Computer modelling of the ablation casting process and prediction of strength properties of AC-42000 castings

Marcin Małysza[1,2], Sabina Puzio[2], Katarzyna Major-Gabryś[2],
Mirosław Głowacki[2], Dorota Wilk-Kołodziejczyk[1,2], Jadwiga Kamińska[1]
[1] Center of Casting Technology, Łukasiewicz Research Network – Krakow Institute of Technology, Poland
[2] AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland
malysza@agh.edu.pl; sabina.puzio@gmail.com;
katmg@agh.edu.pl; glowacki@metal.agh.edu.pl;
dwilk@agh.edu.pl; jadwiga.kaminska@kit.lukasiewicz.gov.pl

Keywords: casting, simulations, ablation, gravity sand casting, gravity die casting, mechanical properties

1. Introduction

Simulation process is a preliminary process before performing the real experiment and has already been included in the series of works related to the preparation of a new product manufactured in the casting technology. This approach allows for initial verification, in virtual conditions, of the correctness of the design assumptions. Computer simulations in the process of designing cast parts are already in common use. As a designer tool, they allow for the verification of design assumptions resulting from the nature of the work of the designed part. At the stage of designing the casting technology the possibility of a preliminary evaluation in the means of computer simulations allows to reduce the number of real time tests and prototypes, which allows to reduce costs [1–5]. One of the methods by which you can logically segregate subsequent design steps is the Integrated System for Modelling Materials and Engineering Processes – (ICME). This method is used in various solutions and is described in [6,7]. This consistent approach allows the integration of computer-aided engineering design systems at different levels for design evaluation and manufacturing methods. The presented topic is related to the method of gravity casting into the mould on a sand matrix, which is exposed to water after the filling process. This method is called ablative casting. The essence of the process consists in pouring the metal into sand moulds, which during the solidification of the casting are intensively cooled with water until complete disintegration. In this process, moulds with water-soluble binders are used [8,9]. Numerous authors have confirmed that the microstructure of castings made with this technology is much finer than in the case of the conventional technology of casting aluminium alloys [10-12] By increasing the cooling rate, both the secondary dendrite arm spacing (SDAS) and the size of the eutectic phases are reduced [13–15]. The ablation casting technology is therefore an economic process that enables the production of high-quality castings with a fine structure of dendrites and other secondary phases, characterized by an even distribution. This in turn improves the mechanical properties of the finished castings [16,17].

2. Research methodology

Computer simulations were carried out in Flow3D and Flow3D-Cast. Taking into account the process of physical degradation by washing with water flowing from nozzles under pressure

The publication is co-financed from the state budget under the programme
of the Minister of Education and Science called "Excellent Science" project no. DNK/SP/548041/2022

Doskonała Nauka
Ministry of Education and Science Republic of Poland
Republic of Poland

requires taking into account a number of parameters. The following values of the program data should be introduced, such as: *saturation concentration in fluid*, *mass transfer coefficient at dissolving surface*, *solid solute density*, *mixture density coefficient*, *molecular diffusion coefficient*. These parameters describe the behaviour of the sand matrix in contact with the water flowing out of the nozzles at a given speed. The computer simulations were conducted in a coupled manner. The mathematical model describing the flow phenomena is not able to take into account two liquids in one analysis. In this case, there is a liquid casting alloy that cools down and solidifies, and there is water washing the sand mould. Therefore, it was assumed to combine the results of ablation simulations, and then, based on the obtained results, to conduct another simulation taking into account casting and solidification. Solidification is modelled on the basis of the chemical composition. The amount of microstructure components formed is predicted numerically as a function of the cooling rate. The analysis is conducted in the macro area and it is simplified. Table 1 shows the list of compound components predicted by numerical simulation [18–20].

Table 1. Relationships for calculating the liquidus slopes in AlSi-based alloys [20].

Element	Liquidus slope, ml, I, OC/wt%
Si	–5.584 – 0.081 · Si – 9.76E-04 · Si2 – 0.1169 · Cu + 0.267 · Mg – 0.1 · Zn + 0.124 · Fe
Cu	–2.695 + 6.574E-03 · Cu – 8.191E-04 · Cu2
Mg	–4.033 – 0.088 · Mg – 0.014 · Cu
Zn	–1.449 + 0.092 · Zn – 0.0395 · Cu
Fe	–2.891 + 0.09 · Fe – 0.1048 · Cu
Mn	–1.677

The solidification model of the liquid alloy and the change in the proportion of liquid and solid phases with a decrease in temperature is solved by the formula:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(k \nabla T) + \rho \Delta H_f \frac{\partial f_s}{\partial t} \tag{1}$$

where: T – temperature [°C], t – time [s], ρ – density [kg/m^3], C_p – specific heat[J·kg^{-1}·K^{-1}], k – thermal conductivity [W·m^{-1}·K^{-1}], H_f – latent heat of fusion [J/kg], f_s – solid fraction.

The simulations are based on the CAD geometry (Figure 1A) and boundary conditions taking into account parameters such as initial temperature of the alloy, die temperature, pouring time, alloy chemical composition, the nozzle location, diameter and velocity of the water for the ablation process of sand mould. Examples of the results of the ablation process simulation are presented in the Figure 1B.

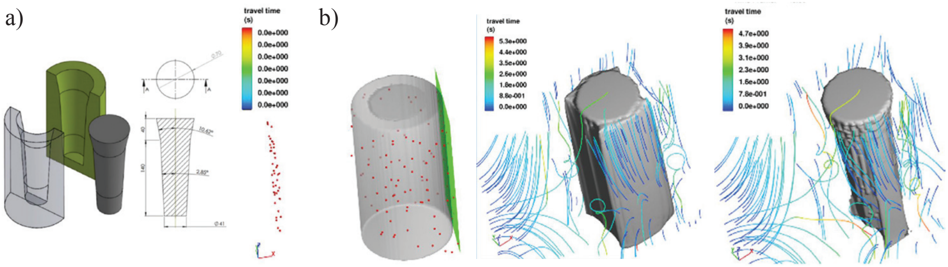

Figure 1. a) Model of the ingot and the mould used in the research; b) Mould ablation process simulation, red dots represent flow line tracing points.

Determining the value of the heat transfer coefficient is done dynamically by the solver. The calculated value is directly implemented in the next simulation in which the casting and solidification processes are analysed. The pouring temperature in the simulation is Tzal = 700°C, the pouring time tzal = 2 s. Two measuring points were used in the cavity volume of the casting mould, the first in the lower part of the cavity, the second in the middle part. The simulation takes into account the prediction of final mechanical properties in the volume of the ingot. Figure 2 shows the example of a cross-section through a virtual ingot detailing the tensile strength and elongation. Additionally, the SDAS prediction is presented.

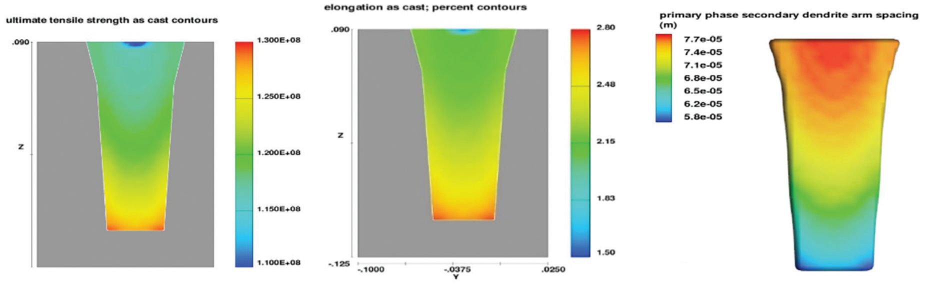

Figure 2. Predicted strength properties in the analysed ingot and SDAS for gravity sand casting.

In Figure 3 the comparison of the real ablation and virtual experiment are presented.

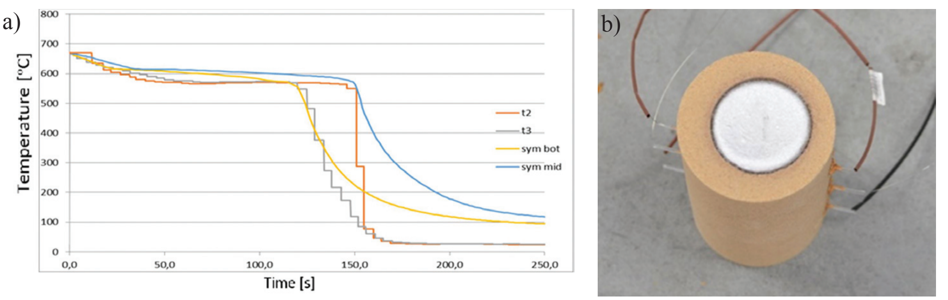

Figure 3. a) Comparison of solidification curves for ablation process real and virtual experiment; b) sand mould with thermocouples.

Simulation and real experiment has a good accuracy. The solidification process in the first phase is very similar. The point of quick cooling is very close to each other. The main crystallization and creation of microstructure occurs between 680°C and 550°C. In that temperature range the curves of simulation and real laboratory trial has convergence. Comparison of the simulation predictions of mechanical properties and DAS are presented in the table 2.

Table 2. Comparison of the simulation predictions of mechanical properties and DAS.

	Cast		Sim		DAS				Sim			
	Rm, MPa	A%	Rm, MPa	A%	bottom	middle	top	avg.	bottom	middle	top	avg.
Sand	109	0.4	130	2	36.1	45.8	36.3	39.4	45	50	55	50
Die	175	3.3	165	4	56.6	74.5	85.5	72.2	58	71	77	68.6
Ablation	172	2.7	170	5.5	33.5	41.2	42.1	38.9	25	29	33	29

The predicted mechanical properties under simulated conditions differ slightly in terms of tensile strength. The differences in sand casting, die casting and ablation casting successively are 19%, 6%, 2%. The biggest difference in strength prediction was observed for sand casting. Significant discrepancies were weighed in the prediction of elongation. For sand casting, the difference is 4 times, for die casting it is 20%, while for ablative casting the difference is 2 times. The prediction of dendrite growth was also compared. In this case, the mean value depending on the height is 25%, 5%, 26% respectively. The most similar results were obtained in the middle area of the ingot. The numerical model and the research carried out allow us to conclude that it is possible to use a computer program to simulate more complex parts in ablation casting technology. Additional simulations are required to correct the parameters related to the prediction of strength properties, especially elongation.

References

1. Abro S.H., Shamsi H.A., Wahab S., Mohsin A.: *Design And Development Of Casting Part By Simulation, International Conference on Energy*. Water and Environment – ICEWE-2021 New Campus, University of Engineering and Technology Lahore 31st March 2021, Lahore, Pakistan, 2021, 452.
2. Dojka R., Jezierski J., Campbel J.: *Optimized Gating System for Steel Castings*. Journal of Materials Engineering and Performance, 27, 2018, 5152–5163.
3. Danylchenko L.: *Comparative analysis of computer systems for casting processes simulation*. [in:] International conference advanced applied energy and information technology 2021, Ternopil National Ivan Puluj Technical University, Ukraine, 2021.
4. Deepthi T., Balamurugan K., Uthayakumar M.: *Simulation and experimental analysis on cast metal runs behaviour rate at different gating models*. International Journal of Engineering Systems Modelling and Simulation, 12, 2021.
5. Jayal A.D., Badurdeen F., Dillon Jr O.W., Jawahir I.S.: *Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels*. CIRP Journal of Manufacturing Science and Technology, 2, 2010, 144–152.
6. Arrazola P.J., Özel T., Umbrello D., Davies M., Jawahir I.S.: *Recent advances in modelling of metal machining processes*. CIRP Annals, 62, 2013, 695–771.
7. Campbell J.: *Castings*. 2nd Edition, Butterworth-Heinemann, 2003.
8. United States Patent No. US 7,159,642 B2)
9. Puzio S., Kamińska J., Angrecki M., Major-Gabryś K.: *Effect of the type of inorganic binder on the properties of microwave-hardened moulding sands for ablation casting technology*. Archives of Metallurgy and Materials, 65, 2020, 1385–1390.
10. Dudek P., Fajkiel A., Reguła T., Bochenek J.: *Badania nad technologią odlewania ablacyjnego stopów aluminium*. Prace Instytutu Odlewnictwa, tom LIV, 2014.
11. Ananthanarayanan L., Samuel F.H., Gruzelski J.: *Thermal analysis studies of the effect of cooling rate on the microstructure of 319 aluminium alloy*. AFS Trans, 100, 1992, 383–391.
12. Thompson S., Cockcroft L.M., Wells M.M.: *Advanced high metals casting development solidification of aluminium alloy A356*. Materials Science and Technology, 20, 2004, 194–200.
13. Jordon J.B., Wang L.: *Monotonic and Cyclic Characterization of Five Different Casting Process on a Common Magnesium Alloy*. International Manufacturing Science and Engineering Conference, Proceeding ASME, Corvallis, Oregon, USA, 2011, 7–16.
14. Jorstad J.L., Rasmussen W.M.: *Aluminum Science and Technology*. American Foundry Society, 368, 1997, 204–205.
15. Weiss D., Grassi J., Schultz B., Rohagti P.: *Ablation of hybrid metal matrix composites*. Transactions of American Foundry Society, 119, 2011, 35–42.
16. Taghipourian M., Mohammadalihab M., Boutorabic S., Mirdamadic S.: *The effect of waterjet beginning time on the microstructure and mechanical properties of A356 aluminium alloy during the ablation casting process*. Journal of Materials Processing Technology, 238, 2016, 89–95.

17. Grassi J., Campbell J.: *Ablation casting, Aluminum Alloys, Characterization and Applications*. eds, Weimin Y., Subodh K.D., 2010, 73–77.
18. Honda, Press materials: *New Technical Details for the Next Generation of the NSX Model*. SAE 2015 World Congress and Exhibition, 2015.
19. Catalina A.V., Xue L., Monroe C.A.: *A Solidification Model with Application to AlSi-Based Alloys*. Shape Casting, 2019, 201–213.
20. Flow3D-Cast manual, 2021.