RISK ASSESSMENT OF CASTING POWDERS ENTRAPMENT IN A 26 TONNE STEEL INGOT USING NUMERICAL SIMULATION

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Abstract

Nowadays, steelmaking companies use numerical simulations as an advanced tool to optimize process parameters, reduce defects, and enhance product quality, aligning with the rising market demand for high-quality steel ingots. For more accurate simulations, it is essential to set the correct material properties, process parameters (such as flow rate and temperatures), heat transfer coefficient, as well as the suitable geometry and corresponding discretization. During the mold filling, one main issue is the trapping in the liquid of casting powders used to protect the steel from reoxidation, which turns in the presence of large non-metallic inclusions in the solidified part and the consequent discard. This work is part of an industrial research aimed at studying the filling and solidification of a 26 tonne square ingot by using numerical simulation with the commercial program ProCAST®. The study investigates the impact of several casting parameters and liquid upgate system geometries on the creation of exogenous non-metallic inclusions through simplified numerical simulations. The reliability of the simulation model was evaluated by an experimental test conducted on an industrial scale: the inclusions measured were all less than the acceptable threshold of <2.0 mm equivalent defect. The research was able to establish the conditions needed to prevent the sporadic entrapment of casting powders, hence enhancing the overall quality of this type of ingot.

Keywords: Numerical simulation, steel ingot, defects, casting parameters, runners

1. INTRODUCTION

In recent years, the market demand for increasingly performing steel components leads companies to invest in process quality to guarantee excellent mechanical properties and performance of their products. For this reason, nowadays, numerical simulation software represents an essential tool for improving casting processes and components. For what concern steel ingots, different studies in the literature focus on simulation to predict defects such as shrinkage porosities and macrosegregations [1-4]. Unfortunately, the research carried out for these components is mainly limited to the assessment of the solidification phase of the ingot due to the greater computational time required by the filling phase towing the large size of these products [4]. Indeed, there are few studies focused on the initial stages of the filling. They evaluate the risk of exogenous macro inclusions and how different configurations, such as the shape and geometry of the inlet nozzle in relation to the casting parameters used, can influence the final characteristics of the component. Eriksson et al. [5], for example, in the case of an ingot of 4 tonne, have demonstrated that a wide angle of the inlet nozzle (25 °) is essential to minimize deformation of the surface of the liquid metal, reducing the risk of powder entrapment in the steel.

With this angle, in fact, the surface velocity never exceeds the limit value that, based on the results obtained from the research, would otherwise lead to the formation of non-metallic inclusions. Bai et al. [6] instead proposed improvement solutions through the modification of the geometry of the inlet nozzle creating a cylinder called *Turboswirl*, in the final part of the runner. This results in an improvement in the first stage of the filling as it avoids the formation of a spout and guarantees a lower surface velocity of the liquid front. The use of this system, however, generates turbulence that can determine, in any case, the risk of powder entrapment. Using a similar approach, J. Yin et al. [7] tried to implement the same cylindrical system, varying the filling angle with the horizontal runner, to improve the flow and reduce the turbulence generated. With this solution, the authors have shown that changing the filling angle compared to the system support plan can reduce the risk of powder entrapment and thus minimize defects inside the ingot [8]. Another study [9] uses the divergence of the inlet nozzle to enable metal to flow along the walls, avoiding the formation of the spout and allowing to have a more homogeneous and less turbulent filling with the addition of a refractory element (*swirl blade*). On the other hand, in this configuration, the risk of air entrapment with the formation of large bubbles that could cause problems and contamination of the liquid metal is high. However, the mentioned solutions and studies suggest mathematical models with few references to industrial examples and experiments. For this reason, in this study the possible causes of powder entrapment in a forged bar obtained from a 26 tonne ingot were investigated using numerical simulation. Additionally, the geometry of the inlet nozzle and casting parameters of the process have been modified to assess their impact on defect formation in the early stages of filling.

2. EXPERIMENTAL PROCEDURE

This work investigated a square ingot with a variable mass between 20 and 26 tonne, produced by the company ASONEXT S.p.A. in Ospitaletto (Italy). The liquid steel (1.2738) was poured from the ladle into the column of refractory bricks. At 200 mm from the bottom of the ingot, six bags containing the casting powders were hung for a total weight of 54 kg. At the end of the filling phase, the exothermic powders were distributed evenly across the free surface. At the end of the solidification and cooling steps, the ingot was subjected to the subsequent stages of forging and thermal treatment. The resulting forged bar was then examined by ultrasound using a Krautkramer USN 60 instrument with an orthogonal 2 MHz probe. A cross section was then cut at 500 mm from the bottom of the bar and some samples were taken in accordance with the critical areas observed. The samples presenting defects were subsequently examined using a Leica Reichert Mef 4 optical microscope (OM) and an EM-30AX PLUS Scan Electron Microscopy (SEM) equipped with an EDAX EDS detector. In order to identify the causes of the defects in the bar, a series of simulations were subsequently carried out to obtain information about the conditions of entry of the liquid metal varying some casting parameters (initial flow rate) and the geometry of the filling system. An overview of the simulations set up and their changed conditions is shown in **Table 1**.

Table 1 Overview of the simulations set up with and their changed conditions

Conditions	Simulation type	Initial flow rate (kg/min)	Geometry of the filling system
1	Complete	3,000	Standard
2	Alternative	1,500	Standard
3	Alternative	4,500	Standard
4	Alternative	500	Standard
5	Alternative	1,500	Trap
6	Alternative	3,000	Trap
7	Alternative	1,500	Elbow nozzle
8	Alternative	3,000	Elbow nozzle

Simulation 1 was set complete of filling and solidification according to the industrial ingot cast. The other simulations, named alternative, consider only the first minutes of the filling phase, and vary in the initial flow rate (1,500, 4,500 and 500 kg/min) and/or in change of the geometry. Regarding the geometry, alternative geometrical solutions were considered concerning the standard channel system used, such as adding a trap at the end of the runner (simulation 5 and 6) and a modified nozzle, using an elbow configuration (simulation 7 and 8). The casting system used for the simulations is shown in **Figure 1** a) [10] and the standard configuration usually used for the inlet nozzle and the two different geometrical alternatives are reported in **Figure 1** b), c) and d).

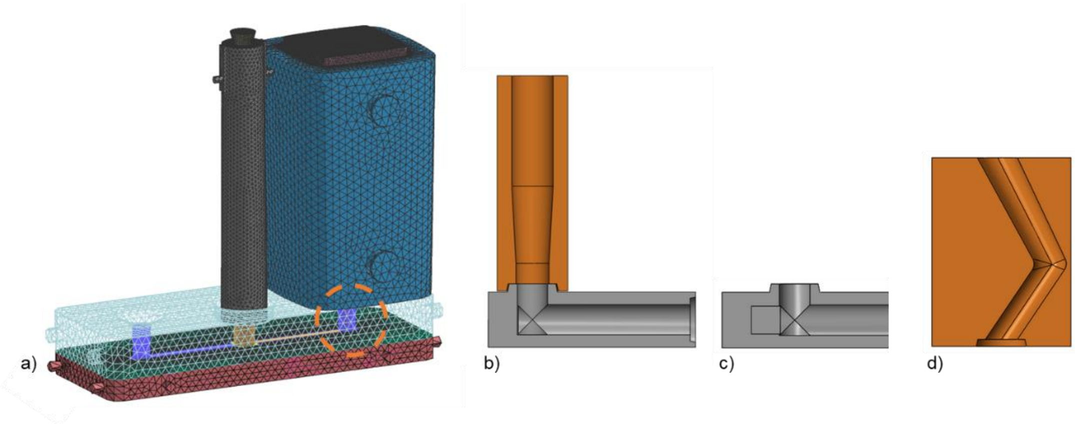

Figure 1 a) Casting system used for the numerical simulation: in the circle the position of the inlet nozzle; b) detail of the standard configuration of the inlet nozzle; c) detail of the last part of the runner with the trap; d) elbow nozzle configuration

The simulations were set using the commercial software ProCAST® 2022 [11], based on Finite Element Method (FEM). The casting system of the ingot was discretized by 149,977 surface elements and 2,542,802 volume elements (**Figure 1** a). The materials were chosen from the database present in the software, and their thermo-physical properties were verified with experimental tests using the Hot Disk Thermal Constants Analyser TPS2500 in accordance with ISO 2207-2 [12]. The initial temperature of the system was set at 10 °C and the temperature of the steel at 1,560 °C. The Heat Transfer Coefficient (HTC) was set as a function of the temperature in the range between 150-600 W/(m^2·K) to consider the contraction of the steel during the solidification [13,14]. The data used to set the boundary conditions were obtained from the industrial casting of the 26 tonne steel ingot analyzed.

To assess the possibility of casting powders entrapment through the numerical simulation, the Weber number was calculated [5]:

$$We = \frac{u_{steel}^2 \cdot \rho_{steel}}{\sqrt{\gamma \cdot g \cdot (\rho_{steel} - \rho_{slag})}} \tag{1}$$

where u_{steel} is the tangential velocity of the steel on the free surface; ρ_{steel} and ρ_{slag} are the steel density and the slag density; g is the gravity and γ represents the slag-steel interfacial tension. The slag density was set 2,500 kg/m³ and three different slag-steel interfacial tensions were considered according to the literature (0.5 N/m, 1.0 N/m and 1.5 N/m [15]).

3. DISCUSSION AND RESULTS

The ingot analyzed presented some criticalities, especially in the area located at the entry of liquid metal (bottom side). From the analysis carried out using ultrasounds, it was possible to observe the presence of macro-inclusions of maximum magnitude equal to 1.8 mm AVG. Different samples were taken and metallographically examined. In **Figure 2** a) is shown a micrograph of the defect obtained through OM analysis and in b) a micrograph at higher magnifications obtained by the SEM. In **Table 2** the results of the chemical analysis of the areas investigated with the EDS detector are shown.

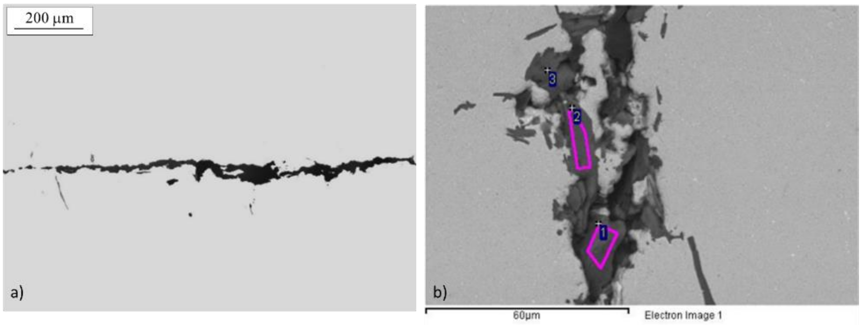

Figure 2 a) Detected defect by optical microscope (OM); b) Detected defect by scanning electron microscope (SEM) and investigated areas for the chemical analysis

Table 2 Chemical analysis obtained by EDS detector (wt%)

Area	O	Na	Mg	Al	K	Ca	Cr	Fe
1	58.05	1.46	0.85	35.28	0.78	0.99	0.39	2.21
2	58.90	0.62	-	38.20	0.22	0.61	0.69	0.76
3	59.02	1.10	0.82	35.41	0.72	2.23	-	0.70

The presence of elements such as sodium (Na) and potassium (K), typical constituents of the casting powders, suggests that the defects observed are due to the casting powders entrapment [16]. The simulation 1 helped to understand the reasons for the defects related to the presence of a significant initial spout that reaches 450 mm of height (**Figure 5** b). Considering that the bags containing the powders were placed 200 mm from the bottom, it is reasonable to affirm that the breaking of the bags occurred in the first stage of filling, due to the spout, but in the absence of a significant liquid foot on the bottom of the ingot. To verify the possibility of casting powders entrapment in numerical simulation, the Weber number was calculated. In **Figure 3** the trend of the Weber number as a function of steel tangential velocity and steel-powder interfacial tension is shown. The limit value, beyond which it is possible to have problems with entrapment, is 12.3 [17] and this case is exceeded by velocity values between 0.7 and 2 m/s.

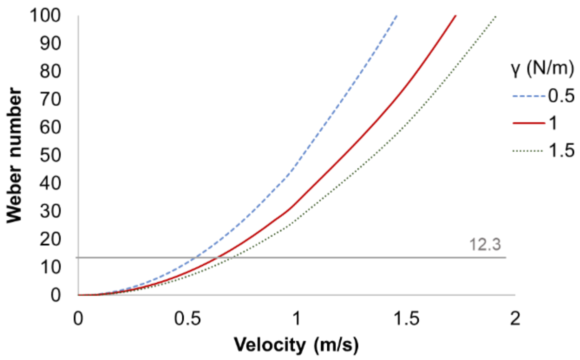

Figure 3 Weber number as a function of steel tangential velocity and steel-powder interfacial tension

Considering simulation 1, the maximum critical values (between 0.7 and 2 m/s) are reached in the initial phase, particularly between 7 and 29 s. After 29 s, with the change in flow rate, the speed tends to value of 2 m/s, and then reduces until it stabilizes after 1,300 s. For this reason, the risk of powder entrapment occurs in the first stage of the casting while, after 1,300 s of filling, the speed values are particularly low. It is further reduced around the end of the filling: an example is shown in **Figure 4**.

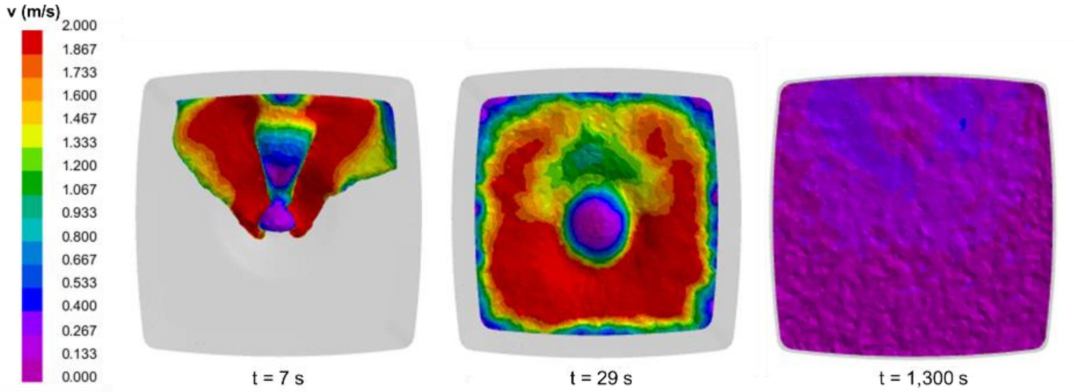

Figure 4 Tangential steel velocity at different time steps: from the left to the right after 7, 29 and 1,300 s

The defects previously detected are attributable to problems at the first stage of the filling. To find a solution to the entrapment of powders, several alternative configurations have been studied evaluating the effects of different flow rates and geometrical configurations of the refractory inlet. As assumed, decreasing the flow rate means decreasing the height of the initial spout, going from 450 mm with a flow rate of 3,000 kg/min to 200 mm with 1,500 kg/min. In both situations, however, the risk of powder entrapment is still observed in the arrangement of the bags at 200 mm from the bottom. In order to better assess the trend of the height of the initial spout as a function of the casting conditions, two simulations were also carried out with initial flow rates of 4,500 and 500 kg/min respectively. Considering these two additional conditions, the height of the spout appears to have some linear dependence from the flow rate, as shown in **Figure 5** a).

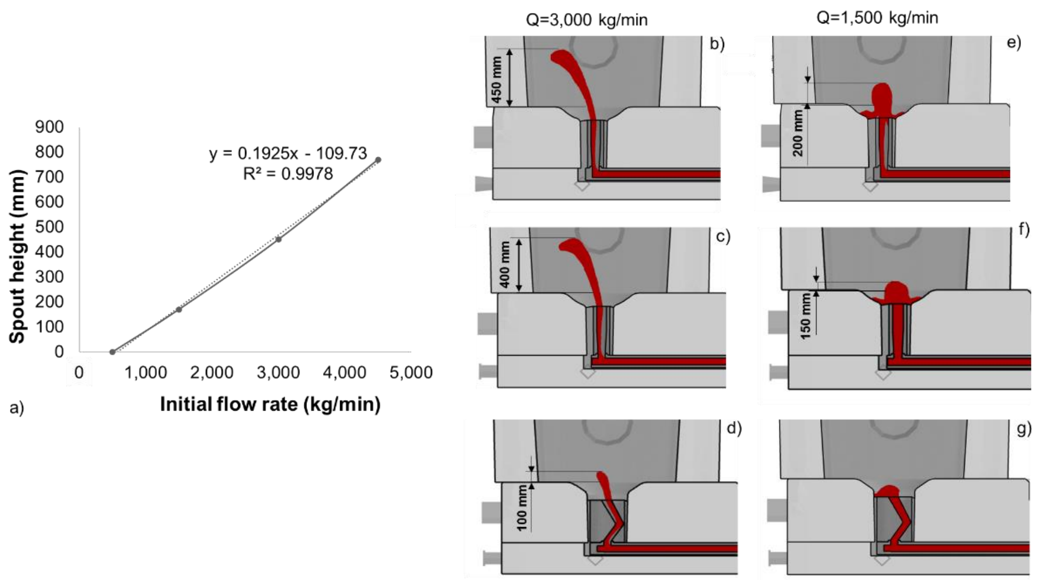

Figure 5 a) Trend of the height of the spout as a function of the initial flow rate with standard condition; Height of the initial spout in the standard configuration (b-e), with the trap (c-f) and with the elbow nozzle (d-g) with the variation of the initial flow rate of 3,000 kg/min (b-c-d) and 1,500 kg/min (e-f-g)

Figure *5* shows the maximum height reached by the spout with the different configurations considered, with a flow rate of 3,000 kg/min (b-c-d) and 1,500 kg/min (e-f-g). Since the initial spout appears particularly high, the use of a trap at the end of the runner was evaluated to homogenize the flow and eliminate non-metallic particles present. Considering 3,000 kg/min, the addition of this element is very useful for decreasing the height of the spout which is lowered approx. 50 mm (**Figure 5** c-f). The modification of the nozzle with the use of a modelled refractory in addition to the trap helps to decrease the height even further around 100 mm (**Figure 5** d). Additionally, thanks to the presence of the trap a better nozzle filling is possible, but only in the case of low flow rates. Modifying the nozzle in addition to the trap, on the other hand, allows for a much more homogeneous filling of the inlet nozzle channel even for higher initial flow rates.

4. CONCLUSION

A square ingot of 26 tonne was investigated in order to establish the cause of the defects found in the bottom part of the forged component. The key conclusions are as follows:

- casting powder is the cause of the defects, as shown by the metallographic analysis;
- simulation confirms the causes of the defects considering the critical threshold of the Weber number. Additionally, in the first stage, a high initial steel spout was present;
- the height of the steel spout depends linearly on the initial flow rate;
- the use of a trap and of an “elbow” nozzle strongly appears to reduce the height of the metal spout.

REFERENCES

[1] HEIDARZADEH, M., KESHMIRI, H. Influence of mould and insulation design on soundness of tool steel ingot by numerical simulation. *Journal of Iron and Steel Research International*. 2013, vol. 20, issue 7, pp. 78–83. https://doi.org/10.1016/S1006-706X(13)60130-2.

[2] TKADLEČKOVÁ, M., MICHALEK, K., GRYC, K., SOCHA, L., JONŠTA, P., SATERNUS, M., PIEPRZYCA, J., MERDER, T. Research and development of the solidification of slab ingots from special tool steels. *Archives of Metallurgy and Materials*. 2017, vol. 62, issue 3, pp. 1453–1458. https://doi.org/10.1515/amm-2017-0225.

[3] KOTÁSEK, O., KURKA, V., VINDYŠ, M., JONŠTA, P., NOGA, R., DOBIÁŠ, M. Comparison of casting and solidification of 12 ton steel ingot using two different numerical software. In *METAL 2021- 30th Anniversary International Conference on Metallurgy and Materials.* TANGER, 2021, pp. 147–152.

[4] WU, M., LUDWIG, A., KHARICHA, A. Simulation of As-Cast Steel Ingots. *Steel Research International.* 2018, vol. 89, issue 1. https://doi.org/10.1002/srin.201700037.

[5] ERIKSSON, R., JONSSON, L., JÖNSSON, P. G. Effect of Entrance Nozzle Design on the Fluid Flow in an Ingot. *ISIJ International*. 2004, vol. 44. https://doi.org/10.2355/isijinternational.44.1358.

[6] BAI, H., ERSSON, M., JÖNSSON, P. G. An experimental and numerical study of swirling flow generated by TurboSwirl in an uphill teeming ingot casting process. *ISIJ International*. 2016, vol. 56, no. 8, pp. 1404–1412.

[7] YIN, J., ERSSON, M., CONEJO, A. N., ANDERSSON, N., JÖNSSON, P. G. Numerical Study on the Influence of the Filling Angle on the Fluid Flow during the Ingot Side Teeming Process. *Steel Research International.* 2021, vol. 92, no. 10. https://doi.org/10.1002/srin.202100102.

[8] TAN, Z., ERSSON, M., JÖNSSON, P. G. Mathematical Modeling of Initial Filling Moment of Uphill Teeming Process Considering a Trumpet. *ISIJ International.* 2011, vol. 51, issue 9, pp. 1461-1467. https://doi.org/10.2355/isijinternational.51.1461.

[9] ZHANG, Z., YOKOYA, S., TILLIANDER, A., JÖNSSON, P. G. A Numerical Study of Swirl Blade Effects in Uphill Teeming Casting. *ISIJ International.* 2010, vol. 50, issue 12, pp. 1756-1762. https://doi.org/10.2355/isijinternational.50.1756.

[10] MANTELLI, A., VISCARDI, C., PELI, M., ROBERTI, R., GELFI, M., POLA, A. Analysis of the risk of casting powders entrapment in a 26-ton ingot by numerical simulation. In: *Conference Proceedings - 39th national AIM conference.* 2022. Padova.

[11] ESI Group, ‘ProCAST User’s Manual 2022’.

[12] ISO 22007-2. *Plastics – Determination of thermal conductivity and thermal diffusivity Part 2: Transient plane heat source (hot disc) method.* Vernier, Geneva, Switzerland: ISO, 2015.

[13] LI, W., LI, L., GENG, Y., ZANG, X., JING, Y., LI, D., THOMAS, B.G., Air Gap Measurement During Steel-Ingot Casting and Its Effect on Interfacial Heat Transfer. *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science*. 2021. https://doi.org/10.1007/s11663-021-02152-3.

[14] LAN, P., ZHANG, J. Q. Numerical analysis of macrosegregation and shrinkage porosity in large steel ingot. *Ironmaking and Steelmaking*. 2014, vol. 41, no. 8, pp. 598–606. https://doi.org/10.1179/1743281213Y.0000000172.

[15] MILLS, K. C., DÄCKER, C.-Å. *The Casting Powders Book*. Cham: Springer International Publishing, 2017. https://doi.org/10.1007/978-3-319-53616-3.

[16] ROSYPALOVÁ, S., DUDEK, R., DOBROVSKÁ, J., DOBROVSKÝ, L., ZALUDOVÁ, M. Interfacial tension at interface of a system of molten oxide and molten steel. *Materials and technology*. 2014, vol. 4, issue 3.

[17] JONSSON, L., JÖNSSON, P. Modeling of Fluid Flow Conditions around the Slag/Metal Interface in a Gas-stirred Ladle. *ISIJ International*. 1996, vol. 36, no. 1, pp. 11–27. https://doi.org/10.2355/isijinternational.36.1127.