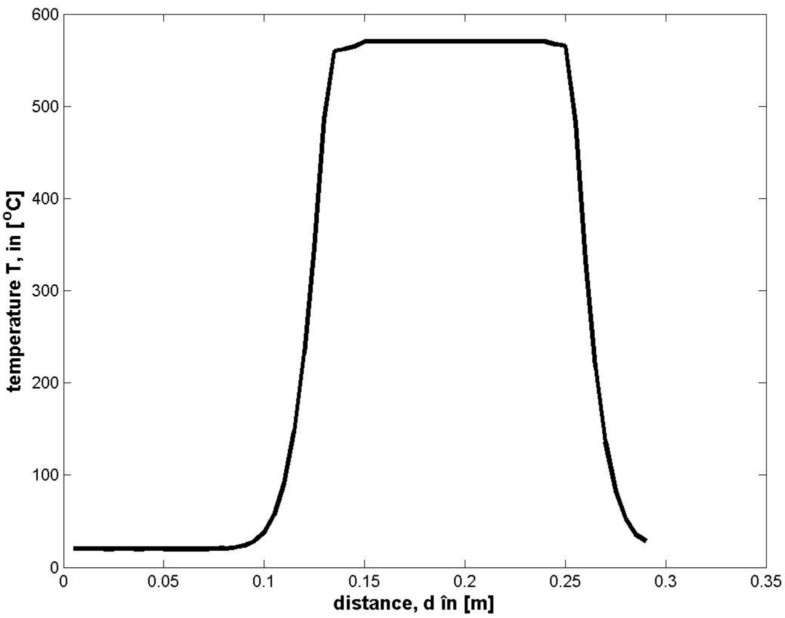

Fig. 11. The temperature on the vertical wall axis at a time t = 325 s (step time q = 6500)

5. Experimental Verifying

To verify results and conclusion obtained by simulation, piece was realized experimental. Casting was from alloy ATSi12- eutectic. Was realized a casting mould from sand with clay binder and bentonite. The mould was realized by an aerated model realized from polystyrene. The mould used for casting is presented in figure 17. Figure 18 shows casting with gating system after we extract from form. Casting was sectioned from the symmetry plane to visualize position and the shrinkage volume this is showed in figure 19. The shrinkage from casting has an estimated volume from 4.3 cm^3. This volume is determined by measuring shrinkage surface from the median section and the depth of this. The shrinkage volume determined by simulation is 4.6 cm^3 (table 2).

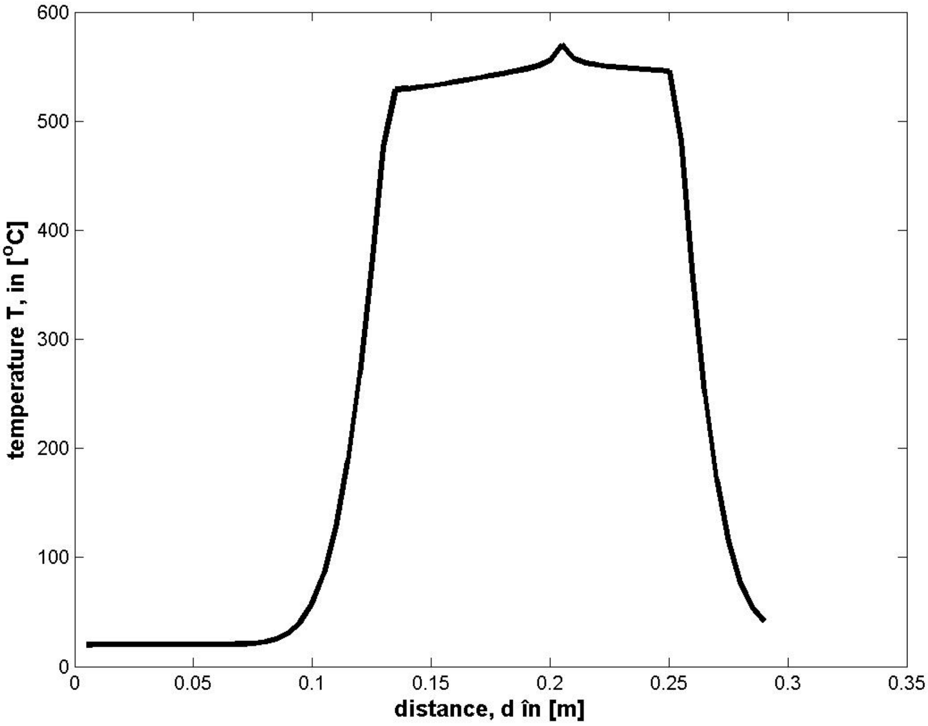

Fig. 12. The temperature on the vertical wall axis at a time t =471.55 s (step time q = 9431)

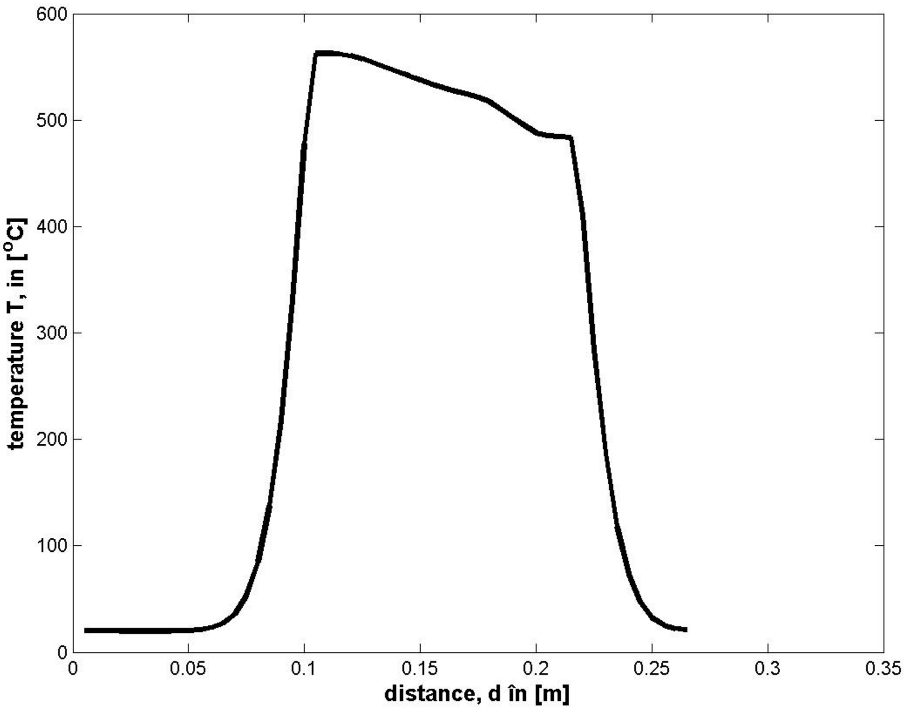

Fig. 13. The temperature on the bottom side of horizontal wall at a time t = 325 s (time step q = 6500)

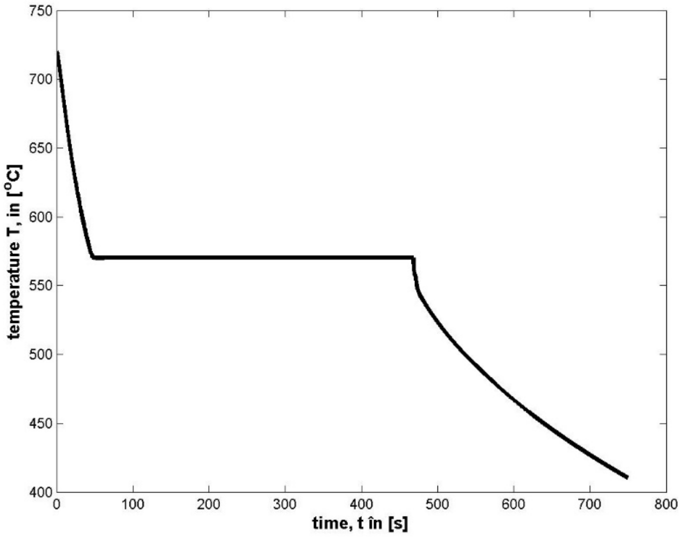

Fig. 14. The temperature variation on casting hot spot (mesh 42 23 1)

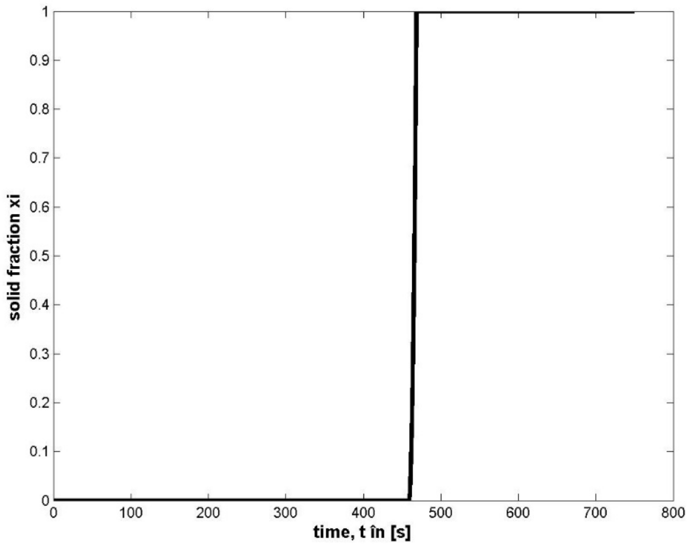

Fig. 15. The variation of solid fraction on the casting hot spot (mesh 42 23 1)

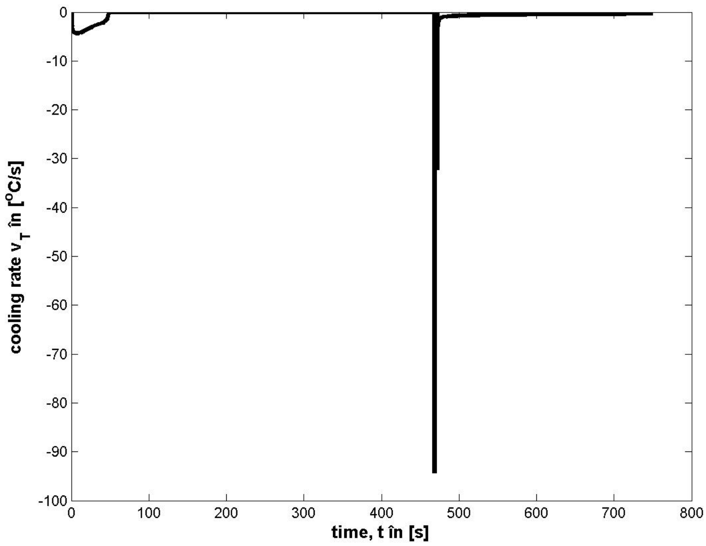

Fig. 16. Cooling rate in the casting hot spot (mesh 42 23 1)

Fig. 17. Polystyrene model of casting

Fig. 18. Casting and gating system

Fig. 19. Shrinkage location in experimental casting

The numerically results about solidification casting and shrinkage size are showed in table 2.

6. Conclusion

The analysis of the section in the symmetry plane of experimental casting confirms that the results obtained with simulation about the position, appearance and the shrinkage volume from casting:

- Concentrated shrinkage (macro shrinkage) is positioned into the central area of the horizontal wall and it go down to the upper part of vertical wall axis;
- The upper edge of concentrated shrinkage corresponds with results obtained by simulation;
- On the vertical axis in the lower rib area appear micro shrinkage spread and coincide with hot spot showed by simulation;
- The results about shrinkage volume obtained by simulation are close to experiment. From this point of view, the difference is about 6% and can be explained by measuring error of shrinkage volume from piece realized experimental and by contraction piece after solidification.

Table 2. Numerically results acquired by the casting solidification simulation

No.	The characteristic	Symbol	Meas. unit.	Value
1	Solidification time of hot spot	t_sol_p	S	471.55
2	X - coordinate of the hot spot (origin of coordinates in the down-left casting corner	x	mm	12.5
3	Y - coordinate of the hot spot (origin of coordinates in the down-left casting corner	y	mm	47.5
4	Casting volume	Vp	cm^3	89.5
5	Runner gate volume	Vrt	cm^3	129.5
6	All volume of cast alloy	Vtot	cm^3	219
7	The cut-off time to casting feeding	t_al	s	94.8
8	All volume of liquid alloy in mould at cut - off time to casting feeding	V_L_tot_	cm^3	162.08
9	Volume of liquid alloy in gating runner at cut - off time to casting feeding	V_L_r	cm^3	46.36
10	Volume of liquid alloy in casting at cut - off time to casting feeding	V_L_p	cm^3	115.72
11	Shrink coefficient of cast alloy solidification	β	%	4
12	All volume of shrinkage in casting	Vret	cm^3	4.62

The study and the results obtained shows that to obtain realistic results about position and shrinkage volume from casting is necessary that numeric results and graph provided by simulation software to be processed and interpreted after by the following methodology:

- We establish the total volume of liquid alloy casted in mould (casting + gating system);
- We establish the time when supplying is interrupted from gating system (from funnel);
- We establish (we approximates) the time when shrinkage start forming from casting (this close to and little later before supplying is interrupted);
- We establish the solidified alloy volume until that time;
- We establish contraction coefficient of casting alloy;
- We calculate shrinkage total volume;
- We localize upper edge of shrinkage according with upper edge of liquid alloy, which is inside of piece when the shrinkage is forming;
- We localize hot spot from casting, this correspond with the top inferior shrinkage;
- We analysis the temperature gradient from hot spot area to establish if exist tendency to form micro shrinkage;
- We determine the volume area where micro shrinkage is forming according with liquid alloy volume isolated in the area with lower temperature gradient;
- We calculate micro shrinkage volume according with this volume and the contraction coefficient at solidification of casting alloy;
- We calculate by minus (difference) macro shrinkage volume (total volume of shrinkage minus (difference) micro shrinkage volume.

To cover this step about establish position and the shrinkagevolume from system, software must display numeric and graphic the following data:

- The solidification time for ensemble;
- The movement map of the solidification front;
- The temperature repartition curve (temperature gradient) in the wall axis;
- The liquid alloy volume from casting, gating system and riser.

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