COB-2021-1055
COMPUTATIONAL SIMULATION FOR EVALUATION AND OPTIMIZATION OF CASTING PARAMETERS FOR ALUMINUM-SILICON ALLOYS

Carlos Costa de Carvalho
Diego David Silva Diniz
Jackson de Brito Simões
Federal Rural University of Semi-Arid Region, Engineering Department. Avenida Universitária Leto Fernandes, Sítio Esperança II - Caraúbas – RN – Brazil. Zip Code: 59780-000.
carlosufersa@gmail.com; diego.diniz@ufersa.edu.br; jackson.simoes@ufersa.edu.br

Abstract. The casting process is employed in various sectors of industry, moves several companies, and generates thousands of jobs. In the recent decades, the computer simulation made it possible to increase productivity and resource savings through the elimination of empirical methods (trial and error) in gating and feeding design, predicting defects before the prototype manufacturing process. In the other hand, the number of studies involving casting simulation is still considered low, as well as the qualification necessary to develop related projects; the reason is that this technology is still considered recent and little explored. This work aims to present a computational modeling study focusing on the optimization of casting process through the analysis of the following parameters: heat transfer coefficient (HTC), mold temperature, pouring temperature, and pouring time. The mold was designed in the software Autodesk Inventor 2019, and then exported to the ESI ProCAST 2019; the simulations were conducted considering the gravity sand casting process for the AlSi7Mg aluminum-silicon alloy. Thus, 16 simulations were carried out in which the casting quality was evaluated through three metrics: maximum local porosity, average porosity and hot spots. The results presented the possibility of predicting the behavior of phenomena present in the casting process, in which the HTC parameter and the pouring time had less significant influence on the casting quality. Finally, it was possible to optimize and quantify the study variables in a gating design of a flywheel; it was verified that the low levels of casting defects ensured the component quality.

Keywords: Porosity, casting, simulation, optimization, alloys.

1. INTRODUCTION

Sand casting is one of the most versatile fabrication methods; it can be used for complex shape parts, made of ferrous and nonferrous metals (Sultana, 2018). It can be defined as the process of pouring molten metal in a cavity mold with the corresponding shape and size of the produced part (Moro, 2007). The casting process is employed in various sectors of industry, moves several companies, and generates thousands of jobs. This manufacturing process is relevant in our daily lives, and it leads to a large amount of parts daily manufactured. Cast parts are used in 90% of all equipment and machines (Oliveira, 2020). The figure 1 shows an example containing the amount of casting parts in a motorcycle Honda® CG Fan 160. The casting parts vary from the engine parts to the suspension forks, showing that it is a versatile and widely used process.

In Brazil, most foundry companies are small and have family management (Oliveira, 2020). The geometry of feeding and gating system is obtained by the trial and error method, and this technique is time consuming and increases the cost for the company (Sultana, 2018). A good way of solving this problem is the use of simulation, which is the process of using a set of equations implemented in a computer program in order to imitate the actual casting process. The casting simulation is a tool that can be used to visualize mold filling, solidification, cooling, and to predict defects such as shrinkage porosity (Ravi, 2008). The improvement of this technology made the simulation an essential tool for casting defect troubleshooting and method optimization (Ravi, 2008).

Consequently, in the last decades, the foundry companies radically changed the way they offer products and services, from being a subcontracting company to being a company that uses technology and develop products with the customer. Thus, the use of computer simulation became part of the routine of companies that want to remain competitive in the market (Oliveira, 2003). In the other hand, the high cost of simulation software licenses and the difficulty in finding skilled engineers, has prevented its dissemination in the companies (Ravi, 2008).

Figure 1. Cast parts in a motorcycle Honda model CG Fan 160.

The metal casting is influenced by a large number of factors, which can be related to the material, casting geometry, and process (Ravi, 2008). The present work aims to evaluate some variable in the process. The green sand casting process parameters are essential for improving the quality of cast products (Sultana, 2018).

In this paper, it was used a commercial software that uses the finite element method (FEM) to perform the necessary calculations in the simulation. It has different modules, which allow the modeling of heat transfer, fluid dynamics (mold filling), radiation, and residual stress. Furthermore, it is possible to perform microstructure, heat treatment, and porosity simulations. As for the types of casting, it is possible to work with the main methods currently available, such as gravity die casting (GDC), high pressure die casting (HPDC) and low pressure die casting (LPDC), continuous casting, and centrifugal casting.

The alloy used in this work is the AlSi7Mg, from the Al-Si system. According to ABAL (2007), aluminum can combine with most of the existing metals, forming metallic alloys; this feature becomes a differential, as it is possible to create alloys for specific applications, with adjusted characteristics of mechanical resistance, corrosion resistance ability, conductivity, machinability, and ductility. Thus, these are the most important cast aluminum alloys, mainly due to their high fluidity, low shrinkage in castings, high corrosion resistance, good weldability, easy brazing, and low thermal expansion coefficient (Almeida, 2008).

2. METHODOLOGY

This research was conducted by the Federal University of Semi-Arid Region (UFERSA) in partnership with the Intelligent Materials and Structures Laboratory (LaMMEA), from Federal University of Campina Grande (UFCG). The paper methodology is divided into two parts: the part 1 is for the aluminum-silicon alloy parameter optimization, and the part 2 is for the optimized parameters application in a gating and feeding design of a flywheel.

For this paper, two software were used: Autodesk Inventor 2019 and ESI ProCAST 2019. Autodesk Inventor is CAD software used in the molds design for the simulation. The CAD modeling was designed, saved with an appropriate extension, and then exported to the second software: the ESI ProCAST. In this software, the mesh was made and a set of parameters were chosen before the simulation start. The methodology phases of this study can be seen in the flowchart presented in Figure 2.
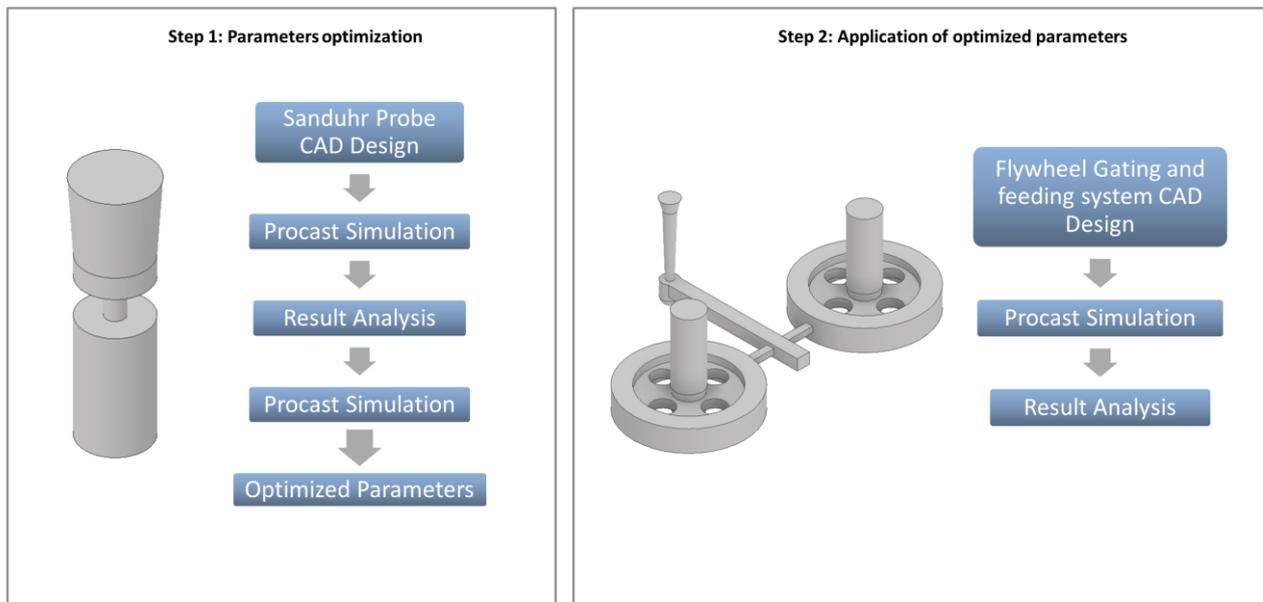
Figure 2. Methodology used in this paper. Step 1: Parameters optimization, and step 2: Application of optimized parameters.

As stated previously, the parameters optimization was made in the step 1. The same mold exposed by Kucharčík (2014) was used; it is a type of experimental mold for simulations and validations called Sanduhr Probe, which is used by a foundry company to assess porosity. After the mold was designed in the CAD software, the mesh was generated and the parameters were set in the ESI ProCAST program. The alloy used in this paper was the AlSi7Mg, and for this optimization four important parameters in the sand casting process were chosen: the heat transfer coefficient (HTC), mold temperature, pouring temperature, and pouring time. Four values were chosen for each parameter, and then they were combined and simulated, making a total of 16 simulations at the end of the process.

These are just a few of the numerous casting variables that can be modified, where some have more influence than others. Thus, it would be unfeasible to do an optimization job with all possible variables, as the number is large and most have no considerable influence on the final result. Also, it is important to emphasize that some parameters such as the HTC are experimentally determined and the values presented are just to evaluate their influence in the sand casting process. The parameters and values are shown in the table 1:

Table 1. Parameters for the AlSi7Mg alloy optimization.

Parameter	Value			
Heat transfer coefficient – HTC (W/m^2.K):	250	500	750	1000
Mold temperature (°C):	30	80	130	180
Pouring temperature (°C):	700	800	900	1000
Pouring time (s):	3	5	7	9

These parameters were used in order to verify their influence on Al-Si alloy casting. In each of these simulations, three metrics were evaluated: maximum local porosity, average porosity, and hot spots. The simulations results were put in a table and analyzed in order to pick the best of them, which were simulated again in order to evaluate if the defects reduction were satisfactory.

The step 2 is the application of the optimized variables in a design of the gating and feeding system for the fabrication of two flywheels, based on the work of Sultana (2018). Two simulations were made: one for comparing with the article results and the second one with the optimized parameters. In the article, the design gating and feeding system was simulated in Click2cast software with the AlSi7Mg alloy (Sultana, 2018). The green sand gravity cast was simulated, using pouring temperature of 713 °C, and the mold temperature of 20 °C. Also, the mesh used has 2 mm element size. Both of the parts simulated in this paper are shown in the figure 3.
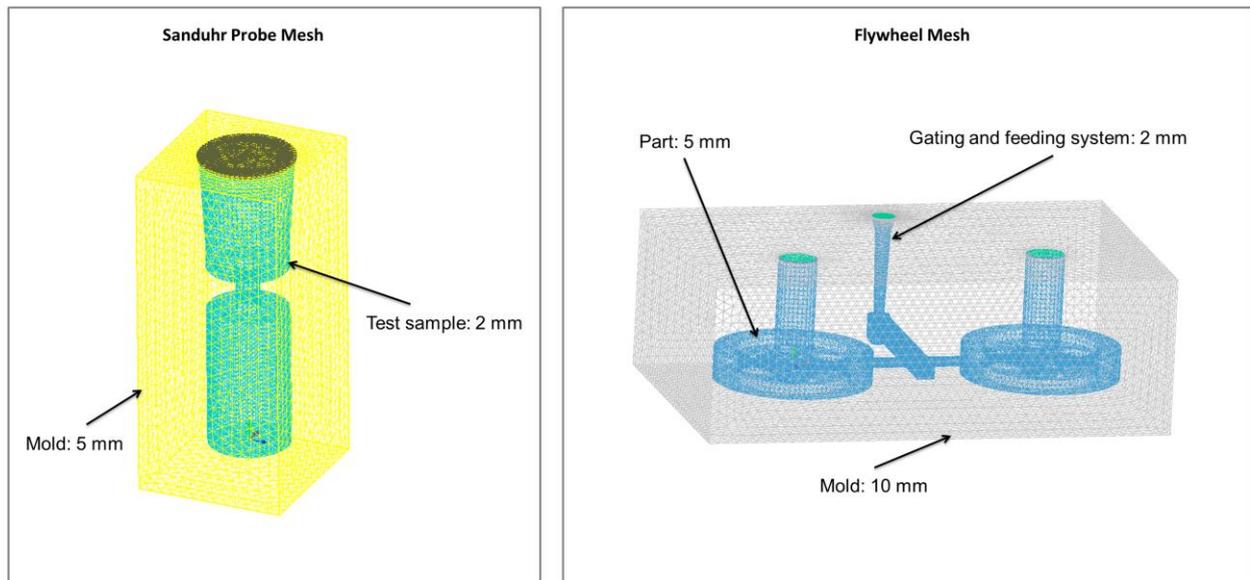
Figure 3. Mesh used in the simulations for the steps 1 and 2.

This software uses triangular mesh elements for 2D surfaces and tetrahedral mesh elements for 3D parts. The choosing of elements mesh sizes were made due to the need to reducing the computational time in the simulation as much as possible; thus, the sections with smaller dimensions have the smallest mesh size. The Sanduhr Probe mesh (step 1) has about 173 thousand elements, where the mold elements size is 5 mm and the test sample size is 2 mm. The flywheel mesh (step 2) has approximately 900 thousand nodes, reinforcing the need for robust machines for this type of simulation. In this tetrahedral mesh, the element sizes are as follow: 2 mm for the sprue, runner, and in-gate; 5 mm for the parts and risers; and 10 mm for the mold.

3. RESULTS

3.1. Step 1: parameters optimization

In the first step, 16 simulations were conducted in order to evaluate the parameters behavior and their significance in the process; the main results are shown in the table 2. The best results were picked for two more trials, used for choosing the best parameter values for the AlSi7Mg alloy in the sand casting process.

The first property analyzed was the heat transfer coefficient (HTC), where simulations were performed for the values of 200, 500, 750 and 1,000 W/m²K. It is noteworthy that the HTC values are difficult to obtain, because it is related to the heat transfer at the interface between the metal in the mold cavity and the mold material. Therefore, as this is an experimental variable and it was not possible to find such values in the literature, HTC was used in order to visualize its influence on the gravity sand casting of Al-Si alloys. Analyzing the HTC, the average values of maximum local porosity are considered high (37.9%), and may be unacceptable for certain projects that require greater forces acting on the components at this point specifically. Analyzing the standard deviation value in the maximum local porosity (only 0.8%), it is possible to infer that the HTC has little significant influence, as the porosity values practically did not change in response to the changes in this parameter values. Therefore, as the HTC's actual value for the conditions presented is not known, HTC of 500 W/m².K was chosen as the optimized value for this part, as this is an intermediate value. The average porosity values did not change, remaining around 1%, showing the insignificance of HTC in this process.

The hot spots values are presented in inverse proportion to the porosity, i.e. the lowest values of porosity resulted from major hot spots, and vice versa, and this was expected due to the alloy solidification process characteristic.

The mold temperature was significant, and the average maximum local porosity, which was 37.9% on HTC, dropped to 36.4%. The standard deviation rose from 0.8% (HTC) to 2.2%, showing that variations in this parameter produced significant changes in the response, making it of great value in this study. The local maximum porosity values dropped from 36% at 130 °C to 33.5% at 180 °C. Therefore, the value chosen in the optimization step will be 180 °C which is a mold preheat temperature that can be easily reached in practice.

As well as the mold temperature, the pouring temperature was also very significant in this process, with an average maximum local porosity of 35.3%. The hot spots average was the largest of all (297.4 s) and its standard deviation (105.8%). The standard deviation value was 2.7%, making it the most important variable in terms of response to

variation of parameters. Therefore, at first, 900 °C will be used as the pouring time optimized value. This value was chosen instead of 1,000 °C, as 100 °C less represents energy savings in the process, and in large production it can represent a significant profit.

Similarly to HTC, pouring time remains the least significant variable among the four analyzed. Its average at maximum porosity is the highest (38.1%) and its standard deviation remains at 0.3%. However, the average porosity dropped to 0.5%. For this parameter, its optimized value used was 3 seconds, but it may vary according to mold characteristics and part size.

Table 2. Simulation results for the AlSi7Mg alloy optimization.

AlSi7Mg		Maximum Porosity	Average Porosity	Hot Spots
HTC (W/m².K)	200	36.7	0.6	277.1
	500	37.7	0.6	197.1
	750	38.1	0.6	187.4
	1,000	38.6	0.6	178.9
	Average	37.9	0.6	192.3
	Standard deviation	0.8	0.0	45.3
Mold temperature (°C)	30	38.6	0.6	178.9
	80	37.5	0.5	203.5
	130	36.0	0.5	238.0
	180	33.5	0.4	283.3
	Average	36.4	0.5	225.9
	Standard deviation	2.2	0.1	45.3
Pouring temperature (°C)	700	38.6	0.6	178.9
	800	36.3	0.4	252.4
	900	33.6	0.3	333.5
	1,000	32.5	0.2	424.6
	Average	35.3	0.4	297.4
	Standard deviation	2.7	0.2	105.8
Pouring time (s)	3	38.5	0.5	160.1
	5	38.0	0.5	173.0
	7	37.9	0.5	177.2
	9	37.8	0.5	177.9
	Average	38.1	0.5	172.1
	Standard deviation	0.3	0.0	8.3

Based on the values chosen from the table 2, two simulations were carried out, called "optimization 1" and "optimization 2". In the first simulation, the value of pouring temperature was 900 °C and the other parameters are shown as follows:

- HTC = 500 W/m².K;
- Mold temperature = 180 °C;
- Pouring temperature = 900 °C;
- Pouring time = 3 s.

The results showed a very low average porosity (0.1%); however, the maximum local porosity was 31.2%. In optimization 2, the variables were practically the same, with the exception of the pouring temperature value (1,000 °C).

- HTC = 500 W/m².K;
- Mold temperature = 180 °C;
- Pouring temperature = 1,000 °C;
- Pouring time = 3 s.

In the results in the table 3, the maximum local porosity dropped to less than half, from 31.2% to 13.3%.

Table 3. Optimized results for the AlSi7Mg alloy optimization.

AlSi7Mg	Maximum Porosity	Average Porosity	Hot Spots
Optimization 1	31.2	0.1	556.1
Optimization 2	13.3	0.1	698

Based on the optimization 2 results, the shrinkage porosity can be observed in the figure 4. Note that the upper section of the Sanduhr Probe is its feeder, and the porosity in this location is not considered. Therefore, there is a small portion of porosity above the part center. The results show that even with the best parameters was not possible to remove completely the porosity in this particular mold, the Sanduhr Probe. One of the explanations for this phenomenon is the alloy composition, which contains magnesium. The aluminum and magnesium alloys are more problematic for casting. However, these alloys have good strength, ductility, and good response to heat treatments (Abal, 2007).
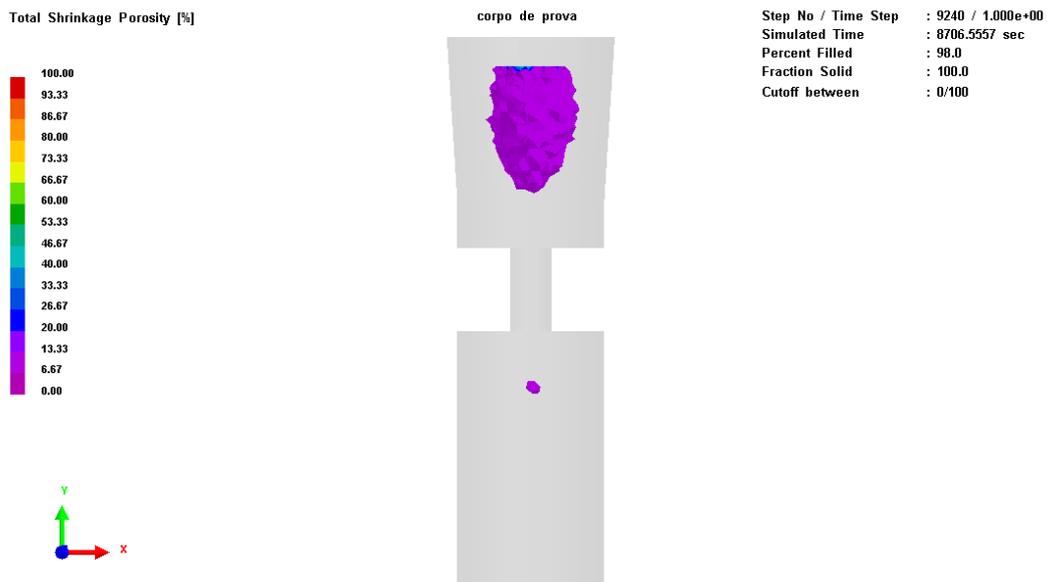

Figure 4. Porosity results on test sample mold with optimized parameters.

3.2. Step 2: Application of optimized parameters

The application of optimization results occurred in the mold design of two flywheels, developed by Sultana (2018). However, the first simulation was performed using the parameters used by Sultana´s article in order to compare both simulations. The second simulation was made with the optimized parameters obtained in the step 1. Also, the values of HTC and pouring time are the same for both trials, since they were not provided by the studied article; the pouring time was chosen as 7 seconds because the pouring basin and sprue have small diameter. Thus, very short filling times cause high velocities of the molten metal inside the mold which can lead to defects in the part. Only the parameters with the greatest influence, such as the mold temperature and the pouring temperature were changed. The table 4 shows the values applied in both simulations.

Table 4. Optimized results for the AlSi7Mg alloy optimization.

AlSi7Mg	Article parameters	Optimized parameters
HTC (W/m^2.K)	500	500
Mold temperature (°C)	20	180
Pouring temperature (°C)	713	900
Pouring time (s)	7	7

The simulation of this model lasted over 7 hours and took 21 thousand cycles. The porosity results can be seen in figure 5.
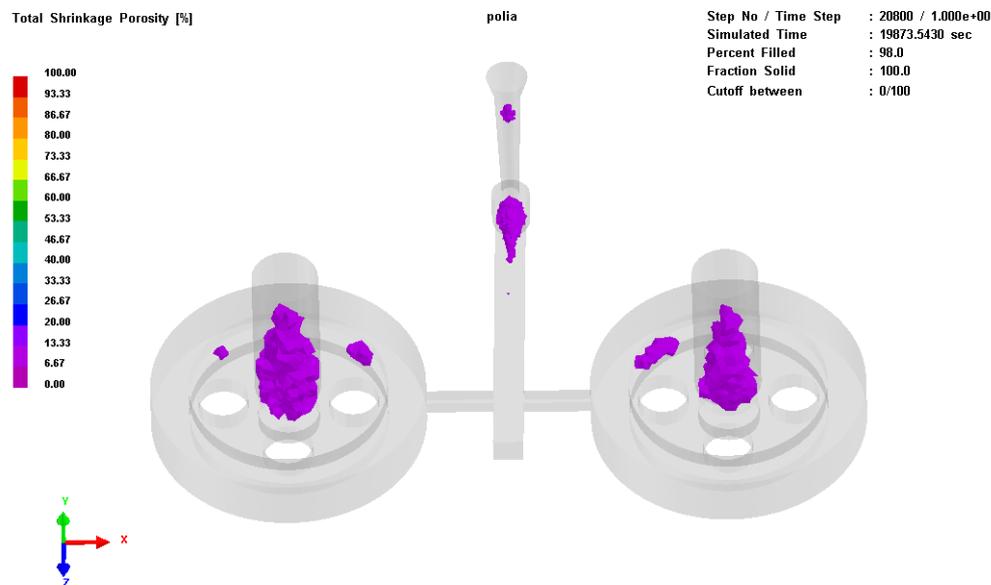

Figure 5. Porosity results on the flywheel mold with Sultana (2018) parameters.

This replication of the literature's results is essential because it is a form of qualitative validation. In this sense, the results were satisfactory, since there is a similarity between the simulation in this paper and the results presented by Sultana (2018), which can be seen in Figure 6.
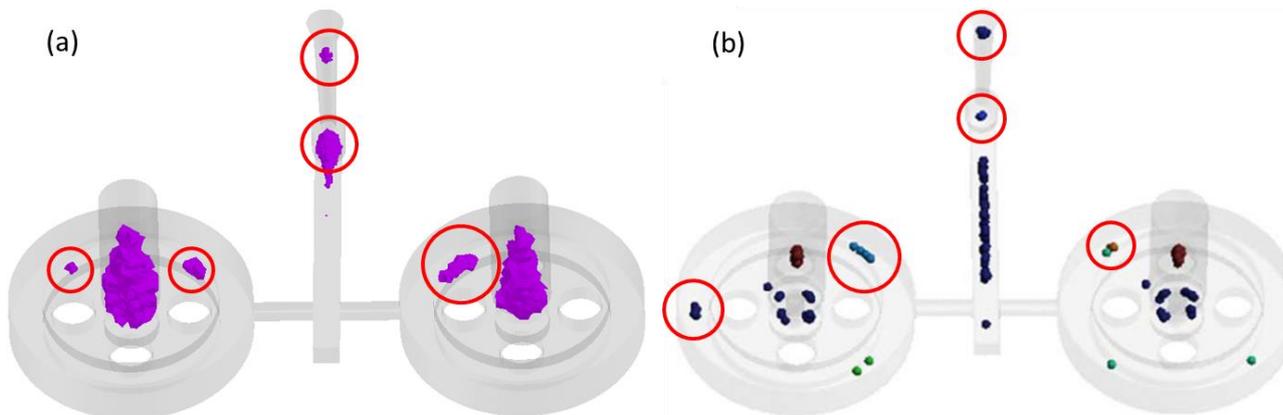

Figure 6. Porosity results simulated in this paper (a) and the results presented by Sultana (2018) (b).

Even though they were simulated in different software, the two results were similar and show most of the porosity points in similar spots. Nevertheless, figure 6 shows that these two results have similarities that qualitatively validate the simulation made in this work. For example, the porosity located in the sprue and in the sprue base well, which have different dimensions, but in the same places. Furthermore, three defects in the edge of the flywheels can be noticed in both simulations, where one of the porosities is located on the right side and the others on the left side. Note that even though the parts are exactly symmetrical, the left side has more defects than the right in both cases. There is also porosity in the risers, which concentrated most of the porosity. However, a point that can make a quantitative analysis difficult is the fact that the two software present porosity different ways: in ESI ProCAST, it is shown in percentage, whereas Click2cast shows it in cubic meters.

The second simulation was performed with the optimized parameters, using the same mesh and the same alloy: AlSi7Mg. Thus, using the optimized parameters, the flywheel design simulation was performed, which can be seen in Figure 7. As the temperature was higher than in the first simulation, it took longer to be done, about 8 hours. The results were satisfactory, as the part was free of defects, which were concentrated in the sprue, in-gates, and risers.
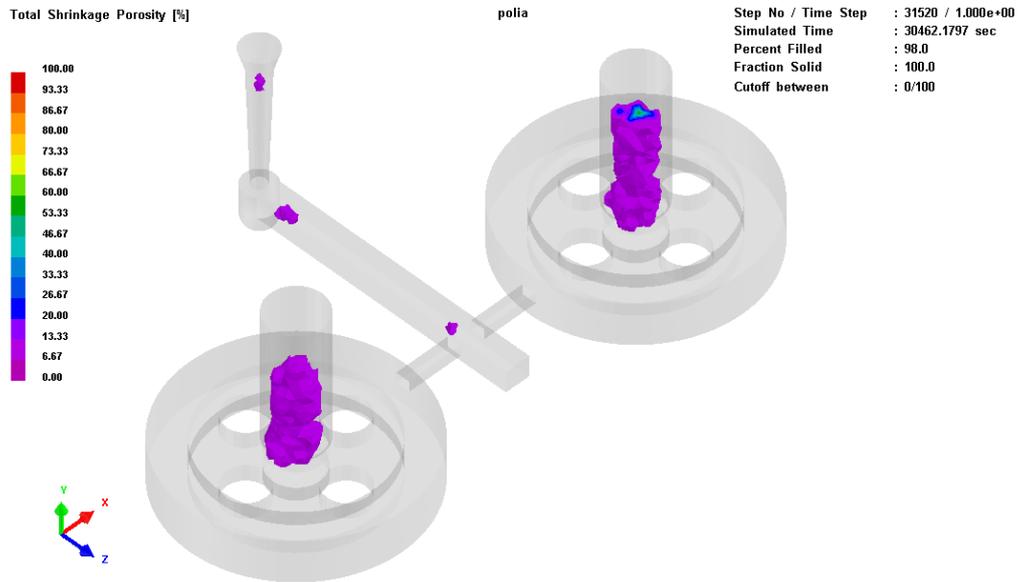

Figure 7. Porosity results on the flywheel mold with optimized parameters.

In the figure 8 it is possible to see the comparison between the two simulations performed in this research. Note that in the first simulation (a) there are defects in the flywheel, while in the second (b) the part is free of porosity.
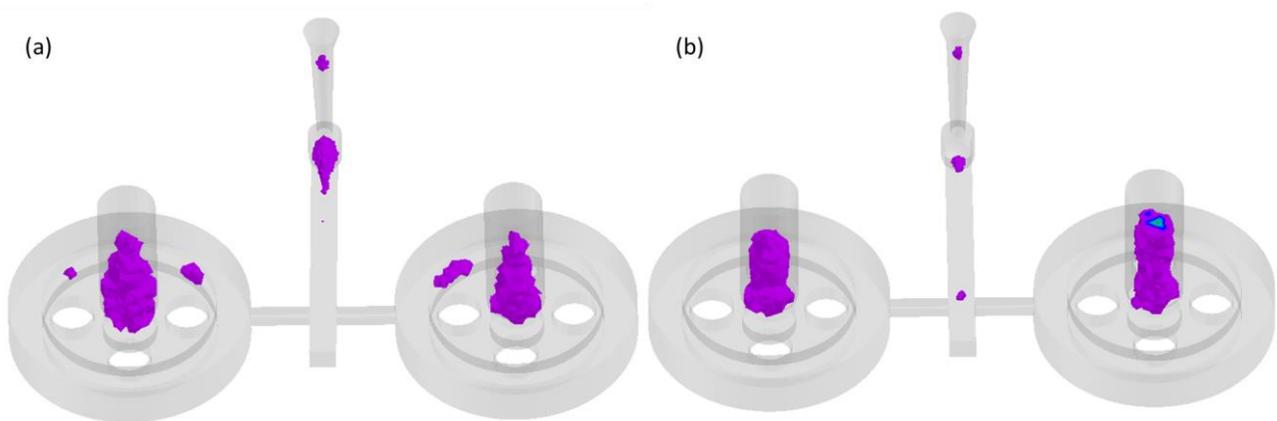

Figure 8. Porosity results with Sultana (2018) parameters (a) and the results using the optimized parameters (b).

For hot spots, there are no terms of comparison with the results of the Sultana (2018) article, as they were not provided. However, comparing the simulations performed in this work, it was possible to get an idea of how hot spots lead to porosity formation. In figure 9 it is possible to see the hot spots and porosities in the two simulated cases.

In the parameters simulations of the article by Sultana (2018), the hot spots were present throughout the part, in addition to the sprue, in-gates, and risers. The implication of this is the presence of porosity in almost the same regions, which affected the part quality. For the second case, there is still the presence of hot spots in the channels and risers, but not in the part, which was free of porosity.
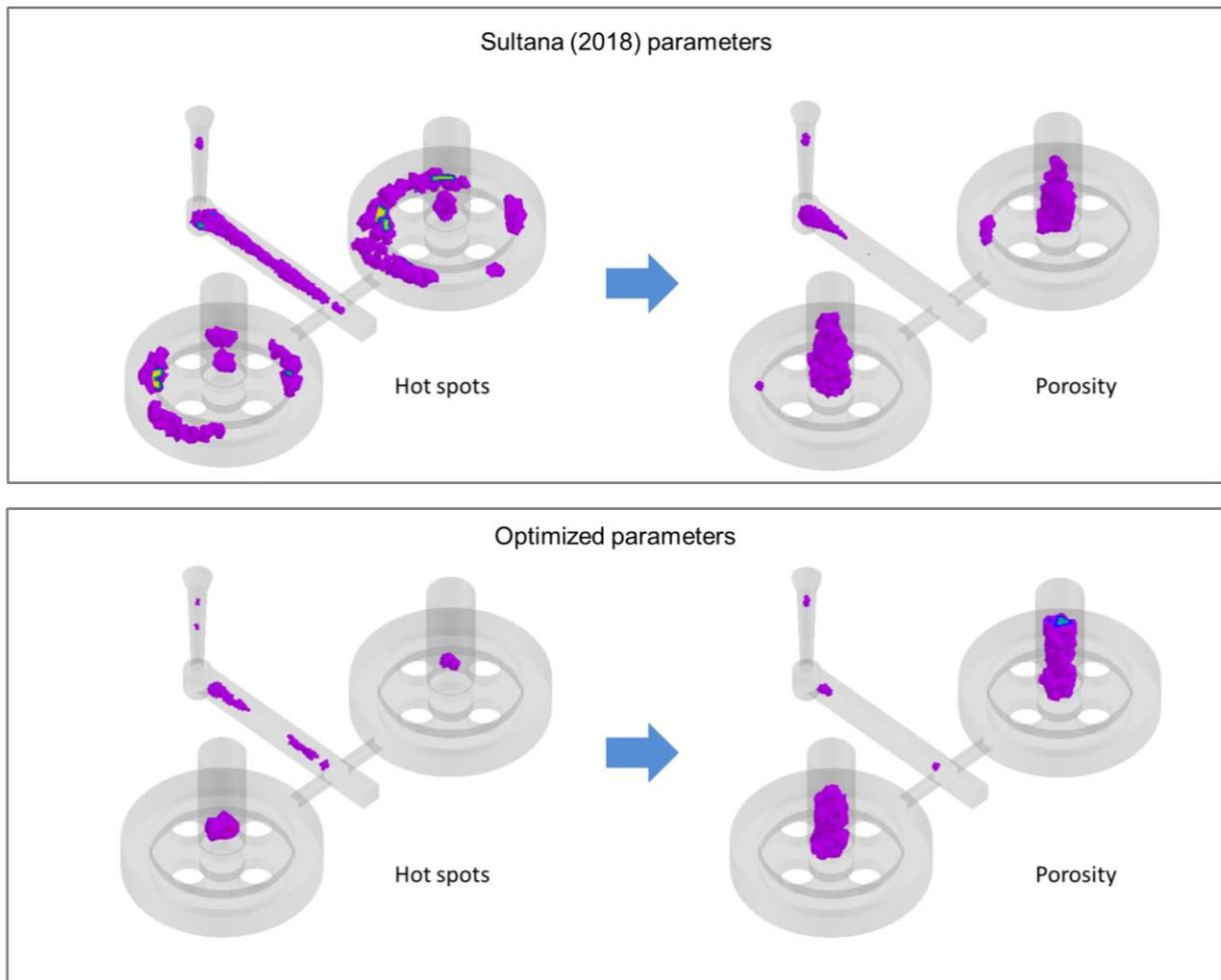
Figure 9. Hot spots and porosity results using Sultana (2018) and optimized parameters.

4. CONCLUSIONS

The results show that casting simulation is a valuable tool nowadays, and with it is possible to reduce internal defects in castings, increasing the competitiveness of companies in this field. Thus, the use of simulation software reduces the production costs of mechanical components by reducing experiments. Through the use of experimental planning techniques in conjunction with simulation software, it was possible to optimize the main casting parameters. The use of these two tools together was responsible for eliminating defects in a cast part.

Given all the parameters presented in the simulations, it is concluded that the Al-Si alloy presented behave according to a characteristic pattern, where HTC and the casting time are less impactful. On the other hand, mold and pouring temperatures vary the most in response to the variation of parameter values in the simulations.

Thus, this work proves to be useful for the application of these optimization techniques in companies that use more basic software, considerably reducing machine hours in casting projects.

Therefore, it is essential to determine what the gravity sand casting process most influencing parameters are. Also, the mold preheating was important to remove porosity in the flywheel, since the porosity present in Sultana (2018) article was removed after the optimization.

5. REFERENCES

ABAL, 2007. Fundamentos e Aplicações do Alumínio. Disponível em: <https://edisciplinas.usp.br/pluginfile. php/4638869/mod_resource/content/0/09_1fundamentos-Alumnio.pdf>. Acesso em: 3 de abr. de 2021.

Almeida, G. F. C. et al. Estudo de ligas al-si fundidas em molde de areia verde: efeito da adição de refinador e de modificadores de grão nas propriedades mecânicas. 18º CBECiMat - Congresso Brasileiro de Engenharia e Ciência dos Materiais. P. 9083-9093. Porto de Galinhas, 2008.

Kucharčík, L.; Brůna, M.; Sládek, A. Influence of Chemical Composition on Porosity in Aluminium Alloys. Archives of foundry engineering, Slovakia, Vol. 14, Issue 2/2014 (5 - 8).

Moro, Noberto. Processos de fabricação. Disponível em: < http://norbertocefetsc.pro.br/downloads/fundicao.pdf>. Acesso em: 1 de maio de 2021.

Oliveira, C. G.; Guesser, W. L.; Baumer, I. O uso da simulação do processo de fundição no desenvolvimento de peças em ferro fundido nodular. IV Seminário de Fundição, Volta Redonda, RJ, 14 a 16 de Maio de 2003.

Oliveira, Reinaldo José de. Avaliação da competitividade das micro, pequenas e medias empresas de fundição de ferro e/ou aço: survey no mercado brasileiro. 139 f. Tese (Doutorado) – Universidade Nove de Julho - UNINOVE, São Paulo, 2020.

Ravi, B. Casting Simulation and Optimisation: Benefits, Bottlenecks, and Best Practices. Indian Foundry Journal. January 2008, Special Issue.

Sultana, N.; Rafiquzzaman, M.; Rahman, Y.; das, A. Solidification and Filling Related Defects Analysis Using Casting Simulation Technique with Experimental Validation. International Journal of Mechanical Engineering and Applications. Vol. 6, No. 6, 2018, pp. 150-160. doi: 10.11648/j.ijmea.20180606.12.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.