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Professional paper

Application of CAD/CAE/CAM Systems in Permanent-Mold Casting Improvement

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Abstract: This paper presents the application of CAD/CAE/CAM systems at the improvement of the manufacturing the flotation balls for grinding ore. Flotation balls need to satisfy the appropriate requirements in terms of dimensional, chemical, mechanical and physical properties. These properties are directly related to technology of ball manufacturing, in this case - permanent-mold casting technology. Software tolls from the group of CAD/CAE/CAM systems were used for designing the casting parts, casting and feeding systems, mold and simulation of permanent-mold casting process. Based on results of casting process simulation the casting process in real industrial conditions was realized. After the casting process, testing of casting parts has been performed. The testing gave satisfactory results, so the presented methodology, based on CAD/CAE/CAM systems, is acceptable for manufacturing program in foundry.

Keywords: casting; design; flotation balls; simulation

1 INTRODUCTION

Casting process is a very old process, which has been used for a long time, based on empirical rules due to insufficient knowledge of processes that occur during melting, casting and solidification of casting part in mold. Although as a manufacturing process it dates thousands of years before the new era, the fundamental principles of casting have not significantly changed since the very founding of casting technology. Scientific findings were permanently upgraded and, as a result, they provided a wide range of reliable casting technologies and materials, which were successfully processed by these technologies. The application of modern CAD/CAE/CAM software systems is frequent in the research projects of the casting process. Their importance is in the efficient design of casting parts and casting system elements, as well as in the simulation of the casting process itself, which brings crucial conclusions for the production process - the quality of processes and products.

Yuwen et al (2012) presented the application of FLUENT software (based on finite element theory) to simulate liquid metal free surface and temperature field of casting filling process numerically. This paper also predicted defects on casting filling process, and this provides a basis for process optimization [1]. Štefanić et al. (2012) presented an application of CAD techniques and RP technologies in the manufacturing of the casting part model by using 3D printing [2]. Dabade et al. (2013) used a MAGMASoft software to simulate casting process, in order to analyze various defects in casting process, by detecting their cause through simulations of dimensionally and positionally different variants of casting and feeding systems [3]. Jie et al (2014) used the Pro Cast software package to improve the aluminum alloys casting process, and they concluded that the increasing of the cast temperature and casting process speed solves the porosity problem [4]. Bhatt et al. (2014) presented the design of feeding system of casting part and solidification simulation for cast iron by using AutoCast software [5]. Choudhari et al. (2014) presented the design of a feeding system (feeder location, feeder shape and size, and feed aids) by using AutoCAST X numerical simulation software [6]. Anglada et al (2015) presented simulation of the High Pressure Die Casting (HPDC) process, which is a complex type of simulation. By using ProCast software, they developed simulation models of processes that were able to adequately represent the thermal behavior of the mold and the casting part [7]. Yang et al. (2015) used Pro Cast software for simulation gravity and centrifugal investment casting processes. The experimental verification indicated that the simulation results were in good agreement with the experimental results [8]. Nimbulkar and Dalu (2016) presented the application of software Auto-Cast for casting process simulation. Particularly, the authors emphasized the significance of gating system design and feeding system design for the correctness of the casting part through numerous simulations in the mentioned software [9]. Dučić et al. (2017) presented the optimization of the sand-casting process by using the MAGMASoft software package. By simulating casting process, the authors verified the validity of designed casting system (basin, sprue, runner, ingates, feeders) [10, 11]. Mingguang and Yong (2017) analyzed hot cracking in the investment casting. In order to analyze the hot cracking in the investment casting, the Pro Cast software was adopted, and the investment casting process was simulated. The filling field, temperature field and stress field were analyzed, and the cause of crack was predicted [12]. Hodbe and Shinde (2018) emphasized the significance of the simulation of the casting process as indicators of potential defects of the casting part, such as: porosity, shrinkage, blowhole and pinhole. Their study deals with solving a real industrial problem using one CAM software system for simulation of the casting process [13].Tao et al. (2018) presented the importance of numerical simulation in order to optimize the investment casting process. The subject of their research was to increase simulation efficiency and reduce memory consumption [14]. Kwon and Kwon (2019) presented CAE simulation by using simulation software (AnyCasting) in order to optimize the gate and runner design of an automobile part [15].

One of numerous casting technologies is permanent-mold casting technology, which is very significant for manufacturing process. Permanent-mold casting is characterized by good dimensional accuracy and quality of casting part surface, fast solidification that gives a fine grain structure in the cast metal (production of harder casting parts), possibility of casting all significant alloys, short casting time, long working life of the mold and the possibility of automation of the process [16]. The subject of this paper is permanent-mold casting, more precisely, improvement of the production of copper-ore milling balls, which are produced by permanent-mold casting. The main goal of the paper is to present a methodology for applying scientific knowledge embedded in modern software tools in solving a real industrial problem.

2 METHODOLOGY

This section presents a methodology for improvement of ball casting manufacturing process. The proposed methodology is based on the application of CAD/CAE/CAM systems, which enable the design of casting system, numerical simulation of the casting process, technology development and generation of NC code for the production of molds on the CNC milling machine. The activity flow of the proposed methodology, which contains five steps, is shown in Fig. 1.

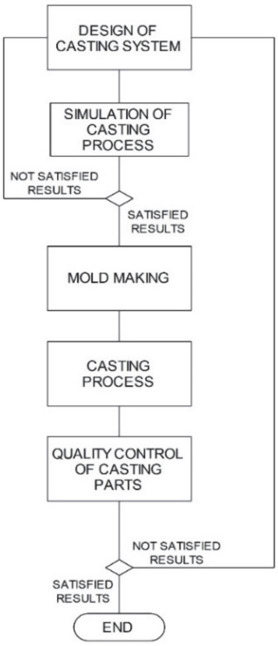

Figure 1 The activity flow of the proposed methodology

The first step is the design of the casting system, which involves creating CAD models of the casting part and every element of the casting system (basin, sprue, sprue well, ingate, feeder). Geometry design (shape and dimensions) of these elements is based on the research of eminent researchers in the casting field. After the first step follows a validation of the designed system. Validation takes place in a second step called the simulation of the casting process. Casting process simulation enables visualization of the casting process and analysis of simulation results that give a clear picture of the quality of the process and products. If the simulation results are not satisfactory, a return to the first step and a redesign of the casting system will follow. If the results of the simulation are satisfactory, the implementation in the foundry follows. The third step in the proposed methodology is to make a mold on a CNC milling machine using a CAD/CAM software system. When the mold is made, the fourth step is the permanent mold casting process. The casting process is realized with the process parameters that were used in the software simulation. After the casting process, the final step is to check the quality of the casting part. If the casting part meets the quality requirements, the proposed methodology ends. If the casting part does not have the desired performance, an analysis and redesign of the casting system are followed, and the other steps of this methodology are repeated.

The proposed methodology is of a general nature, acceptable for a different class of casting parts. The characteristics of the casting part and its purpose will influence the procedures in the steps given in this methodology.

3 DESIGN OF CASTING SYSTEM

Flotation balls, used in copper ore preparation technology, need to satisfy appropriate requirements in terms of dimensional, chemical, mechanical and physical properties. Flotation balls are made of white cast iron, and their chemical composition is within the following limits: C = (3.2 - 3.8)%, Si = (0.4 - 0.8)%, Cr = (2.2 - 2.8)%, Mn = (0.4 - 0.8)%, P_{max} = 0.1%, S_{max} = 0,1%. When referring to surface and volume hardness, limit values for 25 to 150 mm diameter balls are 58 - 65 HRC for surface hardness and 56 - 64 HRC for volume hardness. The flotation ball surface must not have defects such as: shrinkage pores and obvious porosity, shrinkage cavities, cold shuts, poor connections, rough surface etc. In terms of the internal quality of the ball, porosity, blowholes, nonhomogeneity of the ball material, shrinkage in the casting part are not permitted. They arouse the stress concentration which dramatically shortens the lifetime of the ball. The quality of casting technology has a major impact on the occurrence of many of these side effects. Flotation balls are made by permanent-mold casting technology, by casting in shape of a symmetric cluster. Proper and complete molds filling is an important task in the casting process, which achieves high quality casting parts. The role of the gating system design and feeding system design is very significant in achieving this goal. Fig. 2 shows CAD model of casting system with casting parts (eight flotation balls).

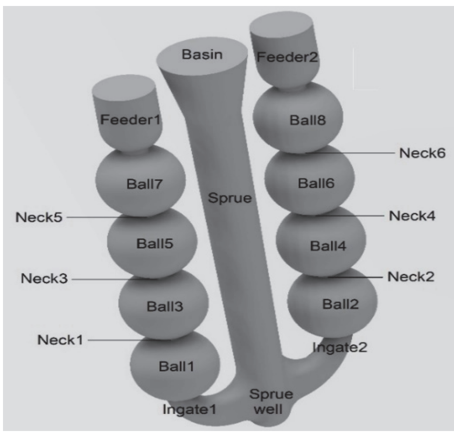

Figure 2 Casting parts (balls) and elements of casting system

Basin is the first element of gating system, which has a task to direct molten metal from casting pot to sprue. Two types of basin, which are the most present in construction solutions of the gating systems, are: conical and offset basin. In this case a conical basin is used, and according to

Campbell [17] geometrically best variant of conical basin. The sprue is a part of ingate gating that connects a basin and a sprue well (extended base of the sprue). Its task is complex, and involves bringing melted metal into the next segment of the gating system with minimal defects, despite high velocities of fluid. In this case, a conical sprue with a round cross-section was used. The conical sprue, whose round cross-section is changing, according to the equation of continuity, reduces turbulence and the ability to absorb air. The advantage of a round cross-section is that the smaller surface is exposed to cooling process and the resistance to metal flow is less. The next segment of the gating system is the sprue well, whose main task is to reduce air intake into ingates. Two symmetric ingates have task to deliver molten metal in mold cavities intended for balls. Balls are connected between themselves with necks which are dimensioned to enable the quick filling of the next ball and allow easy separation of balls after the casting process. At the end of the casting system there are feeders, whose function is to compensate the lack of molten metal due to its volumetric shrinkage during cooling. During cooling, there are three different stages of volume contraction, i.e. shrinkage: liquid phase shrinkage, shrinkage during freezing and solid phase shrinkage (Fig. 3).

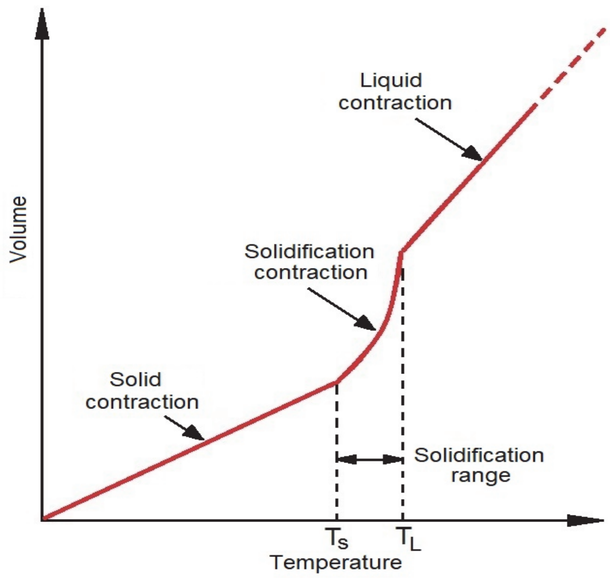

Figure 3 Schematic illustration of three shrinkage regimes: in the liquid, during freezing and in the solid [17]

Contraction of volume is manifested through side effects: internal cavities, surface deformations, surface craters. One of the indicators of casting process quality is continuity of the flow of molten metal in the field of solidification that is feeding. Elimination of these side effects is carried out by proper design of feeders, which are to be removed from the casting part after cooling. In this case, two symmetrical feeders are designed based on two basic rules for feeding the casting part.

Rule 1: The feeder must harden, the earliest, at the same time as casting part, or later. This is Chvorinov's heat transfer criterion.

Rule 2: The feeder must contain enough molten metal, in order to compensate for the casting part volume shrinkage of metal in the area for which the mentioned feeder is intended.

Based on CAD model of balls and casting system, the other CAD models, subassemblies, assemblies (mold, cooling chambers), necessary for realization of casting process simulation, were created. Fig. 4 shows CAD model of a half of the mold.

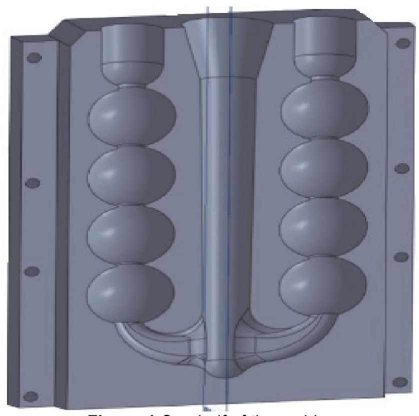

Figure 4 One half of the mold

Fig. 5 shows the whole assembly which includes all the elements connected in one whole. The shown assembly (with each element separately) in the STL format represents the input CAD file for simulation of permanent-mold casting process in the next section of the paper.

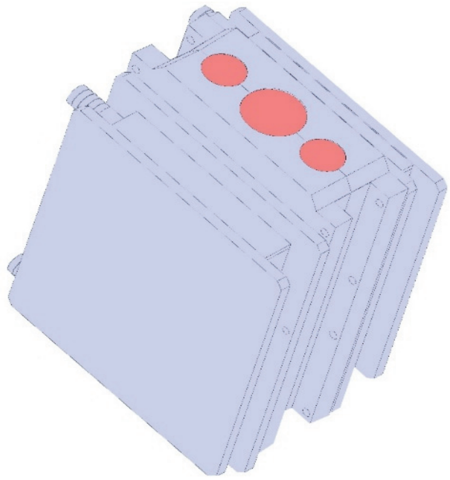

Figure 5 Assembly of permanent-mold casting system

4 SIMULATION OF CASTING PROCESS

One of the basic functions of computer aided engineering (CAE) is simulation and visualization of the process. Casting simulation systems allow performing virtual experiments that have a goal to simplify complex technical challenges. They also provide the ability to manage design and process parameters that affect the quality, cost and efficiency of manufacturing. In this particular case, the MAGMASoft software system for the simulation of the casting process was used.

Inputs into the simulation are:

- STL files of each element of casting process (mold, casting part with casting system and feeding system, cooling chambers),
- chemical composition (C = 3.5%, Si = 0.8%, Cr = 2.6%, Mn = 0.6%, P = 0%, S = 0,1%),

- heat transfer coefficients for materials pairs that are in contact in different ways during casting process
- temperature of molten metal (1400 °C),
- mold temperature (before the casting process the mold is heated on temperature 120 °C, and during the casting process, the temperature of the mold reaches 700 °C and it is necessary to protect the mold with thermal insulation coatings),
- temperature of water that flows through mold cooling chambers (20 °C).

After adjusting the input parameters follows running of the casting process simulation and analysis of its results that describes the quality of casting process, which is directly related to the quality of the casting part. Temperature criterion shows temperature values during solidification, and it is an indicator of directional solidification, which is a prerequisite for the successful casting process. Fig. 6 shows temperature during solidification of casting part, i.e.: 2% solidification (a), and finished solidification process 100% (b).

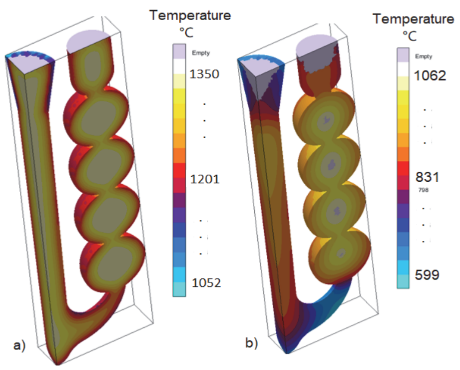

Figure 6 Temperature criterion a) solidification 2% and b) solidification 100%

Two connected criteria are: Liquidus to solidus and Hot spot criteria. The Liquidus to Solidus criterion (Fig. 7) shows the time it takes to pass so the material volume passes from the liquid to the solid state. In this particular case, this criterion shows the connection between balls is the last solidifying volume of casting part. This is a very positive occurrence for the continuous filling of the mold cavity, since connections between balls are very important in the transfer of molten metal.

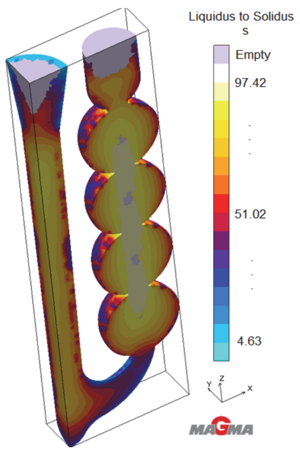

Figure 7 Criterion Liquidus to solidus

The hot spot criteria (Fig. 8) show hot spots in the casting part, i.e. those volumes in the casting part that have a significantly longer solidification interval. These criteria confirm the positive occurrence detected through the Liquidus to Solidus criteria.

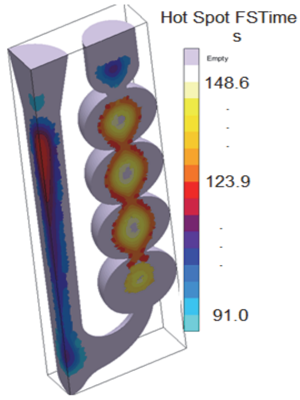

Figure 8 HOT Spot criteria

Porosity criterion (Fig. 9) shows porosity in the casting part at the end of solidification process. In this case, porosity is detected at the center of the ball and its maximum diameter is less than 10 mm. Porosity in the center of the ball does not have a significant impact on wear because the ball never wears until the very end, so the result given by the Porosity criterion is very good and acceptable.

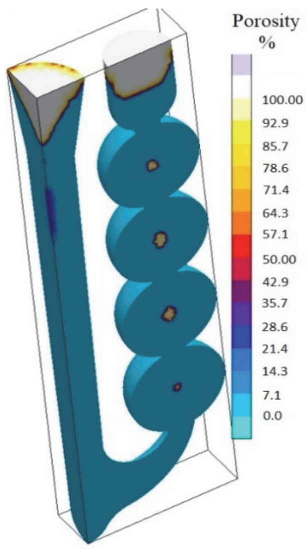

Figure 9 Porosity criterion

The results of the performed simulation accomplish the basic goal of each casting process - obtaining a healthy casting part, so the designed casting system is acceptable for implementation in real industrial conditions.

5 CASTING PROCESS AND QUALITY CONTROL OF CASTING PARTS

The mold of designed casting system is made from gray cast iron on the CNC milling machine by using a CAM system. In the CAM system the mold manufacturing technology is developed, through precise defining of technological sequences, processing simulations and post-processing (obtaining a NC code). Fig. 10 shows a simulation of one technological sequence (face milling) in the CAM system and a final mold layout after manufacture.

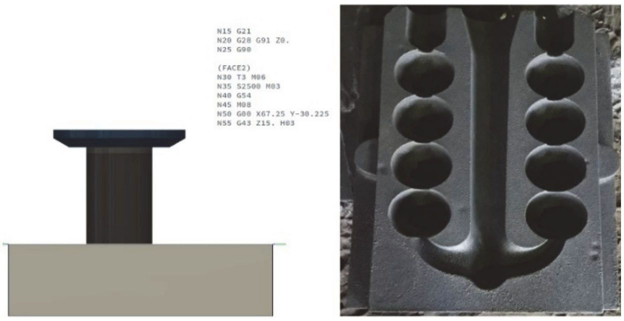

Figure 10 CAM simulation and final mold layout

After mold making follows casting process and then checking the quality of the casting part. Checking the flotation balls quality includes the control of their internal and external layout, surface and volume hardness. External layout of the ball is satisfying, because no cracks, cavities nor obvious roughness is observed. When it comes to the internal quality of the ball, no porosity was observed in the cross-section (Fig. 11). Although the software simulation detected porosity at the center of the sphere, this porosity was not detected, as it is likely to be the micro porosity detected by the software.

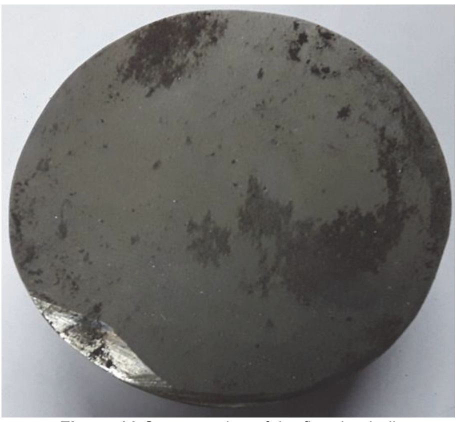

Figure 11 Cross-section of the flotation ball

For measurement of surface hardness, the cross sections are formed along the ball diameter with the defined measuring points (Fig. 12).

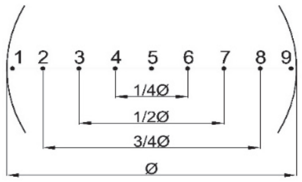

Figure 12 Arrangement of measuring points of surface hardness

Fig. 13 shows testing the ball surface hardness (Rockwell "C" method) in points 1 and 9.

Preparation of the ball includes cutting off the spherical cap, 2.5 mm height. In this way flat and finely grinding surface, were obtained. Hardness testing was performed with three stamps on those flat surfaces. The surface hardness values at the measuring points are given in Tab. 1.

Table 1 Results of the surface hardness of the ball

Position	1	2	3	4	5	6	7	8	9
HRC	58	54	55	54	52	54	56	56	58

The volume hardness is calculated by the *AVH* (Average Volumetric Hardness) Eq. (1):

$$AVH = 0.289 \cdot A + 0.437 \cdot B + 0.203 \cdot C + 0.063 \cdot D + 0.008 \cdot E \qquad (1)$$

where: A is the mean value of the measured surface hardness in points 1 and 9; B is the mean value of measured surface hardness in points 2 and 8; C is the mean value of measured surface hardness in points 3 and 7; D is the mean value of measured surface hardness in points 4 and 6; E is the value of measured surface hardness in point 5.

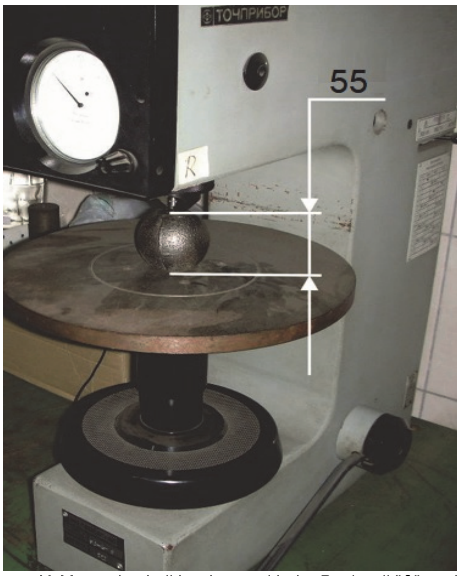

Figure 13 Measuring ball hardness with the Rockwell "C" method

In this case AVH is 56.4 HRC. Thus, the mean value of surface hardness of the ball (measuring points 1 and 9) is 58 HRC, and the value of volume hardness is 56.4 HRC, which indicates that the hardness of this ball is satisfying. In fact, the values are within acceptable frameworks, which makes the developed casting technology acceptable for the industry.

6 CONCLUSION

Paper presents the methodology which includes the application of CAD/CAE/CAM systems in the improvement of the permanent mold casting process. The proposed methodology is applied in the manufacturing of flotation balls for grinding ore. The idea of this paper is to avoid the traditional design of casting systems, based on attempts/error principle, by application of modern CAD/CAE/CAM software tools. The attempts/error principle makes the manufacturing non-efficient and non-economical. Software from the CAD/CAE/CAM group allows efficient process design, virtual experiments, and control process parameters with the goal to obtain the best solution for the manufacturing process. After several re-designs of the casting system (the first step in the methodology), the proposed and applied methodology has shown great results at improving flotation balls casting process. The flotation balls, made by this methodology, meet all qualitative requirements, as confirmed by ball testing after the manufacturing processes.

The evident limitation of this methodology is the first step, i.e. the design of the casting system. This step can be repeated many times until a good casting system solution is obtained. Future research directions will be dedicated to reducing the repetition of the first step, using intelligent optimization techniques. The use of intelligent optimization techniques will eliminate wandering in defining the dimensions and geometry of casting system elements. In this way, the proposed methodology will be even more effective for implementation.

Acknowledgements

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