Experimental Verification of a Software for Simulation of Centrifugal Casting Solidification

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Abstract
The software was developed to simulate the solidification of centrifugally castings with a rotationally symmetry. For the cast alloys that solidify in a temperature interval. The software uses a mathematical model with finite differences and cylindrical coordinates. It is shown an experimental verification of this software. The cooling curves obtained by simulation are compared with those obtained by experimental thermal analysis. The verification was carried out for the case of a cylindrical hollow part aluminium of cast alloy - silicon alloy. The experimental results are very close to those obtained by simulation. This confirms the validity of software.

Keywords
solidification simulation, casting, thermal analysis, aluminium-silicon alloy

1. Introduction

At Transylvania University of Brasov, have been conducted several simulation software for casting solidification. The software made the Transylvania University of Brasov based on original mathematical models [1, 2, 3, 4]. The software made in Brasov can accurately reproduce all types of solidification (including eutectic solidification type, hypo- and hyper-eutectic, peritectic etc., which include the solidification temperature constant).

To meet the diversified research and technological design for industry, they were made software, adapted to accurately simulate of special casting processes [3, 4, 5, 6]. In this regard Brasov were made software to simulate the continuous and respectively centrifugal, casting solidification. In the case of centrifugal or continuous castings, these have rotational symmetry. Therefore, to simulate the casting solidification by these processes can be used a software based on a cylindrical coordinates. These have the advantage to do the volume solidification simulation of parts with a rotational symmetry using mathematical models 2D. This leads to a significant shortening of the simulation time.

2. Aim of Paper

Recently at Transylvania University was developed software (SIM SOLSOL-CIL) to simulate castings solidification with rotationally symmetry that is casted of hardening alloys as solid solution. They solidify in a temperature range. The software uses a mathematical model in cylindrical coordinates. It can simulate the gravitational castings solidification, and those centrifugally castings. To use this software in design and research to optimize technologies was necessary to verify the accuracy of the results provided by the software. The paper sets out the results of this software by experimental thermal analysis. The check is made for a casting of an alloy aluminium - silicon with a solidification range.

3. Working Mode

A method currently used to verify the software to simulate the castings solidification is based on experimental thermal analysis. For this, the experimental curves recorded the temperature variation in a points of the casting - mould assembly. These are then compared with similar simulated curves determined by the verified software.

This method was applied on the solidification simulation software designed to rotationally symmetrical castings. The experimental measurement of the temperature variation (relative to time) inside the casting inside and the mould, through centrifugal cast, it is difficult to achieve due to the rotational movement. Therefore, the software was tested under static casting. For this purpose, a cylindrical tubular part was poured (wall thickness b = 30 mm and D = 160 mm outside diameter). The figure 1 shows the assembly casting - mould for which carried out the verification. The part was cast from aluminium alloy - silicon ATSi12. The table 1 shows the chemical composition of the alloy used to sample casting. According to the diagram of the binary balance Al - Si alloy shown in figure 2, has a slightly hipoeutectics composition. It presents a small solidification interval. Inside the casting moulds, two thermocouples were fitted, one to the axis of the wall (point A) and the second to 1 mm from the inner surface (Point B). The thermocouples were placed halfway up the casting. The figure 1 shows the thermocouples emplacement inside the mould.

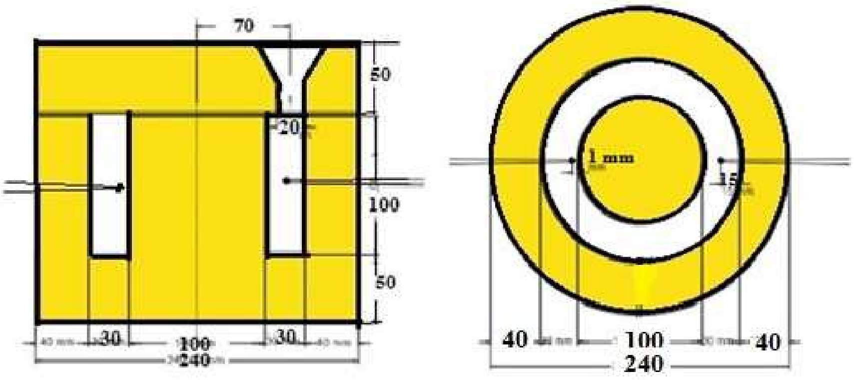

Fig. 1. Casting - mould assembly used in the experiment (tubular cylindrical casting, Dext = 160 mm)

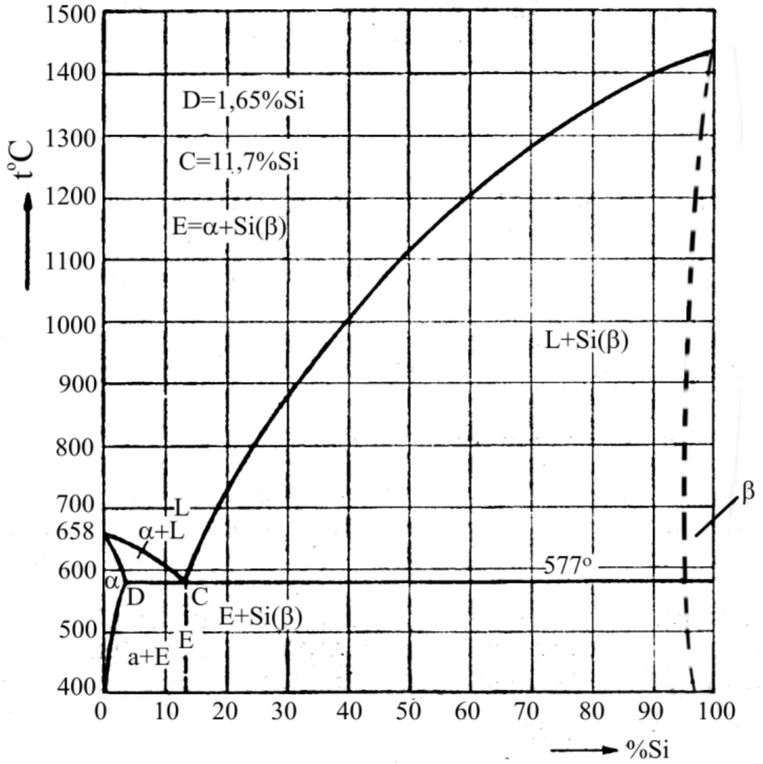

Fig. 2. Al- Si diagram of thermal equilibrium

Table 1. Chemical composition of the experimental cast alloy

No.	Element	Standard content	Content in the experimental alloy
	Symbol	%	%
1	Al	rest	87.293
2	Si	9.6-12.0	9.732
3	Fe	0-0.9	0.794
4	Cu	1.50-3.50	0.816
5	Mn	0-0.500	0.141
6	Mg	0-0.300	0.277
7	Cr	0-0.100	0.026
8	Zn	0-1.00	0,724
9	Ti	-	0.031
10	Pb	0-0.100	0,074
11	Sn	0-0.200	0,055
12	Ni	0-0.500	0.024
13	V	-	0.013

The theoretical eutectic temperature of Al-Si binary alloy is T_{E0} = 577 °C.

The alloying elements of the alloy eutectic, temperature changes of binary Al - Si. Eutectic temperature alloys Al-Si industry is given by:

$$T_{Ecalc} = T_{E0} - (12.5/[Si])\cdot\{(4.43[Mg]+1.43[Fe] + 1.93[Cu] + 1.7[Zn] + 3[Mn] + 4[Ni])\}, \quad (1)$$

where: T_{E0} - eutectic temperature is in equilibrium binary diagram Al-Si, T_{Ecalc} - eutectic temperature for the alloy that contains other alloying elements, [Me] - concentration of metallic alloying element respectively.

Applying this relationship for the alloy poured into the experiment that theoretical eutectic temperature of the alloy cast relation become:

$$\begin{aligned} T_{Ecalc} = 577 - 12.5 / 9.732\ \{4.43[0.277\} + 1.43[0.794] + 1.93[0.816] + 1.7[0.724] + \\ + 3[0.141] + 4[0.024] = 577 - 7.3 = 569.7\ °C \approx 570\ °C \end{aligned} \quad (2)$$

This value (570 °C) is close to solidus temperature that the experimentally - values was recorded. For this alloy, the experiment revealed the eutectic temperature range, T_{Eexp} = 568 ÷ 570 °C. The mould was made of sand (SiO_2) with sodium silicate binder hardened with carbon dioxide (CO_2).

4. Experimental Results

The figure 3 shows aspects of the experiment. It is shown the mould, filling the mould, the alloy solidification in the mould, the equipment to thermal analysis. The figure 4 shows the recorded temperature curves of the experiment. Based on the numerical results recorded by thermocouples, the temperature of the cast alloy was determined at the starting point of the thermal analysis (considered the starting point of liquid alloy cooling in the experiment), as well as the temperature and time of the start and of the end of alloy solidification in the two points. The values of these parameters are given in table 2.

The experimental curves reveal a small range of the solidification temperature. The temperature of solidification starting (the liquidus temperature) it is superior to eutectic temperature. The solidification range is relatively small, approx. 2.4 - 3.6 °C.The experimental curves revealed for alloy casting solidification starting temperature (liquidus temperatures) T_{L2} = 573.608 °C and T_{L1} = 570.431 °C. The solidus temperatures experimentally measured are T_{EUT1} = 569,992°C and T_{EUT2} = 568,048°C.

5. A Simulation - Experiment Comparison

The results of the experimental thermal analysis were compared with those obtained by the solidification simulation with the developed software. For this purpose, the cooling and solidification of the casting in the experiment was simulated (the part from figure 1).

a) Mould cavity

b) Alloy pouring

c) The equipment to temperature measuring and recording

d) Casting solidification

Fig. 3. Cast of experimental sample

Table 2. Experimental results

Point of measuring	Initial temperature	Cooling start time	Temperature of solidification start	Experimental eutectic temperature	Solidification start time	Solidification end time	Cooling in liquid state time	Solidification time
-	T_0	t_0	T_L	T_{Eexp}	t_{0L}	t_{SS}	$\Delta t_L = t_{0L} - t_0$	$\Delta t_S = t_{SS} - t_{0L}$
-	°C	s	°C	°C	s	s	s	s
"A" point	675.812	178	573.608	569.992	330	1435	108	1105
"B" point	656.329	183	570.431	568.048	322	1414	139	1231

"A" point – 15 mm from outer surface; "B" point – 1mm from inner side

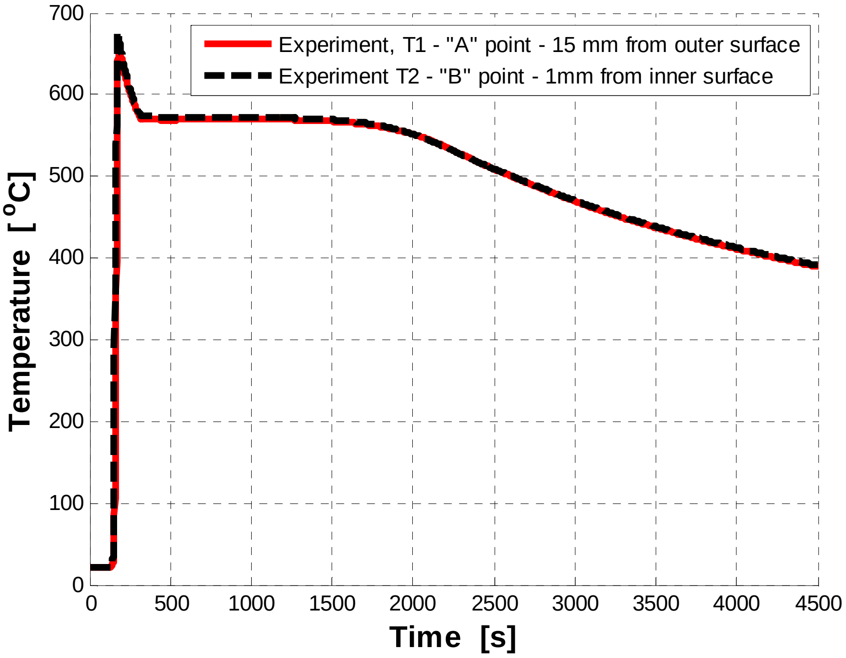

Fig. 4. Temperature variation recorded by experiment

In the simulation, we used the values from table 3 [8, 9]. For the liquidus and solidus temperatures have been used the experimentally measured values in the two points (A and B respectively). The temperature variation curves obtained by simulation for the two points (A and B) are shown in figure 5. For a better comparison of the results obtained by simulation with the experimental ones, for each point in Figures 6 (point A) and 7 (point B) are overlaid on the same graph, the curve obtained through experiment and simulation.

Table 3. Geometrical and thermophysical characteristics used in the simulation

No.	Parameter name	Symbol	Unit	Value
1	Outer diameter of part	D	m	0.16
2	Inner diameter of part	d	m	0.10
3	Part length	L	m	0.10
4	Outer diameter of mould	L_{Fo}	m	0.24
5	Mesh step of mould dividing	Δ	m	0.001
6	Time step	τ	s	0.005
7	Environment temperature	Tex	^{0}C	20
8	Coefficient of heat exchange with the environment	αex	W/m^2/K	10
9	Liquidus temperature of the alloy in A point (in B point)	Tsme	^{0}C	574 (572)
10	Solidus temperature of the alloy in A point (in B point)	Tsme	^{0}C	570 (568)
11	Coefficient of thermal conductivity of the mould	λsfo	W/m/K	0.6
12	Coefficient of thermal conductivity of the solid alloy	λsme	W/m/K	200
13	Coefficient of thermal conductivity of the liquid alloy	λlme	W/m/K	100
14	Specific heat of the mould	Csfo	J/kg/K	1000
15	Specific heat of the liquid alloy	Clme	J/kg/K	1200
16	Specific latent heat of the solid alloy	Csme	J/kg/K	1000
17	Mould density	ρfo	Kg/m^3	1550
18	Liquid alloy density	ρme	Kg/m^3	2600
19	Latent heat of the alloy solidification	Lme	J/kg	530000
20	Initial temperature of the mould	T0fo	^{0}C	20
21	Initial temperature of the liquid alloy	T0me	^{0}C	676

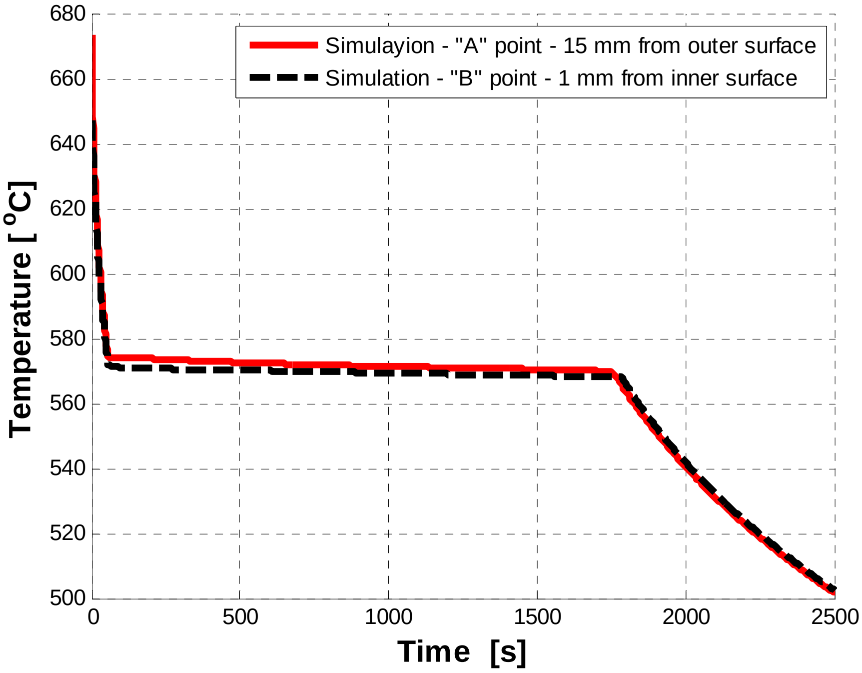

Fig. 5. Temperature variation curves, determined by simulation (with SIM-SOLSOl - CIL)

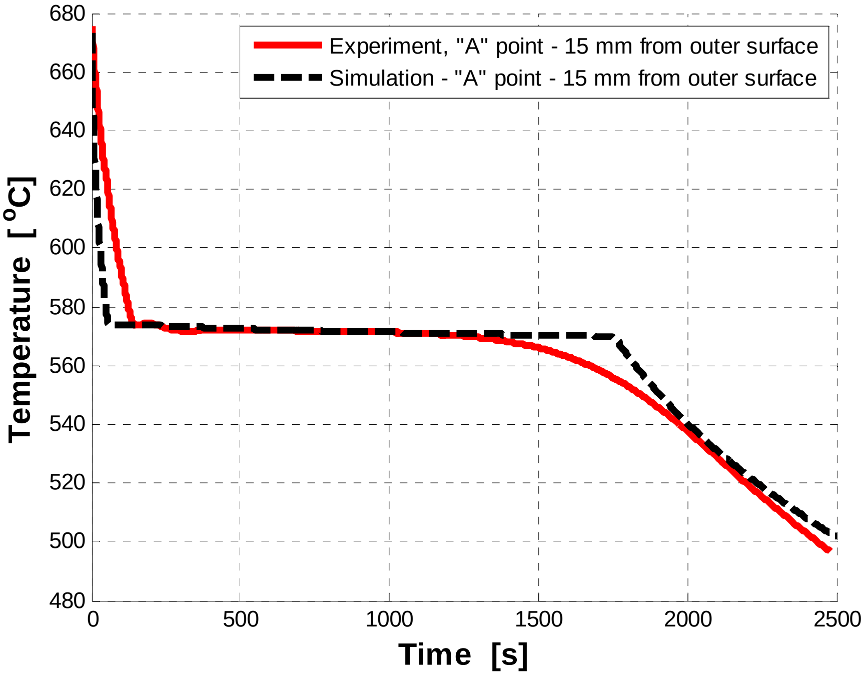

Fig. 6. Experimental and theoretical (by simulation with SIM-SOLSOL- CIL) cooling curves in a point "A" located 15 mm from the outer surface of casting

Figures 6 and 7 show a good correlation between the simulation results and those obtained by experimental thermal analysis for both points ("A" and "B") analysis. Small differences occur in the liquid alloy cooling and in the solidification end zone. The differences in the liquid area can be explained by a possible deviations of the thermophysical characteristics values (specific heat, thermal conductivity for the liquid alloy) used in the simulation. Differences in the end solidifying area can be explained by the sub-cooling of the alloy crystals constitution. The sub-cooling of constitution it are meet near the real solidification end. This super cooling cannot be taken into account by software that simulates macro-solidification.

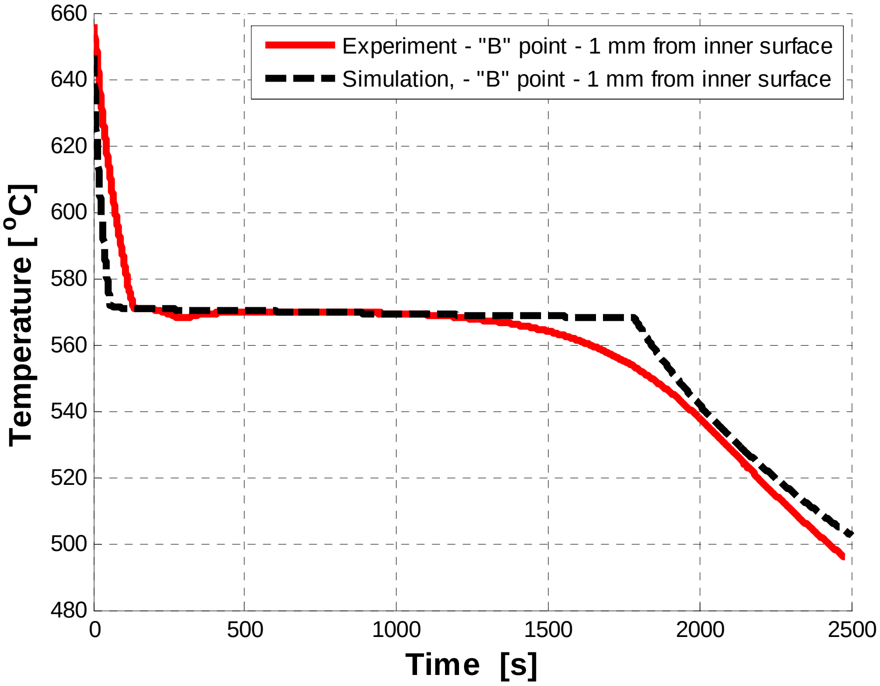

Fig. 7. Experimental and theoretical (by simulation with SIM-SOLSOL- CIL) cooling curves in a point "B" located 1mm from the inner surface of casting

In conclusion, the experimental thermal analysis confirms the simulation results by software, subject to verification. The software-verified SIM-SOLSOL-CIL provides accurate data on solidifying castings (for solidification and temperature distribution) alloy solidification temperature range. As a result, this software can be used with sufficient precision the theoretical and practical research on solidification of parts with symmetry of rotation, and for the design and optimization of casting technologies, including centrifugally cast.

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