ORIGINAL ARTICLE

Numerical Analysis and Experimental Validation of Pouring Casting Metal in Sand Mold

Análisis numérico y validación experimental del vertido de metal fundido en molde de arena

CU-ID: 2177/v31n3e08

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ABSTRACT: Metal foundry represents an important sector within the mechanical industry. The method of casting metal into sand molds has been used for millennia because the freedom it allows the designer in terms of size and shape. The objective of this research is to establish a numerical simulation model, experimentally validated, of molten metal pouring in a sand mold, taking as analysis criteria the internal defects in the body of the bearing support of the 4 500 lb. harrow. In this research, an analysis was carried out, from the Finite Element Method (FEM), of casting process taking into account the molten metal pouring temperature, the mold preheating temperature and the filling speed. These parameters were recorded during the experimental testing of the process. An inspection procedure is shown, in which elements of visual analysis of the piece obtained and of simulation by MEF were used to determine the magnitude and location of internal defects inside the piece. The defects were classified in blowhole, porosity and cold junction, a correspondence was appreciated in terms of their location, between the simulated and the experienced models; while the defects area relative error in these models is less than 10%.

Keywords: Metal Casting, Inspection, FEM, Defects, Harrow.

RESUMEN: La fundición de metales representa un importante sector dentro de la industria mecánica. El método de vaciado de metal en moldes de arena ha sido utilizado durante milenios debido a la libertad que le permite al diseñador en términos de tamaño y forma. El objetivo de la presente investigación es establecer un modelo de simulación numérica, validado experimentalmente, del vertido de metal fundido en molde de arena teniendo como criterio de análisis los defectos internos en el cuerpo del soporte de los rodamientos de la grada de 4 500 lb. En esta investigación se realizó un análisis, a partir del Método de Elementos Finitos (MEF), del proceso de fundición teniendo en cuenta la temperatura de vertido del metal fundido, la temperatura de precalentamiento del molde y la velocidad de llenado, estos parámetros fueron registrados durante el ensayo experimental realizado del proceso. Un procedimiento de inspección es mostrado, en el que se utilizaron elementos de análisis visual de la pieza obtenida y de simulación por el MEF, para determinar la magnitud y localización de los defectos internos en el seno de la pieza. Los defectos fueron clasificados en sopladura, porosidad y unión fría, se apreció una correspondencia en cuanto a la localización de los mismos, entre el modelo simulado y el experimentado; mientras que el error relativo del área de los defectos en dichos modelos es menor al 10%.

PALABRAS CLAVE: fundición de metales, inspección, MEF, defectos, grada.

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Received: 04/12/2021
Accepted: 24/06/2022

INTRODUCTION

Metal casting is a unique process among all manufacturing processes for a wide variety of reasons, the most outstanding is the possibility its geometric configuration offers of making viable the production of components with complex geometry of any metal (Stefanescu, 1998). A wide variety of ferrous metals and alloys can be obtained from the casting process, since they are the most widely used materials in engineering. By virtue of their wide range of mechanical, physical, and chemical properties, ferrous metals and alloys are among the most useful of all metals (Kalpakjian & Schmid, 2008).

The sand mold casting process is one of the ancient manufacturing techniques that uses sand as a refractory medium to increase the casting quality (Sunanda & Jagannadha, 2021). According to Jacob *et al.* (2004), metal casting represents an important sector within the mechanical industry. The traditional method of casting metal in sand molds has been used for millennia. Although the origin of sand casting dates back to ancient times, it is still the prevailing form of casting (Kalpakjian & Schmid, 2008), due to the freedom it allows the designer in terms of size, shape, and quality (Stefanescu, 1998).

Currently there are clear trends in the foundry technology evolution, because efficiency has increased, producing higher quality parts in which dimensional tolerances are reduced. Due to the continuous sector specialization and industry high demands, casting technology is increasingly forced to produce, efficiently, more complex parts (Groover, 2010).

According to Abdullin (2013) cited by Suárez & Coello (2015), the defects occurrence in a casting must be controlled from the very elaboration process of casting technology by the technologists, therefore, having a tool and a methodology to solve this situation is a great help and enables the economic improvement of the process. In that sense, the Computer Aided Engineering (CAE) technology has become a viable tool for the prediction and prevention of castings defects. Thus, according to Kwon (2021), currently CAE technologies development has significantly reduced the existing trial-error process in the construction of foundry molds.

Authors such as Sunanda & Jagannadha (2021), faced the technological challenge that affecting the pulleys quality, caused by defects in the casting process, they use numerical simulation to analyze the mold filling and solidification metal, with which it is possible to predict the defects in the process. Similarly, Rodríguez *et al.* (2004), exemplify the advantages of using simulation techniques to predict defects in castings. The authors show the possibilities of using this type of techniques in the foundry technology field.

Likewise, Sorate *et al.* (2017), perform the feeding system optimization in a casting model of a bearing support, using a CAE program that allows the numerical simulation of metals pouring and solidification. The objective of research is to improve the final quality piece obtained and, therefore, to increase the casting process yield. Similarly, Kabnure *et al.* (2020), use the numerical simulation technique to predict the location and intensity level of the shrinkage phenomenon in a ductile iron cast flange. The numerical analysis allows determining that it is necessary to modify the molten metal feeding system into the mold.

Rajkumar & Rajini (2021), state that, in order to minimize the time and cost in products creation, CAD/ Computer Aid Manufacturing (CAM) tools have been combined with the foundry industry requirements. In this sense, all the authors, mentioned above, emphasize that the numerical simulation of metals pouring and solidification constitutes, at present, a necessary technique that must be used in the initial stages of the technology development for pieces obtaining by casting process, regardless of mold characteristics and material to be foundry.

However, it is a highly advisable practice to validate numerical analysis models based on experimental techniques in order to establish a robust study of casting process. In this sense, Motoyama *et al.* (2020), carry out a study to measure the warping magnitude in thin pieces obtained by sand casting. The authors carry out experimental tests of the casting process and subsequently, based on the experimental results, they make FEM simulations. The deformation results, by both analysis methodologies, in the gray cast-iron piece studied, are compared determining that there are no significant differences.

Internal defects, derived from casting process, in the bearing support body of the 4,500 lb. harrow, are an important factor in the piece's service out, since the presence of geometric discontinuities into the material acts as stress concentrator in face of efforts that, according to De Soto y Limas (2017), are considerable and have their common cause in the unfavorable exploitation regime caused by the field work.

The objective of the research is establishing a numerical simulation model, experimentally validated, of pouring and molten metal in a sand mold, having as an analysis criterion the internal defects in the bearing support body of a 4,500 lb. harrow.

MATERIALS AND METHODS

Procedure Used in the Analysis of Molten Metal Pouring

Figure 1 shows the experimental procedure followed in analyzing geometric characteristics of the support body of bearings in a 4 500 lb. harrow, obtained through the metal casting process.

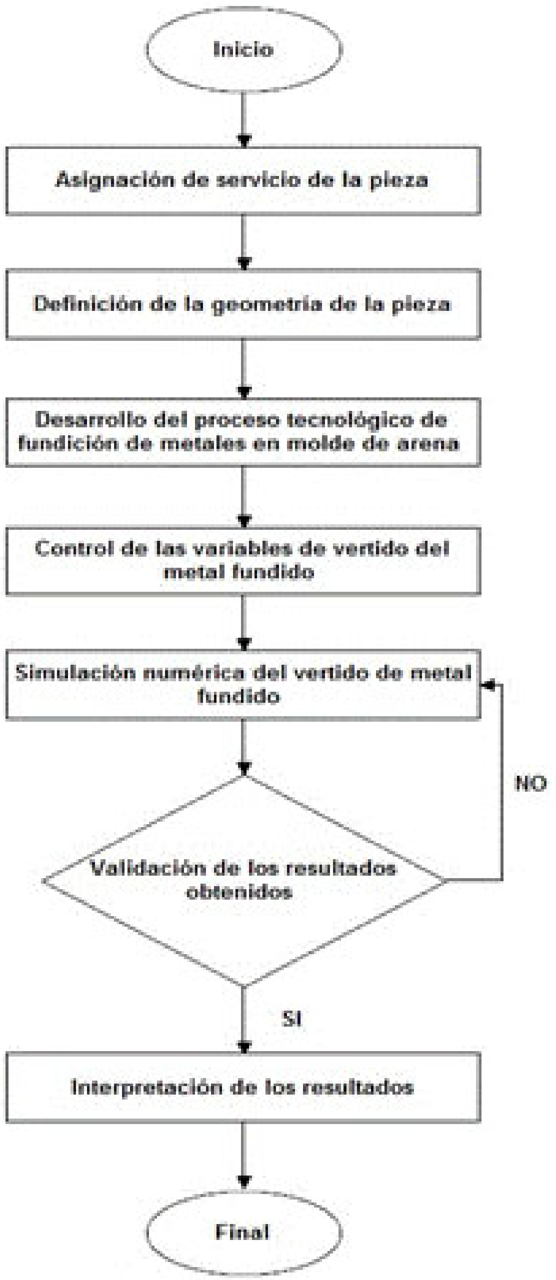


FIGURE 1. Procedure diagram used in pouring analysis of casting metal

The piece service assignment constituted the first step for analysis development, since it is important to determine the exploitation regime and location within the mechanical system, in the same way, the geometric characteristics definition has a great interrelation with the previous step. The piece dimensions, which are obtained by casting process, were determined following the methodology proposed by Navas *et al.* (1990).

The development of metals casting technological process in sand molds was monitored in each of its technological steps until reaching the molten metal pouring; in this last step the most important variables were controlled: mold preheating temperature, pouring temperature and molten metal pouring time. Subsequently, the pouring process molten-metal into the sand mold was numerically simulated, taking into account the effective presence of the appropriate geometric conditions of the piece, as well as the data collected during metal pouring, all of which allowed performing the constitutive pre-process stage of FEM analysis.

The validation of the results obtained by experimental test and numerical analysis constituted the most significant step of the procedure. The achievement of a FEM analysis model that adequately responds to the molten-metal pouring real behavior and the subsequent geometric characterization of defects as trapped air, cold joints and poorly filled mold gaps, will make possible to carry out future numerical simulations that allow mitigating the aforementioned defects.

Finally, the interpretation of the results of the casting metal pouring process to obtain the bearing support body of the 4 500 lb. harrow, contributed to the technological decisions related to the process. In this stage, all the parameters that intervene in the process must be improved, for which the adjusted model of numerical simulation by the FEM is available.

Piece Service Assignment

The present investigation was developed in the Agricultural Logistics Company “26 de Julio” in Bayamo Municipality, Granma Province, Cuba. The 4 500 lb. harrow is intended for soils preparation used for planting agricultural crops of great nutritional importance (Figure 2a) and it is subject to a rigorous exploitation regime due to the ground characteristics (with various obstacles and slopes) where it is generally used.

The bearing support body (Figures 2b and 2c) has crucial importance in the correct performance of the tillage implement, since it is responsible for supporting the shaft where harrow discs are mounted. However, it has been detected that the piece, manufactured in the entity, has presented recurring failures located in the same area. The failure was caused by the geometric discontinuities presence inside the material, associated with the metal casting technological process.

Geometry Definition of the Piece to be Obtained Through the Casting Metals Process in Sand Molds

The piece geometry, which was obtained through the metal casting process, has a circular ring-shaped configuration (Figure 3a), the main dimensions are: 306 mm wide, 224 mm high and 131 mm thickness. The outer diameter is 189 mm and the inner diameter is 145 mm, the mass is 18,211 kg.

The final geometry of the piece is shown in Figure 3b, after submitting it to chip removal machining to eliminate the oversize remaining from the casting process.

Development of Casting Metals Technological Process in Sand Molds

Casting metal technological process, analyzed in this investigation, constitute common elements for the pouring process by gravity of casting metal. It was based on the specified technical task to obtain the support body for the bearings of the 4 500 lb. harrow.

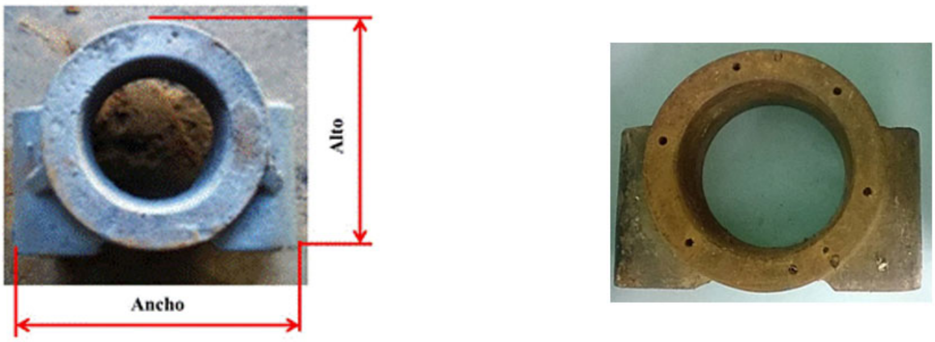
Subsequently, the piece was molded starting from the template placement in the box and then it was filled with sand. Likewise, during this operation the casting feeding system, gas evacuation components and filling indicators were located (Figure 4a).

Then, the sand was tamped with all components and later the template was extracted from the mold (Figure 4b). Finally, a paint layer was applied to mold cavity to achieve a better surface finish and easy removal of piece from the mold once cast (Figure 4c).

Humidity extraction in the sand mold was achieved from the total flaming of its geometry, another important purpose with this action is to enable a lower

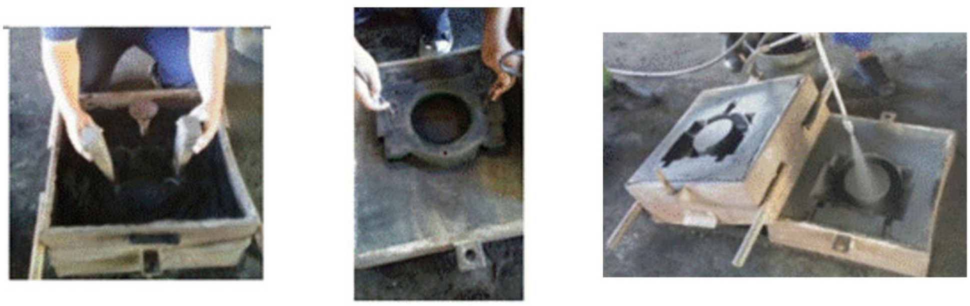
a) b) c)

FIGURE 2. Location of bearing support body on harrow of 4500 lb.; a) Harrow elements set, b) Top view and c) Side view.



a) b)

FIGURE 3. Bearing support body of harrow of 4 500 lb.; a) Piece obtained from the casting and b) Finished piece after chip removal machining.



a) b) c)

FIGURE 4. Technological actions carried out during sand mold preparation for bearing support body of 4 500 lb. harrow; a) Placement of feeding system elements; b) Wooden template extraction and c) Paint layer application into mold cavity.

thermal gradient at the time of casting material pouring. In this investigation, the casting metal pouring was carried out immediately after preheating the mold faces that will be exposed to casting metal.

Undoubtedly, the metal pouring is most responsible and important action in the process, since all the previous steps are synthesized in it. The process temperature was recorded using a UNI-T model UT305C digital laser pyrometer (Figure 5a). The process consisted in thermal values measuring at 10 points on mold surface exposed to contact with metal cast, and then calculating the average.

The procedure for cooling temperature measuring of the piece inside the mold is shown in Figure 5b, it consisted in thermal measurement in a punctual manner from the center of the slot visible area to its outer edge (describing a spiral trajectory from center to out), once the mold was completely filled with metal.

Casting Material Properties

From consulting to expert staff of Agricultural Logistics Company "26 de Julio", it was possible to characterize the material, which is obtained from casting technological process in a blast furnace carried out in the entity, as a laminar gray cast iron with a ferritic matrix. The characterization procedure was developed through metallographic studies, in coordination with the metallography laboratory of University of Granma. Table 1 shows the material properties.

Mathematical Model for the Numerical Simulation of the Piece Casting Process

According to Kwon (2021), the casting metal fluid flow and heat transfer are described from the balance of mass, momentum and energy. These equations allowed, as proposed by Mi *et al.* (2009), characterizing the relationship of velocity, pressure, temperature and fluid density in casting metal into a volume limit in a given space.

The mass balance is described according to Equation 1.

$$\frac{\partial(\rho)}{\partial t} + \frac{\partial(u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho)}{\partial z} = 0 \quad (1)$$

Where: t - time (s), x - distance (m), ρ - density (kg/m^3), U - speed (m/s) and T - temperature (°C).

The moment balance is described according to Equation 2.

$$\frac{\partial}{\partial t}(\rho U_i) + \frac{\partial}{\partial x_j}(\rho U_j U_i) = \frac{\partial \rho}{\partial x_i} + \frac{\partial \rho}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x_j}\right) + \rho g_i \quad (2)$$

Where: μ - kinematic speed (m^2/s) and g - acceleration due to gravity (m/s^2).

The energy balance is determined from Equation 3.

$$\frac{\partial}{\partial t}(\rho CpT) + \frac{\partial}{\partial x_j}(\rho Cp U_j T) = \frac{\partial \rho}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j}\right) + Q \quad (3)$$

Where: Cp - specific heat (J/K), T - temperature (°C), λ - thermal conductivity (W/(m·°K) and Q - magnitude of the heat source (°C).

a)

b)

FIGURE 5. In mold temperature measurements; a) Temperature measurement during mold drying and preheating and b) Cooling temperature measurement of piece inside mold.

TABLE 1. Physical properties of LG1 laminar gray cast-iron with ferritic matrix (Solidthinking, 2017)

Properties	Value	Measurement unit
Liquidus phase line	1,200	°C
Solidus phase line	1 100	°C
Thermal conductivity (300 °C - 1 300 °C)	31,5 - 29,43	W/(m °K)
Density (300 °C - 1 300 °C)	7,279 - 6,833	kg/m3
Specific heat (300 °C - 1 300 °C)	585 - 775	J/(kg K)

CAD Model Construction for Numerical Analysis of Metal Casting Process

In the realization of numerical simulation process, the piece was modeled in a CAD software, based on the process technical specifications and piece dimensional requirements Figure 6a). In the CAD environment, the feed channel was incorporated into the piece with the help of CastIron FEED System computer tool, developed by Reyes (2018), and the filling indicators, which in turn act as feeders (Figure 6b)).

For carrying out FEM analysis of casting process, Click2Cast 4.1 Release program was used (Solidthinking, 2017). To achieve this goal, it was necessary to import the geometry created in CAD environment into CAE system, using a STL file format, which allows interoperability between computer files that use CAD technology.

The simulation parameters are listed below (thermal values were assumed to be constant and act throughout the whole piece geometry):

- The casting metal flow was assumed to be an incompressible fluid.
- The pouring temperature was 1 290,7 ºC (Parameter determined from direct measurements made in the furnace).
- The mold was green sand.
- The mold temperature was 307,5 ºC (Parameter determined from measurements using the UNI-T model UT305C digital pyrometer).
- The filling time was 50,7 s (Parameter determined from the measurement of the metal filling in the mold).

Mesh Generation of CAD Model for Casting Process Numerical Analysis

Mesh main characteristic is that of being a mixed mesh, since it is made up of two fundamental types of elements: tetrahedral and triangular solids, this mesh characteristic allows a batter adjust to piece geometry. The mesh properties are presented in Table 2. Figure 7 shows the analysis model meshed.

TABLE 2. Mesh geometric properties

Properties	Value	Unit of measurement
Tetrahedral elements	27,512	---
Triangular elements	10,558	---
Nodes	7,380	---
Element size	9	mm

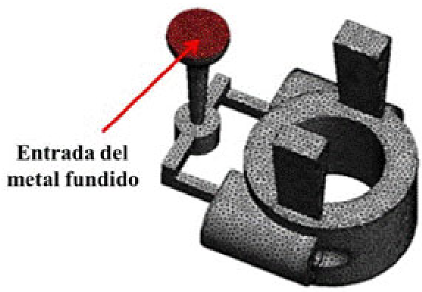


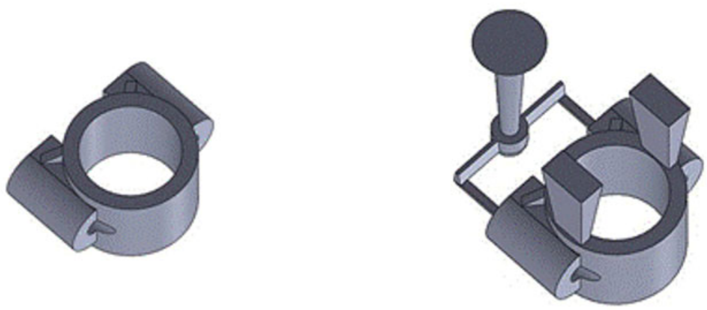
Figure 7. Model of Mesh Analysis.

DISCUSSION OF THE RESULTS

Results of Numerical Simulation and External Visual Inspection

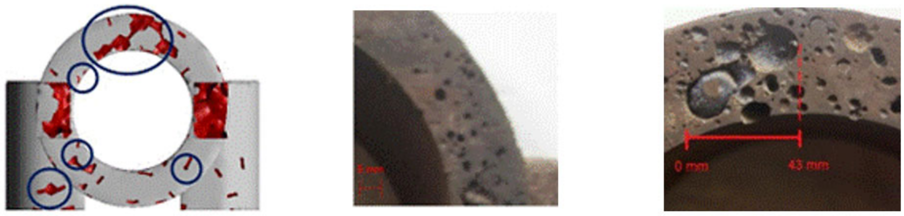
Numerical simulation results are mainly aimed to predicting the behavior of inside piece air trapped. It can be seen that there is similarity, in terms of trapped air location, between the simulated model and the cast piece (Figure 8a).

Measurements are taken on the external defects area found in the piece, once the feeding system and filling indicators have been removed and the front area has been machined until 1 mm has been removed from the surface. The defects found are classified into two types: blowholes (with elongated geometry) and porosities (with a circular geometry) (Figures 8b and



a) b)

FIGURE 6. CAD model of bearings support body of 4 500 lb. harrow; a) Simplified CAD model b) CAD model with feed channel and filling indicators**.**



a) b) c)

FIGURE 8. Area measurement of defects; a) Defects in simulated model, b) Real piece defects porosity type and c) Real piece defects blowhole type.

8c). These defects have their origin, mainly, in the deficient filling, by molten metal, and insufficient evacuation of gases from the mold cavity.

Numerical simulation of molten metal pouring allows establishing the convenient placement of a filling/header indicator in the area shown in Figure 9, which will enable gases correct evacuation through that mold part and consequently, favor the adequate mold filling.

The possibility of carrying out this type of analysis derives from the advantages offered by numerical simulation programs, as shown in their research by Mi *et al.* (2009); Iqbal *et al.* (2012) and Sorate *et al.* (2017), by proposing total or partial modifications in the placement, dimensions and technological elements used for mold filling with casting metal.

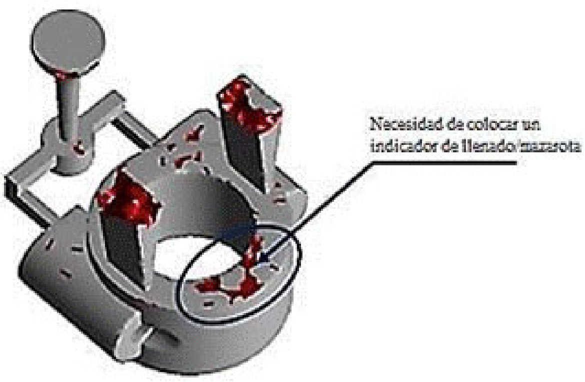


FIGURE 9. Trapped air location in casting piece.

Table 3 shows the defects dimension values, detected from the external visual inspection and numerical simulation of piece casting process. It can be seen that there are no significant differences in the dimensions, since the relative error between them is less than 10%, which can be considered adequate.

The measurement of external defects dimensions in real casting piece were made from photogrammetry, with which it was possible to treat digital images in a CAD environment; while in the simulated model the measurements were made using tools of analysis program by the FEM used.

TABLE 3. Comparative analysis, between real model and simulated one, of external defects main dimensions caused by casting process in piece

	Porosity	Blowing
	Average area	**Average area**
Real model	11,041 mm^2	479,362 mm^2
Simulated model	10,210 mm^2	457,711 mm^2
Relative error	7,526%	4,517%

Results of Numerical Simulation and Internal Visual Inspection in the Piece Obtained by the Casting Process

An effective method to determine the casting internal defects is to make section cuts in the piece, as shown by Kabnure *et al.* (2020). Figure 10 shows that in the section cuts, along circular ring, there was another type of defects in the analyzed piece: cavities produced by the cold joints, caused by the temperature difference between the liquid metal layers in the innermost levels of the piece geometry.

Figure 11 shows the cold joint type defects distribution in the numerical simulation model, although most of them are located in the casting system auxiliary elements. Certainly there are areas inside the piece, especially in the area furthest from the feeding system entrance, where there is presence of this phenomenon. In this area, the confluence of two fluid masses from each feeder occurs.

It is also observed that there is full correspondence in the defects location between the real piece and numerical simulation model. The maximum temperature difference found is 3,6967 °C, this thermal gradient presupposes the piece non-homogeneous solidification. Increasing the mold preheat temperature is an effective action to decrease the thermal gradient between molten metal and mold cavity.

Numerical analysis allows determining the position and magnitude of interface that arises in areas where the cold junction phenomenon exists, which constitutes an important category of internal defects in pieces, that are obtained through the metal casting process. In this sense, Sorate *et al.* (2017) likewise, ponder the numerical analysis advantages in detection of this defects type.

The dimensional analysis of cold junction defects detected in the experimental study and in the numerical simulation is shown in Table 4. It is possible to affirm that there is a correspondence between the analyzed values, since in none of the cases the relative error exceeds 10 %.

These defects persistence in the bearing support body of the 4 500 lb. harrow causes stresses concentration around them. Taking into account the piece very demanding service destination, it is possible to affirm that its useful life is significantly limited by defects associated with the casting process.

Thermal Results of Numerical Simulation and Experimentation

The measurement results of piece cooling temperature inside the mold are shown in Table 5, clearly showing a pattern of decreasing temperature as the measurement moves away from center of slot visible area.

The numerical simulation model of piece is shown in Figure 12, it can be seen that the area with the highest thermal value is the inlet outer face, with a value of 1 280 °C.

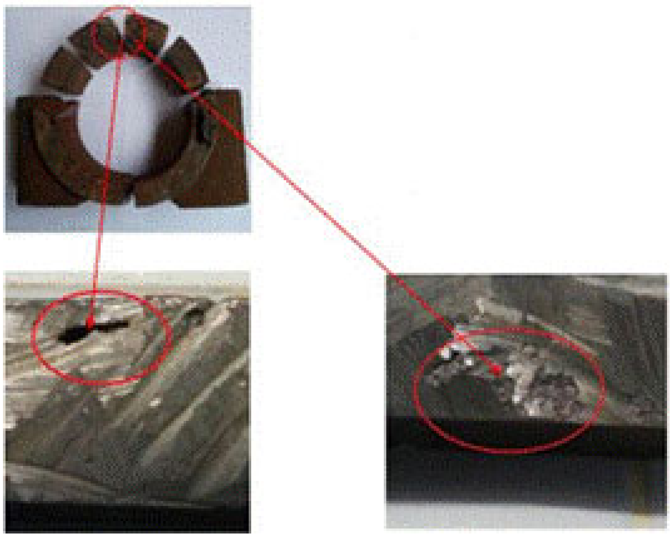


FIGURE 10. Cold junction defect inside the piece.

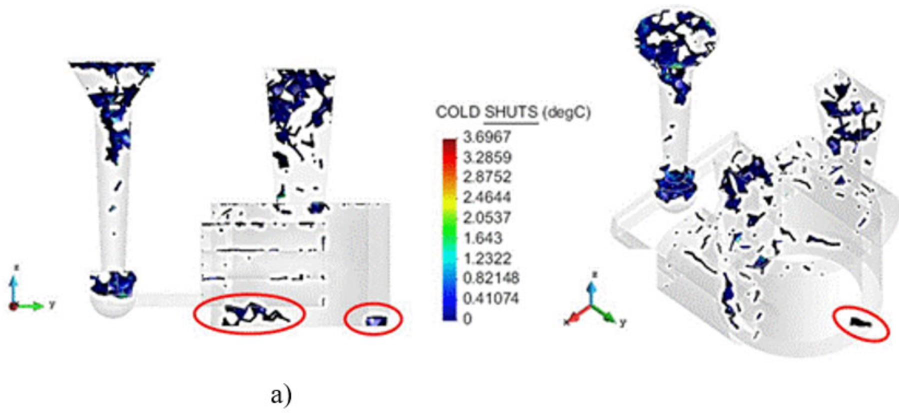


FIGURE 11. Cold junction defects distribution in numerical simulation model; a) Side view and b) Isometric view.

TABLE 4. Comparative analysis, between real model and simulated one, of internal defects main dimensions caused by the casting process in the piece

Characteristics	Average length	Average height	Average area
Real model	44,011 mm	23,647 mm	1 040,728 mm^2
Simulated model	45,209 mm	24,169 mm	1 092,656 mm^2
Relative error	2,722 %	2,207 %	4,989 %

TABLE 5. Measurement of piece cooling temperature inside the mold

Measurement	Thermal data	Measurement unit
1	1 281,2	°C
2	1 279,7	°C
3	1 273,4	°C
4	1 268,3	°C
5	1 259,6	°C
Average	1 272,4	°C

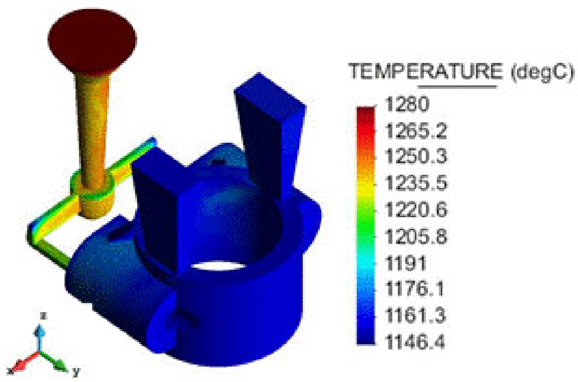


FIGURE 12. Temperature distribution once the molten metal has been poured.

The relative error between thermal value obtained by simulation and average value measured in the real piece is 0,594 %; this means that there are no significant differences between simulated model results and those of real experimentation. Therefore, in this thermal parameter for the proposed piece there is a results convergence.

To validate the results precision, in numerical simulation, the mesh elements size was reduced by half and the temperature values were obtained, once the pouring of molten metal was finished, with a relative error of 4,72%, which indicates that the results obtained are valid and reasonable, since they did not undergo significant changes when reducing the elements in mesh.

CONCLUSIONS

The effective correspondence of location and dimensions of internal defects, found in the bearing support body of the 4 500 lb. harrow, allowed establishing the validation between the simulation model, by the FEM, and the experimental model of metal pouring in sand molds casting process.

The inspection procedure used, which linked visual analysis elements of piece obtained and simulation by the FEM, made it possible to determine that the relative error of defects area is less than 10% between both models.

The internal defects caused by casting process in the piece were classified as: blowing, porosity and cold junction, which, according to the analysis by FEM, can be minimized by making changes in the process technology.

ACKNOWLEDGMENTS

The authors wish to thank the help and collaboration of Agricultural Logistics Company “26 de Julio” Granma, the Computer Aided Engineering Solutions Group (SIAC) of the University of Granma and the engineer Erick Corrales Barrios.

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The authors of this work declare no conflict of interest.

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