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Study on the Effects of Size-Shape Parameter Variation of Exothermic Riser Sleeves and Its Influence on Temperature Dependent Parameters

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ABSTRACT

Using exothermic sleeves allows to reduce the volume of the risers required in the casting of ferrous alloys, as well as the amount of metal used, and the costs involved. In this work, flat plates of nodular iron were casted and the effects of the shape and size of the risers were analyzed. For this purpose, risers with two configurations (with and without exothermic sleeves), three shapes (cylindrical, spherical, oval), and two relative sizes (100% volume and 60% volume) were considered. The mixture that would experience a thermite reaction with the highest temperature was defined. Experimental tests and computational simulations were performed, indicating that the spherical sleeves result in the lowest porosity in the risers and the pieces. It was also found that the risers with exothermic sleeves and 60% of the base volume used satisfy the feeding requirements and reduce the defects in the piece.

KEYWORDS

Metal Casting Simulation, Casting, Risers, Exothermic, Sleeve

Risers are important in a casting feeding system, since they provide additional material during solidification and absorb any contraction or porosity of the part being manufactured. The volume-to-surface ratio of the risers must be greater than that for other sections of the feeding system to ensure that they solidify after the rest of the mold (AFS Molding Methods and Materials Division & Thomas, 2020). However, not all riser volume is available for use in casting. In fact, for conventional feeders, i.e., feeders not covered with sleeves, only 10% to 15% is available for the mold. Most of the material remains trapped in the riser itself or is used to compensate for contractions of the riser itself (Brown, 1999, 2000). As the complexity of the parts increases, more sophisticated riser designs are required, including insulating risers or risers that release energy in contact with the melted alloy (Purwadi et al., 2016). Using exothermic riser sleeves can increase the solidification time by 44%, compared to moldings without risers. From an economical point of view, exothermic riser sleeves offer several advantages over traditional risers in the context of iron casting. These advantages can

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lead to cost savings and improved overall efficiency in the casting process, such as reduced material usage, minimized waste, reusability, improved yield, reduced defects, improved casting quality and productivity, and time savings (Chougule & Ravi, 2006; Coatanéa et al., 2006; Hardin, Williams, & Beckermann, 2013). Exothermic mixtures can be used to produce heat inside the riser, which is frequently described by the Goldschmidt reaction. These mixtures commonly include aluminum particles smaller than 50 µm, and other oxides, such as aluminum oxide (Al_2O_3), commonly called alumina, iron(III) oxide or ferric oxide (Fe_2O_3), and silicon dioxide (SiO_2). Mixtures with adequate proportions of the components would increase the reaction temperature (Junghare et al., 2022; Miki, 2002; Neu & Gough, 1993; Yücel, Turan, & Can Candeger, 2018).

Experimental analyses on the ideal reaction mixture have been presented by Hardin et al. (2013) and Yücel et al. (2018). Thus, if the temperature of the reaction, the amount of aluminum can be increased. In Hardin et al. (2013), simulations are presented to determine the properties that depend on the temperature of the riser, finding an agreement between the measured temperatures and simulation estimations of the solidification process. Among the main conclusions derived from the study is that the use of exothermic sleeves on risers increased the solidification time by 44% compared to moldings that did not use risers. Other authors have studied the phenomenon of solidification in risers using numerical approaches. The use of numerical techniques allows for an analysis of this type of phenomena, which is an economic approach without the use of materials, energy, and labor. However, the control of the errors intrinsic to numerical analysis must be kept at an acceptable level so that the conclusions are extrapolatable to reality. Adequate validation and professionals trained in numerical simulations can help in this regard. For example, Ciobanu et al. (2014) in their three-part publication, use numerical techniques to establish testing criteria during riser analyses. The results suggest that riser analysis operations should be based on solidification time maps and not on temperature maps at the end of solidification. A direct relationship between the solidification time and the square of the modulus has been determined for metals commonly used in engineering. The proportionality constant depends on factors such as the type of sand, alloy used, alloy temperature, among others.

However, not all riser volume is available for use in casting. In fact, for conventional feeders, that is, feeders that are not covered with sleeves, only 10% to 15% are available for the mold. Most of the material remains trapped in the riser itself or is used to compensate for contractions of the riser itself (Butterworth-Heinemann, 1999). This is when the use of insulating risers with better performance than the mold, or even risers that generate their own internal heat, are appropriately justified. In these places, the appearance of microporosities is influenced by the temperature gradient and the local cooling rate during the solidification of the alloy. This can be estimated using the Niyama criterion (Carlson et al., 2001; Chvorinov, 1940; Imafuku & Chijiiwa, 1983; Niyama, 1982;). The Niyama criterion is commonly used in foundry processes to detect microporosity-type defects. It is defined as the relationship between the local temperature gradient and the square root of the cooling rate at the analysis site. Low temperature gradients cause the material to have less pressure to fill interdendritic spaces. This, combined with high cooling rates, makes the material solidify more quickly, further complicating the ability to fill interdendritic spaces. The lower the value of the Niyama parameter, the higher the probability of shrinkage and microporosities. With these tools, detailed studies of the location and size of risers that can be used in moldings have been previously presented by Ou, Carlson, and Beckermann, (2005) and Wlodawer, (2013).

Casting numerical simulation techniques, such as finite element analysis (FEA) and computational fluid dynamics (CFD), are commonly employed to model and analyze the casting process, predict defects, and optimize the final product. By reducing the need for physical tests, these techniques offer valuable insight into the filling and solidification stages, ultimately enhancing the quality of the casting by minimizing surface and internal defects (Das, 2021).

Figure 1. XRD Analysis and Rietveld Refinement of Fe_2O_3 (left) and Al (right)

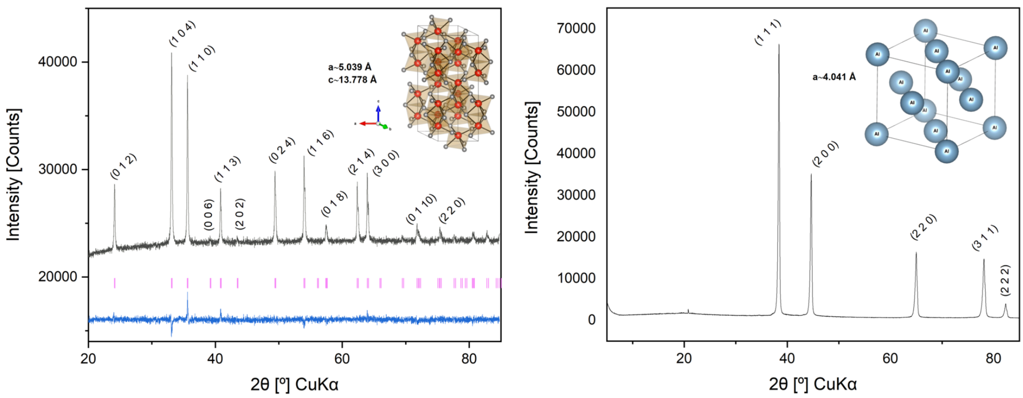


Table 1. Thermochemical Parameters of the Thermite Reaction

	Fe2O3	2Al	Al2O3	2Fe
Mass (g)	159.678	53.964	101.961	111.69
Density (g/cm3)	5.242	2.700	-	-
Volumen (cm3)	30.46	19.99	-	-
ΔHf (Kcal/mol)[KJ/mol]	-195.00*[-816.58]	-	-399.09*-1671.23]	-
ΔGf (Kcal/mol)	-178.00*	-	-376.80*	-
ΔSf (cal/mol/°C)	21.50*	-	12.186*	-

MATERIALS AND METHOD

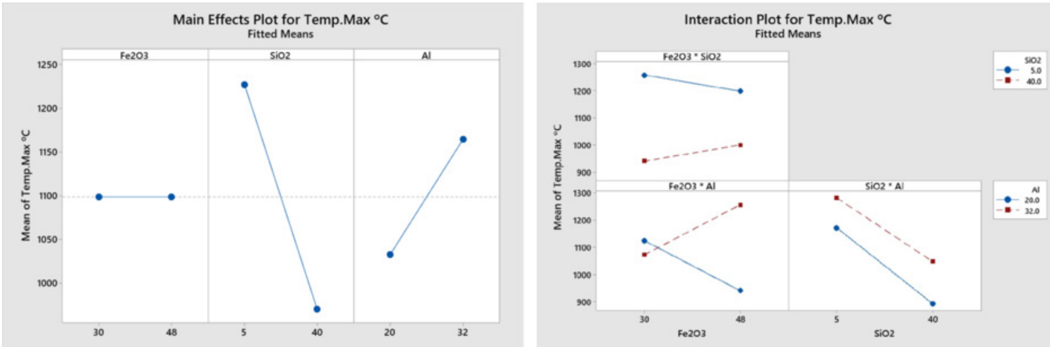
Materials

The experimental part of this research involved the production of a thermite using Fe_2O_3 and Al that was used to manufacture the exothermic sleeve (Neu & Gough, 1993; Mei, Halldearn, & Xiao, 1999; Menon, 2000; Miki, 2002; Saraswati et al., 2017; Wiencke et al., 2018). The materials were obtained from local distributors. To generate enough heat to initiate this compound, a mixture of potassium and Aluminum Nitrate was used as an activator (Neu & Gough, 1993; Twardowska & Aufderheide, 2022). Fe_2O_3 and Al were characterized through XRD analysis and also by applying a Rietveld refinement, as is observed in Figure 1. The thermochemical parameters of the thermite reaction are shown in Table 1 (Roine, 2002). The resin used was based on Furanic, and the characterization of this was such that its proportion of silica sand was defined by Sotomayor, Anrango, and Campoverde (2022). However, it can be mentioned that the sand used corresponded to silica sand from Sibelco's supplier, with an AFS index of grain size of 56.09, a fine powder amount of approximately 2.18%, a moisture content of 0.05%, a pH of 7.08, and a loss on ignition (LOI) of 0.55%. Regarding the ductile iron used for the experimental tests, a quality control study of the composition was made using a spark AES analysis.

Composition

To achieve the best proportions, considering previous research in which the quantities of the different compounds are estimated (Hardin et al., 2013; Yücel et al., 2018), a full factor design of experiment (DOE) was applied using Minitab Software (Fernández, 2020), and then preliminary

Figure 2. Main Effects Plot for Temperature (left) and Interaction Plot of Chemical Compounds for Temperature (right)



tests were carried out to analyze the influence. Of the proportions studied, the results showed that the main option was 48% $Fe_2O_{3,}$ 32% Al, 5% of SiO_2, 10% Furan Resin, and 5% of activator in volumetric percentages, which was the primary one according to preliminary tests in which the maximum heat generation was measured. To make the different shapes of the exothermic sleeves, an additive manufacturing process was used through thermoplastic extrusion of in polylactic acid (PLA) material to first obtain core boxes in which the compound was selected and compacted to the desired exothermic sleeve shape. The main effects of the variation in chemical compounds and the interaction between its combinations are shown in Figure 2.

The variation in the amount of Fe_2O_3 within the composition did not have a significant impact on the observed result. However, in the case of SiO2, it was clearly observed that increasing its percentage within the compound significantly affected its ability to produce heat, reducing the maximum temperature that the exothermic sleeve could reach. On the other hand, the increase in the amount of Al within the compound favored the increase in the temperature of the exothermic sleeve.

When analyzing the simultaneous interaction of two compounds, it can be demonstrated that the joint impact of Fe_2O_3 and low levels of SiO_2 has an effect on the maximum temperature achieved. Nevertheless, while this effect decreases as the proportion of iron oxide increases, it is not significant enough to negate the impact of high amounts of SiO2, which can greatly diminish the maximum temperature achievable. Regarding the combined action of Fe_2O_3 and Al, the greater the amount of Al used, the greater the heat that can be obtained. Concerning the combined action of SiO_2 with Al, it is evident that increasing both the sand and Al significantly reduces the temperature.

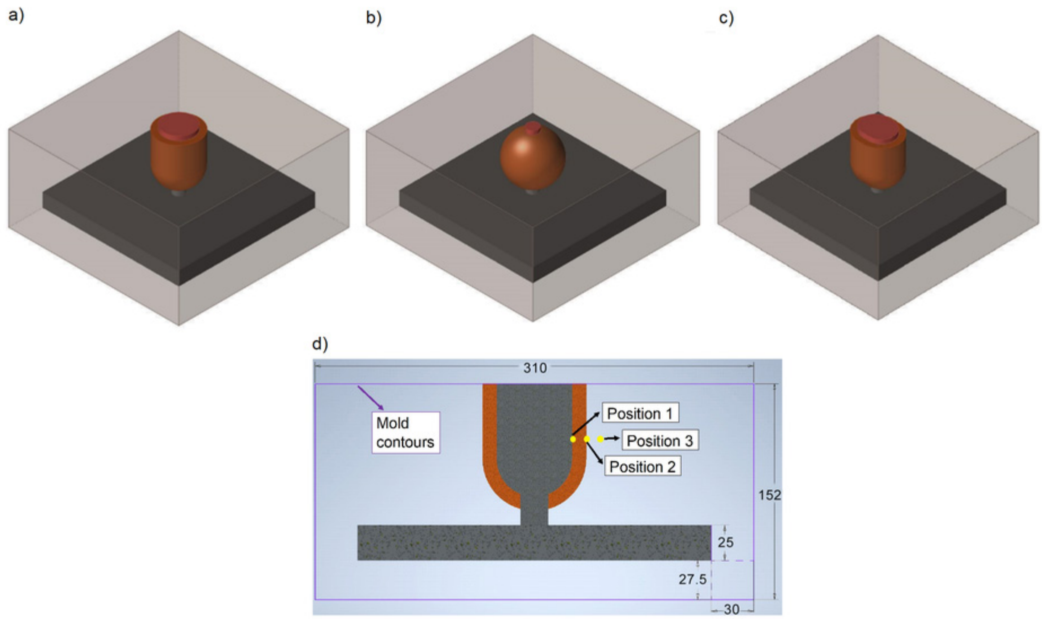
Computational Modeling and Simulation

Once the quantities mix proportions of the exothermic riser sleeve were established, the influence of different variables such as size and shape in exothermic risers was studied using a computational modeling and simulations. To have comparable and experimental support, the Indian Standard IS 15865:2009 (Bureau of Indian Standards, 2009) was used in the same way that Hardin et al. (2013) and Purwadi et al. (2016) did it in their research.

First, to ensure a consistent database, three distinct shapes of exothermic riser sleeves were suggested, cylindrical, spherical, and oval, as illustrated in Figures 3a through 3c, alongside the selection of three separate points for temperature analysis, as depicted in Figure 3d. To measure the evolution of temperature at each of the selected points, type K thermocouples with MAX 31856 temperature sensor modules, programmed on an Arduino board, were used to obtain records at one-second intervals. Data recording was carried out using a direct connection through a COM port on a PC, which allowed for the recording of the different temperatures in real time.

While models were created using CAD software, the drags and copes to fabricate experimentally the different shapes of sleeves were made by using additive manufacturing methods, such as 3-D

Figure 3. Plate Scheme and Shapes of Exothermic Riser Sleeves. a) Cylindrical, b) Spherical Shape, c) Oval Shape, and d) Positions of Thermocouples



printing using PLA filament. Once different models were designed, the Altair Inspire Cast software was used to simulate the casting process with variables considered in the real experimental process (Das, 2021). It is important to mention that the Altair Inspire Cast performs the analysis using metal-enhanced fluorescence (MEF) applied to the analysis of solids as well as computational fluid dynamics modeling (CFD), with the objective of studying the filling and solidification stages that take place during the casting process. Regarding the conditions for discretization of the system, the properties of the materials were shown in Tables 1 and 2; the average thickness of the mesh shown was 1.5 cm, and the element size was 0.75 cm. Regarding the meshing factors of the entrance, mold, and riser, the values adopted were 0.9, 2.583, and 1.0, respectively. The considered filling time was 5.5 seconds; these parameters were general for all geometries investigated.

To improve the analysis based on the simulation time and predicted temperature, a convergence analysis was performed to assess the mesh thickness and element size, and the resulting convergence curves for the cylindrical and spherical risers are detailed in Figure 4.

The results showed that a mesh thickness of 15 mm, which corresponds to a number of elements of 42386 for a cylindrical riser and 43492 elements for a spherical riser, and provides an acceptable temperature prediction efficiently in time, with an error of approximately 0.11%.

RESULTS AND DISCUSSION

Experimental

The experimental part was developed based on the preliminary simulation results; it was possible to show that both the cylindrical and spherical sleeve had the best performance in terms of heat retention inside the riser. For this reason, the experimental part was developed for cylindrical and spherical shapes. The experiment consisted of the creation of casting molds using silica sand and furanic resin to obtain the shapes shown in Figure 3. Moreover, the placement of the calibrated

Figure 4. Convergence Analysis in FEA for the Proposed Systems. a) Cylindrical Riser Shape and b) Spherical Riser Shape

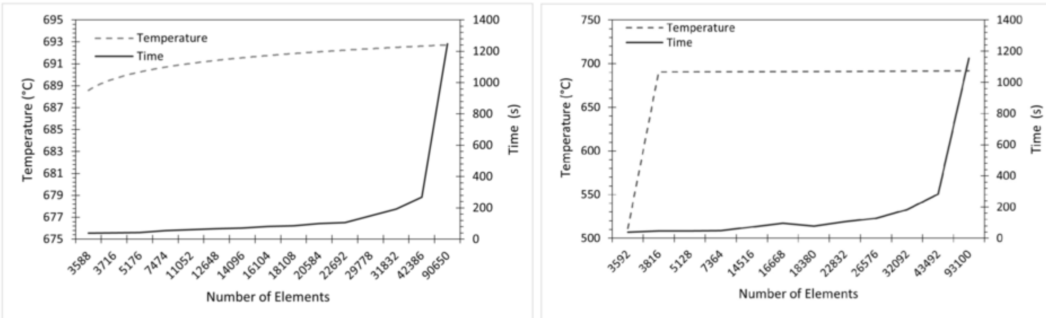


Table 2. Average Composition of the Nodular Iron Used in the Castings

%	C	Si	Mn	P	Cr	Ni	Cu	Al	Mg	Fe	Avg.
Avg. Comp.	3.418	2.358	0.702	0.036	0.093	0.014	0.299	0.015	0.044	92.998	99.977
Std.Dev.	0.140	0.090	0.010	0.003	0.002	0.002	0.012	0.001	0.003	0.161	0.007
Max.	3.558	2.448	0.712	0.039	0.096	0.016	0.311	0.017	0.047	93.159	99.984
Mín.	3.278	2.267	0.692	0.033	0.091	0.012	0.287	0.014	0.041	92.837	99.970

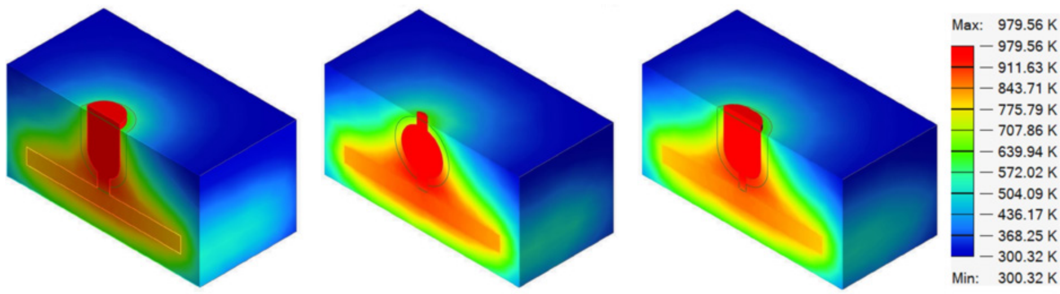
thermocouples and data acquisition system positions are indicated in Figure 3d. In the final stage, the recording of the different temperatures by means of the thermocouples was carried out for time intervals of one second.

The parameters considered for the recording of the data were established to measure the temperatures within the time interval from *t* equal to zero to 3600 seconds. In total, 12 independent thermocouple channels were used; the temperature at which the iron was cast in the different molds was 1380°C. Regarding the composition of the ductile iron used in the experiment, the supplier provided the data from 12 samples of the casting batch that were characterized by spark spectrometry. Table 2 shows the summary of the average values, as well as its standard deviation, maximums, and minimums of the different compositions.

Computational Modeling and Simulations

As mentioned previously, three riser shapes were simulated with and without exothermic sleeves. The most relevant data that could be obtained through the simulations consisted of the initial temperature, final temperature, solidification time, porosity, and microporosity. Figure 5 shows the results of the simulation for the different forms of exothermic sleeves with respect to the final temperature. Subsequently, to compare the influence on the change in the size of the risers, the volume of risers was reduced to 60% of the initial, the thickness of sleeve was maintained equal, and the three forms of risers were simulated again, both with and without exothermic sleeves. It should be noted that the thicknesses of the finite element meshes remained constant. Another fact is the inhomogeneity of the silica sand particles that make up the mold in the experimental part; due to this, the heat transfer coefficients heat transfer coefficient (HTC) were not uniform with respect to what was evidenced in simulations and similar works, such as those carried out by Williams (2016). Although Ciobanu et al. (2014) highlights in the case of simulations in casting processes, the importance of using right thermal parameters of the used materials, allowing adjustments to be made as accurately as possible, with respect to the experimental part. However, it must be considered that at the experimental level, there are many more factors, such as HTC, lack of constant flow during filling, air trapped between

Figure 5. Simulations Results for Proposed Exothermic Riser Sleeves, Cross-Sectional View of Final Temperature



mold and part, or heterogeneity of temperature of liquid metal during pouring, that cannot be captured by simulation, and for this reason the results are not completely identical.

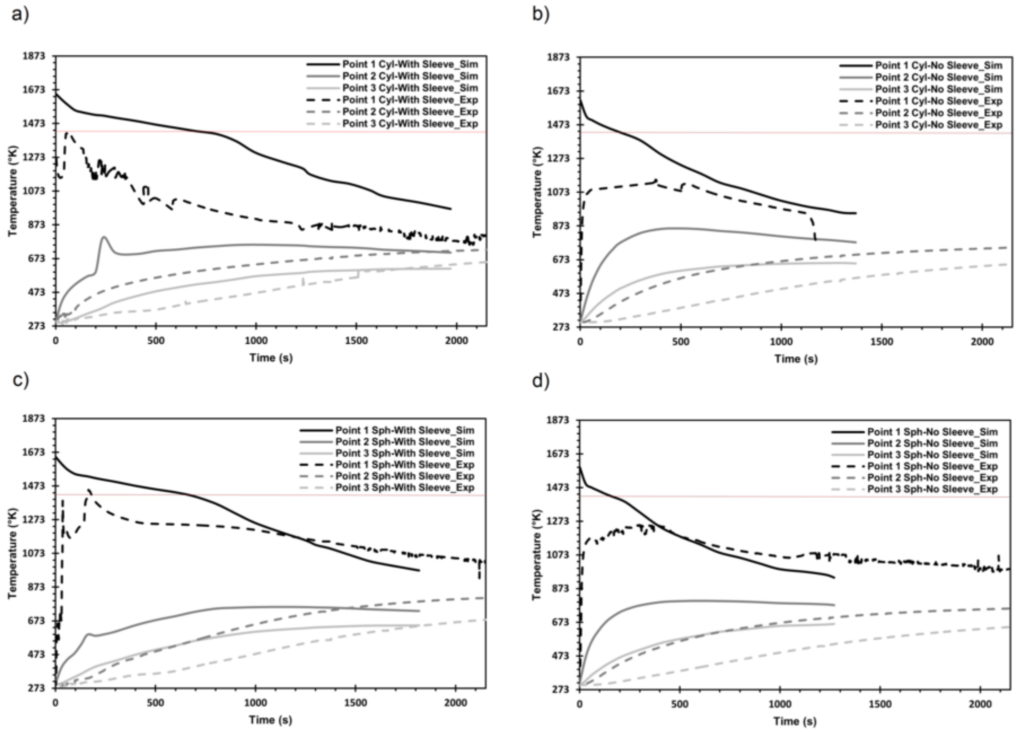
Discussion

Graphs in Figures 6 and 7 display trends observed in both the experimental and simulation phases. In the case of the cylindrical riser, with an exothermic sleeve, in Figures 7a through 7d, it can be seen that the temperature at point one for the simulation is higher than the temperature at that same point for the experimental case. This is because the simulations does not consider all experimental variables present, such as HTC, lack of constant flow during filling, air trapped between mold and part, or heterogeneity of temperature of liquid metal during pouring. Also, simulation processes neglect heat transfer phenomena up to the starting point of solidification. This statement can be better evidenced in points 2 and 3 of the curves shown in Figure 6, which experimentally presents a more linear trend in its curves with respect to the simulation. However, when time equals 2000 seconds, temperatures become approximately the same, showing agreement between simulation and experiment. Analyzing the trends of the curves obtained in Figure 6b, corresponding to the cylindrical riser without an exothermic sleeve, it can be seen that by not using an exothermic sleeve, the temperature inside the riser and its surroundings is significantly reduced. It should also be noted that, in Figure 6a, the use of an exothermic sleeve improves the heat retention, which favors the reduction of imperfections within the piece. In the case of Figure 6c, corresponding to a spherical riser with an exothermic sleeve. In the same way, until an approximate time of about 200 seconds, the temperature was very close to the temperature of the liquidus, thus favoring that the piece did not have imperfections. On the other hand, in Figure 6d, it can be seen how not using an exothermic sleeve reduces the temperature well below the liquidus limit.

Up to this point of the analysis, it can be established that even when the graphs obtained both at the experimental level and in the simulations do not exactly coincide throughout their entire record, they are comparable.

Regarding the study of the size variation in Figure 7, it can be seen how the size change in the different shapes influences both the temperature and the solidification time. It is possible to observe that a reduction in size without the proper shape would not maintain sufficient temperature to keep the metal above the temperature of liquids during the casting and solidification process. This can be better contrasted with the data shown in Figure 9, which concerns the values of the area under the curves shown in Figure 7 for cylindrical and spherical conventional risers. By reducing the riser size from 100% to 60%, when exothermic sleeves are not used, one must take into account the temperature function and the time when the liquidus line is achieved, it can be noted that the area values are higher for the 100% size riser. On the other hand, when an exothermic sleeve is used, it can be noted that reducing the size of the riser from 100% to 60% improves final area values, which are also higher for the 100% size riser. However, the 100% riser area values are almost four times higher compared

Figure 6. Comparative Analysis Between Experimental and Simulation Analysis for Cylindrica and Spherical Risers. a) Cylindrical With Sleeve, b) Cylindrical No-Sleeve, c) Spherical With Sleeve and d) Spherical No-Sleeve



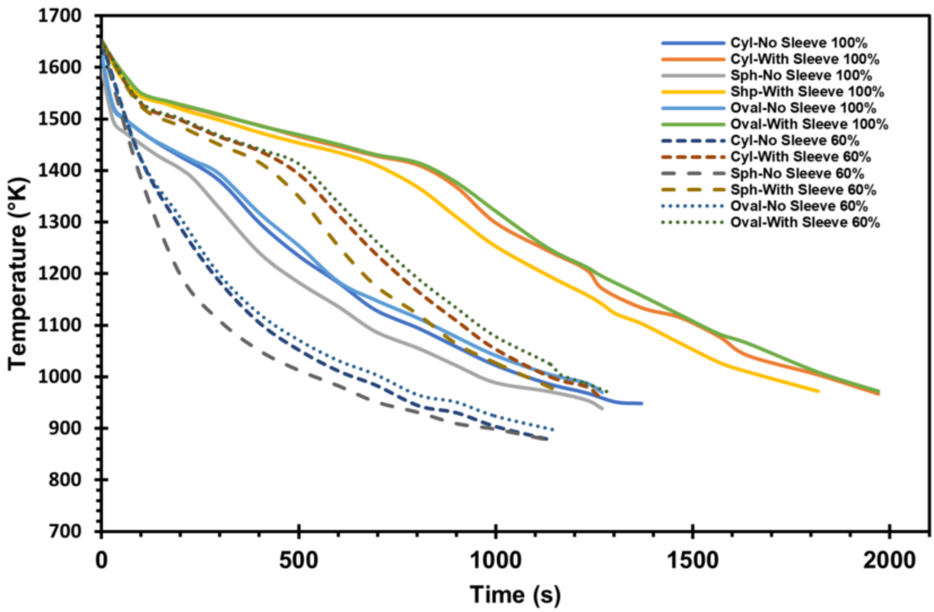
to the values of 60% size conventional risers. This clearly shows that the use of exothermic sleeves improves the behavior of the riser.

Figure 8 shows the cross-section in the risers that were cast experimentally. It can be observed that in the case of the risers in which exothermic sleeves were not used, the porosities are present inside the riser and the metal did not completely flow into the cavity of the piece, generating porosities inside of it. On the other hand, in the case of those risers in which exothermic sleeves were used, the small presence of porosity in the riser and the limited presence of porosity inside the piece is obvious, which contrasts with the results shown in Table 3.

FUTURE RESEARCH

Certainly, some potential areas for future research in the field of exothermic riser sleeves in ductile iron casting could be the optimization of exothermic riser sleeve design by investigating different geometries, sizes, and compositions of exothermic riser sleeves to determine the optimal design parameters for ductile iron casting. This can include exploring the effects of tapering, varying the material composition, and assessing the impact of different riser sleeve shapes on feeding efficiency and defect reduction. In addition, the use of alternative materials for exothermic riser sleeves explores the potential benefits of new alloys or composites. This research can focus on enhancing the thermal properties, mechanical strength, and reusability of the sleeves, while maintaining their exothermic capabilities. When considering these areas, future research can contribute to the advancement of exothermic riser sleeve technology in ductile iron casting, leading to an improved casting quality, cost-effectiveness, and sustainability in the manufacturing industry.

Figure 7. Comparative Study of Temperature Variation Due to Size and Shape Change in Exothermic Risers With- and No- Sleeve in Point 1 of Study Through Simulation



CONCLUSION

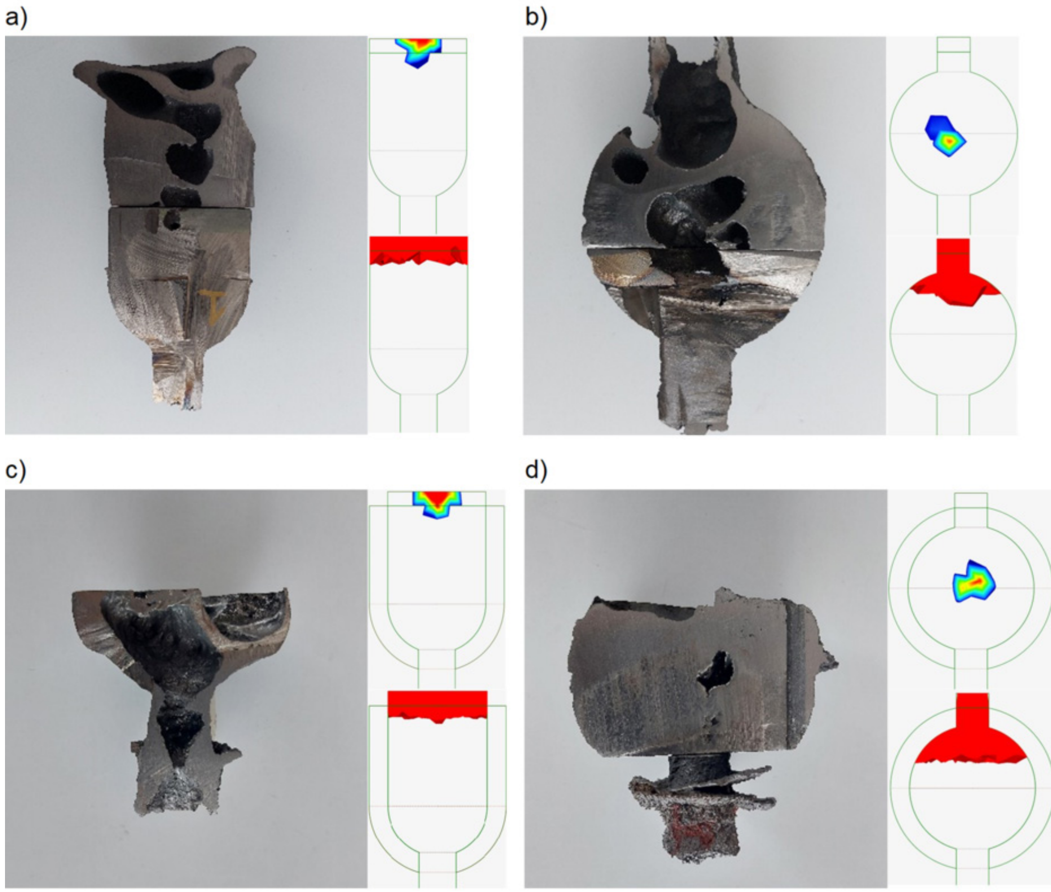
The variation in the size and shape of risers, as well as the inclusion of an exothermic sleeve, modify temperature-dependent parameters. It was verified at an experimental level that the use of exothermic sleeves in risers favors the retention of heat within them, and with this, it is also possible to extend the time that the iron is above the liquidus limit, thus reducing the imperfections in the part to be cast.

The correct use of physical and thermal parameters, such as specific heat and thermal conduction coefficients simulation, has successfully captured the general behavior of the experimental evolution of temperature in three points of a riser sleeve. Small differences can be attributed to real variations in experiments that cannot be fully controlled, such as HTC, lack of constant flow during filling, air trapped between mold, and part or heterogeneity of temperature of liquid metal during pouring, as shown in Figure 6.

Based on the results shown in Figure 9, by reducing the volume of risers with exothermic sleeves from 100% to 60%, the one that shows the best performance based on the analysis of the area under the temperature curve versus time, is the spherical shape. On the other hand, from what can be observed in Figure 7, the flash point occurs faster in the cylindrical sleeve, before the spherical one. However, the exothermic riser sleeve with a spherical shape is the one that presents the least decay in the riser temperature in relation to the exothermic riser sleeve with a cylindrical shape. Furthermore, regarding the porosity and shrinkage volume produced in the risers, it can be observed in Figure 8 that simulation allows for an approximate estimation of the places where the part will present defects.

Figure 9, which compares the area under the curve, shows that even when the riser size is reduced to a 60% of the initial volume, the area under the curve during the solidification time is higher by up to 68%, compared to using conventional risers with an initial volume of 100%. However, it is also

Figure 8. Cross-Sectional View of the Porosity Distribution in Experimental Risers, Simulated Risers (upper right images), and Total Simulated Shrinkage Volume (lower right images). a) Cylindrical No-Sleeve, b) Spherical No-Sleeve, c) Cylindrical With Sleeve and b) Spherical With Sleeve

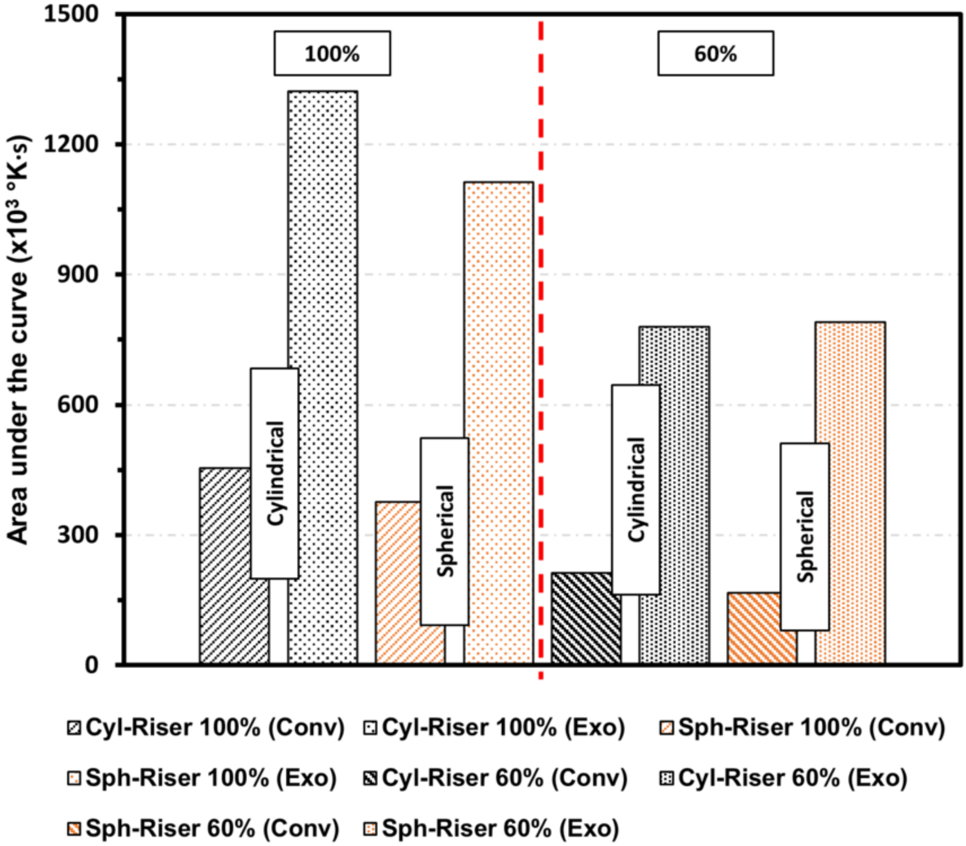


observed that for an initial volume of 100%, the exothermic riser sleeve with a cylindrical shape is the one with better area exhibits. However, when the volume is reduced, the exothermic riser sleeve with a spherical shape is the one with a better area.

Certainly, some potential areas for future research in the field of exothermic riser sleeves in ductile iron casting could be the optimization of exothermic riser sleeve design by investigating different geometries, sizes, and compositions of exothermic riser sleeves to determine the optimal design parameters for ductile iron casting. This can include exploring the effects of tapering, varying the material composition, and assessing the impact of different riser sleeve shapes on feeding efficiency and defect reduction. In addition, the use of alternative materials for exothermic riser sleeves explores the potential benefits of new alloys or composites. This research can focus on enhancing the thermal properties, mechanical strength, and reusability of the sleeves, while maintaining their exothermic capabilities. When these areas, future research can contribute to the advancement of exothermic riser sleeve technology in ductile iron casting, leading to improved casting quality, cost-effectiveness, and sustainability in the manufacturing industry.

In general, based on the findings obtained both in the experimental and computational part of this study, it is clear that the use of exothermic riser sleeves improves the quality of the pieces to be cast. However, the shape that they have, as well as their size, can favor or disadvantage the final quality.

Figure 9. Comparative Values Between Areas Under the Curve Temperature vs. Time for the Cylindrical and Spherical Risers With (dotted) and Without (line) Exothermic Sleeves



It was observed that closed forms, such as the case of the spherical riser, even when they present the highest contact surface area ratio, show inferior performance in relation to risers in contact with the air. For this reason, the use of the last ones is recommended at an industrial level, due to its ease of manufacture and coupling in casting systems. In the same way, it is recommended that in the case of risers in contact with air, covers should be used in order to minimize the possible effects of violent reactions due to activation of the sleeve and, in turn, favor the preservation of the temperature for a longer time inside the riser.

CONFLICT OF INTEREST

We have no known conflict of interest to disclose.

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Table 3. Comparative Results of Porosity and Microporosity Inside Risers for the Cylindrical and Spherical Risers With and Without Exothermic Sleeves for Simulations

Riser Type	Porosity %	Microporosity %	Niyama
Conventional - 100%			
Cylindrical	0.00	0.03	1.23
Spherical	52.40	0.18	0.42
Exothermic - 100%			
Cylindrical	0.00	0.03	1.06
Spherical	0.00	0.04	1.14
Conventional - 60%			
Cylindrical	0.00	0.02	1.28
Spherical	1.25	0.07	0.71
Exothermic - 60%			
Cylindrical	0.00	0.08	0.65
Spherical	8.60	0.24	0.37

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