ARCHIVES
of
FOUNDRY ENGINEERING
10.24425/afe.2026.157968
Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 2026
Issue 1/2026
45 – 51
5/1

Improvement of the Casting Technology for Steel Bucket Tooth according to Lost Foam Casting using Computer Simulation

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Received 17.07.25; accepted in revised form 06.10.25; available online 09.03.2026

Abstract

The research aims to improve the lost foam casting technology for producing steel bucket teeth for excavators. The relevance of this work lies in the need to enhance the quality of castings in challenging operating conditions, as well as to expand the application of advanced casting technologies within the domestic industry. When analysing the process of manufacturing steel bucket teeth using the lost foam technique, the presence of defects in the castings in the form of shrinkage cavities and gas porosity was detected. Using Flow-3D Cast software, computer simulations of the filling and solidification processes of metal were carried out for two variants of the gating-feeding system, the design of which significantly affects the formation of the quality of castings. The simulation results allowed us to analyse the features of the mold filling with metal for the basic version of the gating-feeding system, identify the risks of gasification products entrapment, and assess the effectiveness of the casting feeding during solidification. Based on the data obtained, an improved design of the gating-feeding system was selected to form a high-quality casting without shrinkage defects. The importance of using polystyrene foam patterns with an optimal density (within 25-30 kg/m³) to minimise the negative consequences of their gasification was also shown. The need to install risers on the patterns that perform the function of "overflows" was substantiated, helping to prevent the formation of defects in the casting. A pilot batch of castings confirmed the effectiveness of the developed technological solutions, which provided the basis for their introduction into the serial production of bucket teeth.

Keywords: Steel casting, Computer simulation, Lost foam casting, Bucket tooth, Casting defects

1. Introduction

Modern mechanical engineering requires introducing innovative technologies that ensure high product quality and efficiency of production processes. One promising area is the use of metal casting using Lost Foam Casting (LFC), which combines technological flexibility with economic feasibility [1]. This method enables the casting of complex parts with minimal machining costs, which is particularly relevant for the manufacture of steel bucket teeth for excavators operating under conditions of intense abrasive wear in direct contact with ore, sand, rock and other materials [2].

The bucket tooth is a critical element that is mounted on the bucket adapter and secured with a pin, so high dimensional accuracy requirements are imposed on the tooth castings [3]. Traditionally, investment casting has been used for such parts, which provides excellent accuracy and surface cleanliness [4]. However, this method has a significant drawback - the high cost of castings, which is due to the complexity of the process of manufacturing a ceramic mold: obtaining disposable wax patterns, layer-by-layer application of ceramic slurry and stucco, removing wax from the shell and its subsequent firing. It is more economical to obtain such castings using LFC technology. This technology utilises disposable foam patterns coated with a refractory paint and molded into unbounded silica sand, thereby eliminating the need for cores [5].

In addition to many advantages, LFC has certain disadvantages. In particular, when pouring metal, the degradation products of polystyrene foam can cause the formation of lustrous carbon, gas porosity, or other specific defects in the castings [6, 7]. The possibility of these specific defects is determined by the conditions of interaction of the liquid metal with the foam pattern [8], which depend on the design of the gating system. Therefore, when industrially using LFC to produce castings, it is necessary to predict the likelihood of these specific defects.

An auxiliary tool for the development and optimization of casting technologies for obtaining parts of complexly loaded mechanisms [9, 10] is software. Computer simulation enables the visualization of metal filling, the formation of temperature fields, and shrinkage during alloy solidification, which is especially effective for castings of complex geometry [11]. Certain software can predict the formation of specific defects in the LFC process [12]. Such software has been successfully used to optimize lost foam casting technologies for obtaining parts from cast iron [13] and steel [14], and in these works a sufficiently high level of convergence between experimental and computational results was demonstrated. Therefore, the use of computer simulation is particularly relevant for the development of casting technologies for producing responsible parts using the LFC process.

2. Problem statement

The object of research was a casting of a bucket tooth for an excavator. The sketch of the tooth and its expandable polystyrene (EPS) pattern are shown in Fig. 1. The mass of the cast part is 8.6 kg. Material is low alloyed steel L35GSM, the chemical composition of which is: 0.32 – 0.4% C; 1.2 – 1.4% Mn; 0.6 – 0.8% Si; 0.3 – 0.4% Mo; max 0.03% P; max 0.03% S; max 0.3% Cr; max 0.3% Ni.

In industrial castings at one of the foundries, defects in the form of shrinkage cavity and gas porosity were present (Fig. 2). Typically, shrinkage cavities are formed due to limited feeding of certain parts of the casting. Gas pores in LFC are often a consequence of the capture of EPS degradation products during the pouring process. The conditions of hydrodynamic processes during pouring and metal feeding during solidification are determined by the design of the gating-feeding system.

The purpose of this study was to improve the casting technology of a steel bucket tooth to eliminate casting defects by changing the design of the gating-feeding system, taking into account the peculiarities of the interaction of the metal with gaseous products of thermal destruction of the pattern.

For this, it was necessary to analyse the processes of metal filling and solidification of the casting using computer simulation for the basic version of the gating-feeding system. To determine the causes of the defects formation and propose a design of the gating-feeding system that would ensure the stable production of castings of satisfactory quality.

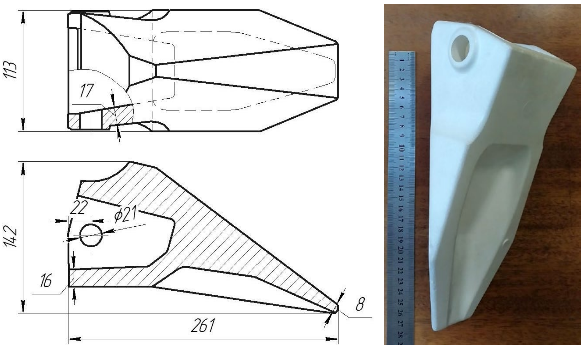

Fig. 1. Sketch of the tooth and its EPS pattern (right)

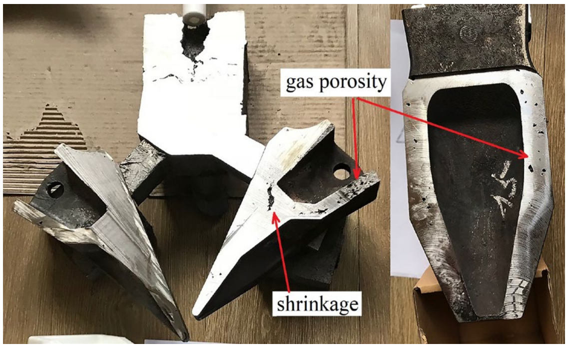

Fig. 2. Defects in castings of bucket tooth

3. Methods of investigation

During practical studies, castings were made using the conventional LFC process. One-time patterns were obtained by sintering EPS beads in molds in autoclaves. A gating system was glued to the obtained patterns, after which the pattern block was covered with a water-based refractory coating. After drying of the coating, the pattern blocks were molded in dry silica sand (Fig. 3) with its compaction by vibration in a metal container. The mold was filled with L35GSM steel melted in an induction crucible furnace. During pouring, the container was connected to a vacuum system with a residual gas pressure of 0.04 MPa to remove the products of destruction of the polystyrene foam. After cooling the castings, the gating system was cut off and the castings were shot-blasted.

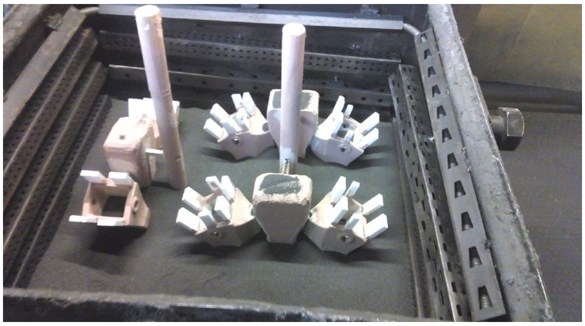

Fig. 3. Pattern blocks in a container during molding

To simulate the casting processes the Flow-3D Cast® software (Version 2023R1; Flow Science, Inc.; https://www.flow3d.com) was used. Since the distinguishing feature of LFC from conventional sand casting is the presence of a disposable foam pattern, the task of simulating the filling process is to accurately describe the dynamics of the metal-foam interface [15]. Flow-3D Cast describes the foam pattern as a constant temperature barrier. The gasification of foam is governed by the rate of heat exchange between the metal and the foam. The calculation mechanism in Flow-3D Cast is as follows [15]. When liquid metal enters the control volume containing foam, the heat transferred to the foam from the liquid metal during one time step is calculated. This amount of heat is then used to calculate the volume of foam that decomposes and heats up to the temperature of the metal. When calculating the amount of foam that decomposes, the heats of fusion and vaporisation of foam are considered. The energy transferred to the foam is subtracted from the metal. The metal is pushed into a cavity equal to the amount of foam removed in each control volume.

Flow-3D Cast allows to predict possible defects that appear on the metal surface due to the thermal degradation residues of foam. The LFC defect prediction algorithm is based on the fact that foam after degradation can leave a residue on the surface of the liquid metal. When the foam melts or evaporates in the control volume, the residue concentration in this volume increases by an amount proportional to the mass of degraded foam. Thus, foam residues accumulate at the metal front and move forward. If the metal front surfaces bend or touch during the filling process, the foam residues will end up inside the metal [16]. Thus, the probability of defect formation is proportional to the concentration of foam residues. That is, defects are more likely to occur in places of highly localized peaks in the concentration of foam residues [17]. For example [18], in locations of the local maximum of foam residue concentration there were defects – cold-shuts and folds.

The size of the computational cell was set to 4 mm. The materials for simulation were selected from the software database: Steel AISI 1040 (which has a chemical composition similar to L35GSM steel and almost the same liquidus and solidus temperatures of 1492ºC and 1428ºC, respectively), Sand Silica, Polystyrene foam - density 25.64 kg/m^3. The pouring temperature of the steel was set at 1600°C, and the initial temperature of the mold, foam and environment was 20°C. The heat transfer coefficients were set as follows (W/(m^2·K): between liquid metal and foam – 3000, between liquid metal and mold – 600, between solidifying metal and mold – 200. The boundary conditions included a metal pressure of 6800 Pa on the upper surface of the sprue, which corresponds to the ferrostatic pressure at the bottom of pouring basin at a metal level height of 96 mm.

4. Results and Discussion

First, the filling and solidification of castings with the basic version of the gating-feeding system were simulated. The filling simulation showed that the metal first enters the feeder, then through the ingates to the middle part of the casting. During the filling the velocity of the melt front in the cavity is 0.05-0.07 m/s (Fig. 4), which exceeds the recommended optimal values. At the end of pouring, the temperature of the metal in the feeder is higher than in the casting (Fig. 5, a).

The calculating results of foam residue for the basic version of the gating-feeding system showed (Fig. 5, b) that at the end of filling the metal concentration peaks are present in several places. The results of the solidification calculation showed that a shrinkage cavity is formed in the central part of the tooth casting (Fig. 5, c). The place of its formation coincides with the location of the cavity in real castings (see Fig. 2).

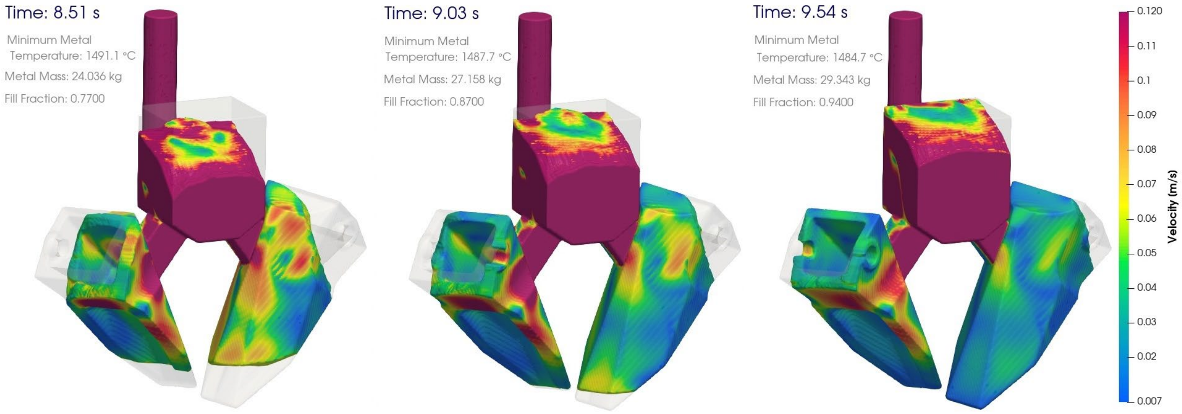

Fig. 4. Melt velocity during filling according to the basic version of the gating-feeding system

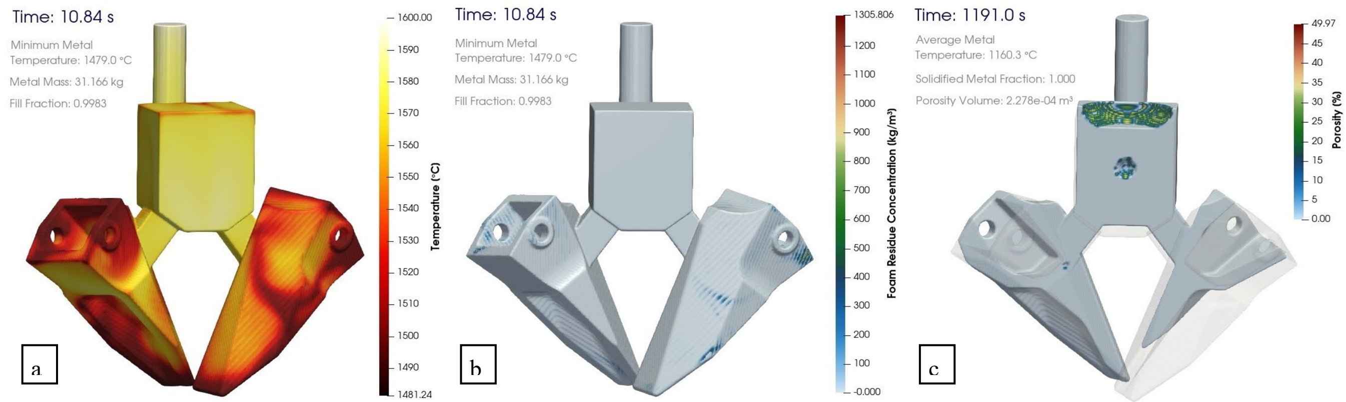

Fig. 5. Temperature fields (a) and foam residue concentration (b) at the end of filling, porosity in the castings (c) according to the basic version of the gating-feeding system

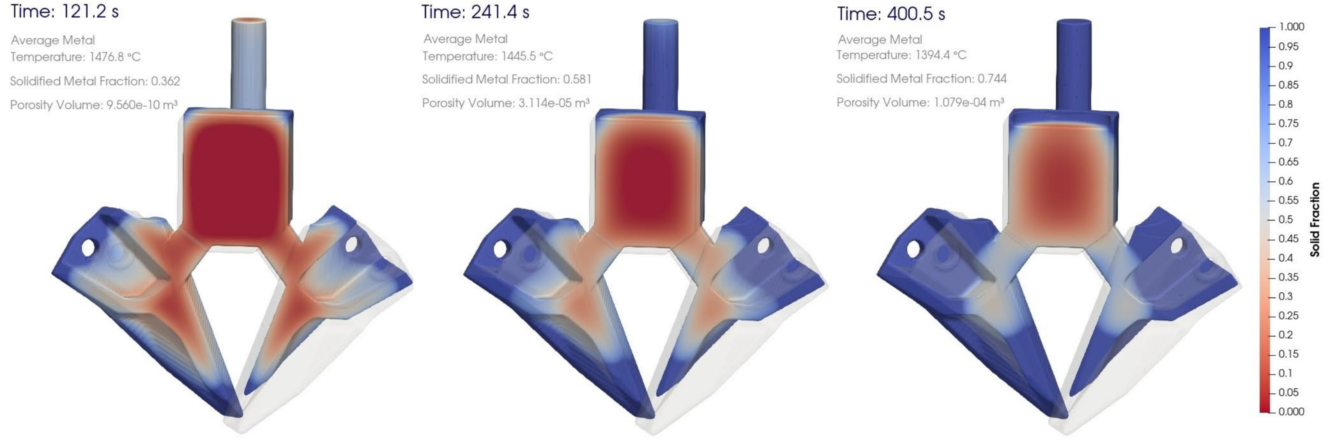

Fig. 6. Solid phase fields during casting solidification according to the basic version of the gating-feeding system

For a more detailed analysis of the cause of the formation of a shrinkage cavity, Fig. 6 shows the fields of the solid phase during the casting solidification. As we can see, there is a hot spot in the central part of the casting. The feeder, although it solidified last, does not provide full feeding of the hot spot due to the unfavourable geometry of the ingate, which connects the feeder and the casting. This is the reason for the formation of the shrinkage cavity in the center of the tooth.

Since the simulation results confirmed that the basic version of the gating-feeding system does not ensure the formation of a defect-free casting, another version was proposed. This gating-feeding system consisted of a massive feeder with two short ingates connecting it to the castings. The simulation results of filling and solidification with this variant of the gating-feeding system shown in Fig. 7 - 9.

The velocity of the melt front in the cavity was 0.03-0.05 m/s (Fig. 7), which is close to optimal values. The decrease in the melt flow rate is evidenced by the increase in the duration of pouring the casting block - for the improved version of the gating-feeding system the pouring time was 12.68 sec with a casting block weight of 30.0 kg, and for the basic version - 10.85 sec with a casting block weight of 31.2 kg.

The temperature of the metal throughout the volume of the casting is more uniform (Fig. 8, a), compared to the basic variant, which is because the metal enters the cavity through two ingates, rather than through one. It is undeniable that in the thin parts of the casting and the parts most remote from the ingates, the temperature of the metal is lower. From Fig. 8, b, it is seen that at the end of filling, the casting surface is almost free from the residues of polystyrene foam destruction products. Only in the upper part of the casting, in particular above the holes, there are locations with the high concentration of foam residue.

The solidification calculation showed that the shrinkage cavity is formed in the feeder, and the casting is free of cavities and pores (Fig. 8, c). The solidification process (Fig. 9) shows that the metal in the feeder solidifies last, and the hot spots of the casting are fed from the feeder through ingates, creating a defect-free casting.

Since the simulation showed that the improved version of the gating-feeding system provided good results, the casting blocks were manufactured and poured according to it. However, during developing the casting technology for obtaining steel teeth, it was found that some surface defects may form in the castings (Fig. 10). Such discrepancies with computer simulation, which did not show the formation of such defects, are because for some blocks, patterns with an excessively high density of 38-42 kg/m^3 were used instead of 25-30 kg/m^3, which is conventional provided for LFC technology.

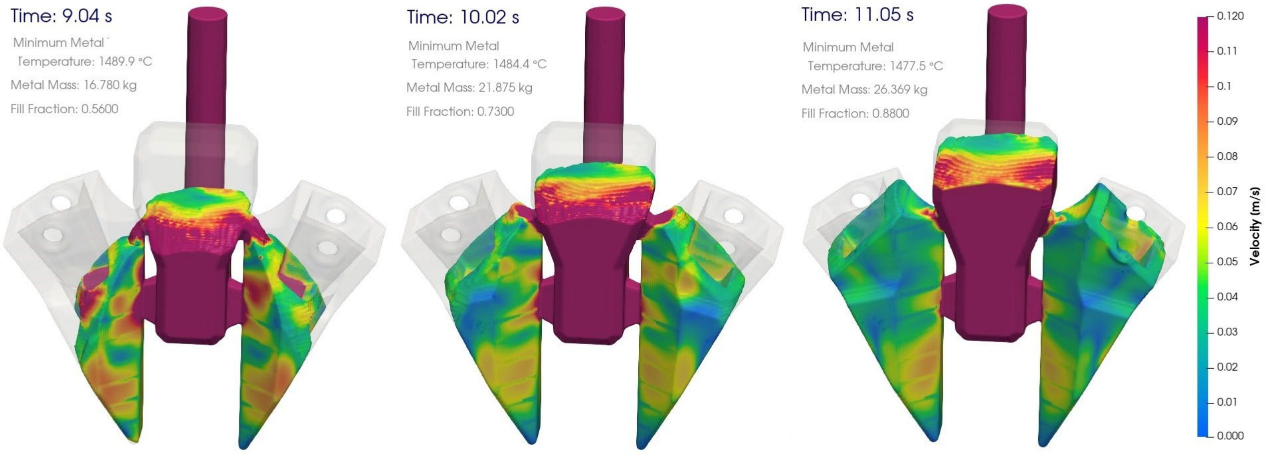

Fig. 7. Melt velocity during filling according to the improved version of the gating-feeding system

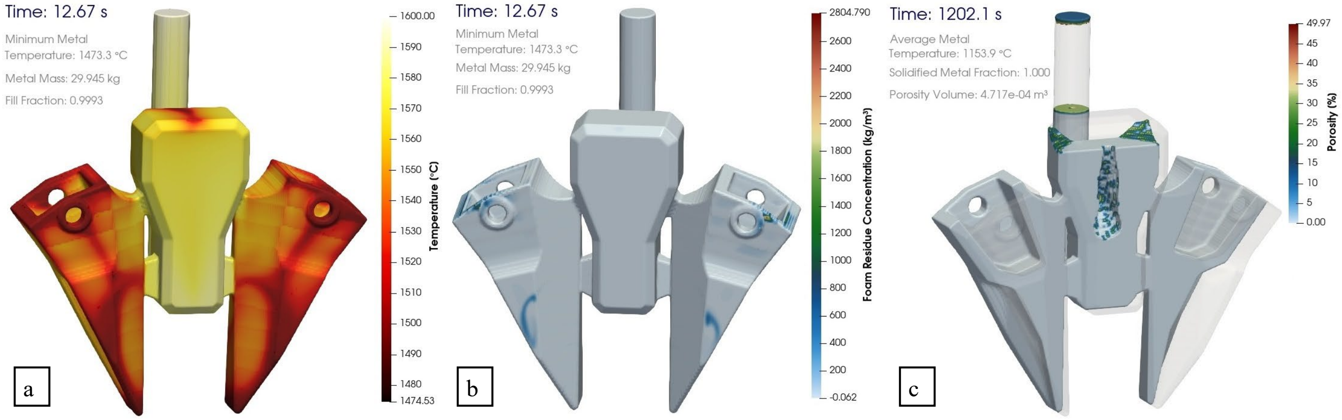

Fig. 8. Temperature fields (a) and foam residue concentration (b) at the end of filling, porosity in the castings (c) according to the improved version of the gating-feeding system

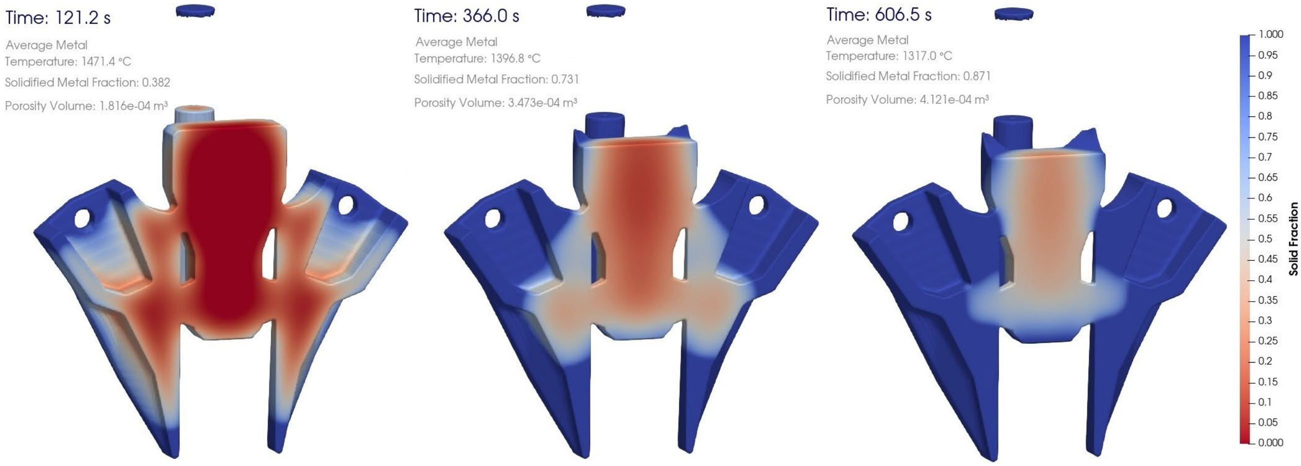

Fig. 9. Solid phase fields during casting solidification according to the improved version of the gating-feeding system

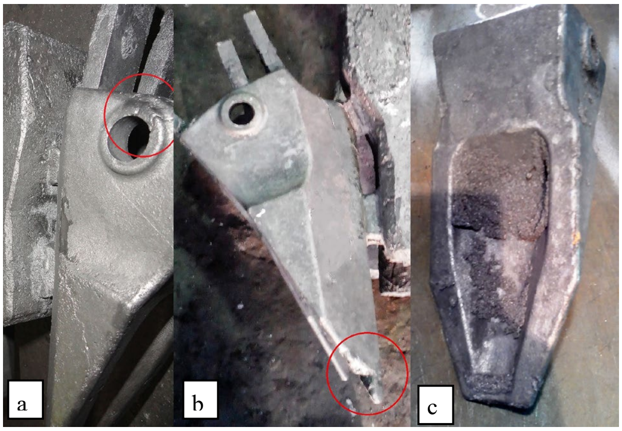

Fig. 10. Casting defects in tooth castings:
cold-shut (a), misrun (c), burn-on (c)

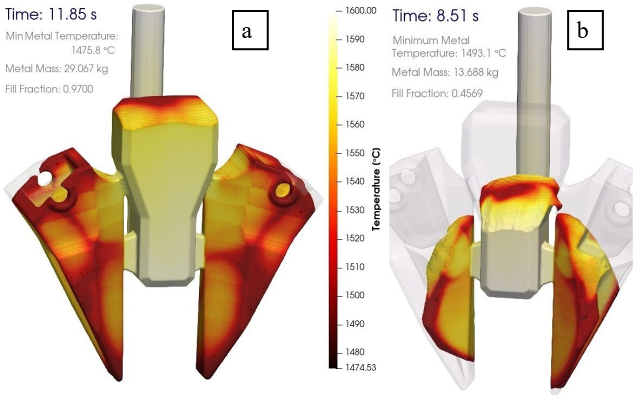

Fig. 11. Temperature fields of critical moments of pouring

In particular, a cold-shut was formed in a thin bridge above the hole (Fig. 10, a). As the simulation shows (Fig. 11, a), this bridge above the hole is formed by two metal flows, the temperature of which is about 1500ºC. Cooling of the melt fronts is also accompanied by the accumulation of foam decomposition products (see Fig. 8, b). When two melt fronts meet, foam residues end up inside the metal, which causes the formation of a cold-shut. To remove these products from this part of the casting, it was decided to install risers above the holes.

Misrun at the tip of the tooth (Fig. 10, b) was also formed in castings for which foam patterns with excessively high density were used. The metal reaches the tip of the tooth with a temperature of about 1500°C (Fig. 11, b). Increasing the pouring temperature up to 1640ºC to “compensate” for the metal cooling from gasification of high-density foam led to the formation of local burn-on the castings (Fig. 10, c), mainly on blocks that were poured first from the ladle. Although at high pouring temperatures, misrun did not form in the castings, such solution was not technologically feasible.

Finally, experimental casting was performed with steel at a temperature of 1590ºC using patterns with a density of 28 kg/m^3, to which the EPS risers were glued. The results of this casting showed that the improved version of the gating-feeding system allows to stably obtain castings of satisfactory quality (Fig. 12, a) in the absence of shrinkage cavities in the body of the tooth casting (Fig. 12, b). The installation of risers on the patterns, which perform the function of "overflows", contributed to the formation of a defect-free end surface of the tooth. It is also worth noting that the castings lacked gas porosity, such as that shown in Fig. 2. Most likely, the incorrect design of the basic gating-feeding system together with the uncontrolled density of the patterns caused the saturation of the liquid metal with gases that were formed during the termodestruction of the foam pattern.

The proposed technological solutions, which included the use of the improved design of the gating-feeding system using risers, manufacture of patterns with a density within 25-30 kg/m^3 (with careful control of the operations of preparing polystyrene foam and sintering the patterns for this), as well as maintaining the steel pouring temperature within 1580-1610ºC, allowed to eliminate the above-mentioned defects and obtain a control batch of suitable castings (Fig. 13). The castings of the bucket teeth, obtained using improved technology, had good surface quality, and their geometric dimensions fully met the requirements of the drawing. These developed solutions were implemented in the technological process of serial production of bucket tooth castings.

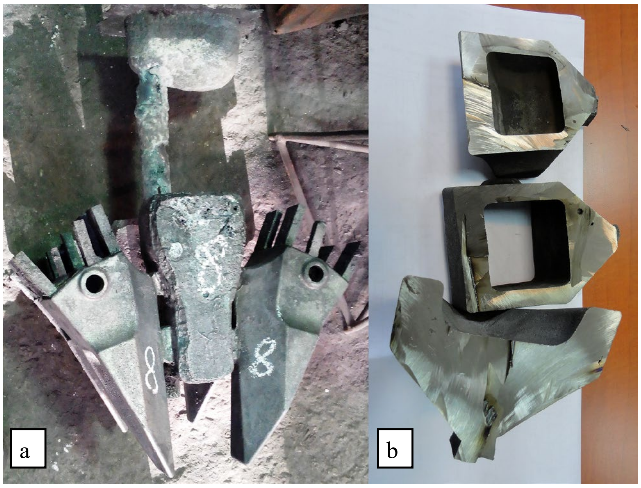

Fig. 12. Casting tree (a) and sections of tooth (b)

Fig. 13. Good quality tooth castings made using improved technology

5. Conclusions

Thus, as a result of the research conducted using innovative approaches to computer simulation, the technology of Lost Foam Casting of such a critical metal product as an excavator bucket tooth, which is operated under conditions of intense mechanical and abrasive loads, was improved. For this purpose, software Flow-3D Cast was used, which made it possible to predict with high accuracy the behaviour of the metal in conditions of complex thermodynamic processes: its fluidity in the liquid state, cooling and solidification. This gave grounds to choose the optimal mode of pouring the mold and feeding the casting during the metal solidification, preventing shrinkage defects. The periodic occurrence of surface defects on castings was also investigated, and the causes of their appearance were eliminated. The work performed demonstrated the effectiveness of using modern simulation software for the digitalization of foundry production. It is expected that the described methods will contribute to increasing the efficiency of LFC and expanding the application of this casting process in the domestic industry.

Acknowledgements

FLOW-3D® software made available through the ***FLOW-3D*** Academic Program.

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