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RESEARCH NOTE

Numerical Investigation on the Effect of Mold Design on Shrinkage of Sand Casted Multistage BB3-6×6 Pump Casing

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A B S T R A C T

Design and manufacturing technology of high pressure multistage pumps which are commonly utilized in oil and gas industries, used to be imported from foreign companies. Due to international sanctions against I. R. Iran, it started to be designed and launched domestically. Nowadays, all production lines including design, manufacturing and testing of these pumps have been performed by Iranian experts and they are highly competitive with similar pumps available in international market. This study presents a part of research on first domestic BB3-6×6 multistage pump design and manufacturing as a national project. Pump casing was designed in and structural static analyses performed on it using Ansys. When the casing was approved, a gating system was devised on pump upper half casing and casting simulation was done by NovaCast. The effect of gating system on shrinkage defects was investigated. Results revealed that sprue size and riser location have a noticeable impact on shrinkage of part. This research illustrated that using simulation approach before manufacturing has a noticeable effect on production cost.

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1. INTRODUCTION

Pumps have continued to grow in size, speed and energy level, revealing new problems that are being addressed by innovative materials and mechanical and hydraulic design approaches [1]. Centrifugal pumps are used in a wide range of applications and they can handle a variety of liquids like water and oil at relatively high pressures and/or temperatures. The combination of rotating impeller and diffuser is called the stage. A multistage centrifugal pump might consist of several stages within a single housing, depending on the amount of pressure rise required of the pump [2]. Multistage centrifugal pumps are commonly used pieces of turbomachinery for applications with high head and flow duty requirements [3].

The history of study and research about pump casing goes back to pump design. Casing analysis is essential for special pumps in oil industry, aerospace, power plants, etc. For instance, Rezvani [4] executed structural analysis and evaluation of a mixer pump. Rosu and Vasiliu [5] did research on the main components of a positive displacement pump by Finite Element Method (FEM). Lienau and Welschinger [6] studied the deformation in an Axially Split Volute Casing Pump by FEM. They also optimized a large pump casing with similar approaches [7]. Golbabaei [8] investigated on the static structural analysis, and geometrical modifications performed for a failed volute casing of a real centrifugal pump using FEM method. To control failure phenomenon, necessary geometrical modifications are applied to the model. Bhawar [1] designed and analyzed a boiler feed pump casing to work at high temperature by using Ansys. They performed some necessary geometrical modifications on the pump casing and acclaimed that the pump casing is safe and reliable.

The casting process is already many centuries old, yet many researchers are still devoted to its study. A most important aspect of production of clean and sound castings is the method by which the molten metal is

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introduce into the mold cavity. One of the gating system duty is to ensure that the flow of metal should be as free as possible from turbulence but at a rate sufficient to avoid undue delay in filling the mold [9]. Previous researches illustrated that mold design parameters have a very strong impact on metal flow and defect formation. Shahmiri [10] studied on the quality of lost foam casting of AL-Si alloy affected by gating system design. Baghani [11] investigated the effect of sprue size and design on flow pattern during aluminum gravity casting using Computational Fluid Dynamic (CFD) simulation. Naveenkumar [12] developed a simulation tool and its application to a pump casing which was manufactured by using a sand casting route and Jayakumar [13] designed a gating system for pump casing and specified hot spots location using FEM simulation. Ochulor [14] demonstrated that increasing sprue height in thin wall ductile iron casting improved mold filling, but more increase led to evidence of defects.

In this paper, the study has focused on the effects of mold design on the defects may occur during casting process of a multistage pump casing. Due to the high cost of experimental investigation on casting of a complex pump casing, the numerical method was utilized to achieve a reliable mold design to eliminate casting defects. First, considering the requirements, pump casing was designed based on hydraulic design using a 3D CAD/CAM software. Then, FEM stress and deformation analysis was conducted on the upper and lower parts of casing using Ansys software. Finite element technology allows simulation of pump casing behavior under various transient and steady state conditions (for example hydro pressure, operating pressure, thermal transient and etc.). When casing structural model was approved, the assembly of pump casing model with gating design were imported to NovaCast software to simulate casting process. This article presents some findings on the effect of different mold design parameters such as sprue height and diameter and also riser location on the defects may occur during casting process of a BB3 multistage pump casing using FEM.

2. PUMP CASING STRUCTURAL DESIGN

To design a pump casing, different parameters shall be considered including:

1. Hydraulic design according to requirements such as head and capacity which leads to hydraulic design and results in mechanic design of pressure casing [15].
2. American Petroleum Institute standard API610 requirements which necessitate pressure casing to be designed to operate without leakage or internal contact between rotating and stationary components while subject simultaneously to the Maximum Allowable Working Pressure (MAWP) and withstand the hydrostatic test and obliges the engineer to design pressure casing with the tensile stress not exceeding 0.25 times the minimum ultimate tensile strength across the full range of specified operating temperatures [16]. Also, the designer shall consider this fact that pressure casing design shall be suitable for casting and machining.

The casing belongs to a BB3-6×6 pump. This pump is an axially split, multistage, between-bearings centrifugal pump with discharge diameter of 6 in. and 6 impellers (=6 stages) [16]. The pumped liquid is oil and when the pump is run at 2980 rpm, the Best Efficiency Point (BEP) corresponds to 100 m^3/h flow rate and 370 m head. Bearing in mind all mentioned aspects and considering head and capacity requirement, 3D model of pump was designed using Catia software. The schematic view of the pump studied here, is shown in Figure 1.

2. 1. Numerical Method

The purpose of this analysis is to verify and improve, if necessary, the designed multistage pump casing. The finite-element program Ansys is used to construct the FEM model. Once developed, casing 3D model was transferred into the Ansys. The model was meshed using 1644345 elements and 2510606 nodes for lower half casing and 1595615 elements and 2454083 nodes for upper half casing (Figure 2). The pump is approximately 1576.5 mm long with a power input of 200 KW. Static structural analysis was performed to find out the maximum equivalent stresses developed in the casing due to MAWP and hydro test pressure (1.5 times of MAWP, according to API610 [16]). The required casing material was duplex stainless cast steel EN 1.4517. Due to the lack of this material, during the analysis, EN 1.0619 was selected as the casing material which is the closest material to EN 1.4517 in Ansys material library. Table 1 presents mechanical properties of both materials.

2. 1. 1. Stress and Deformation Analysis Based on MAWPE

Using mechanical properties of 1.0619, uniform pressure at room temperature equal to MAWP=60bar was applied to all internal wet areas and Von-Mises stresses have been evaluated, as well as casing displacements in general. Maximum allowable working pressure (MAWP) is defined as maximum continuous pressure for which manufacturer has designed the pump when pumping the specified liquid at the specified maximum operating.

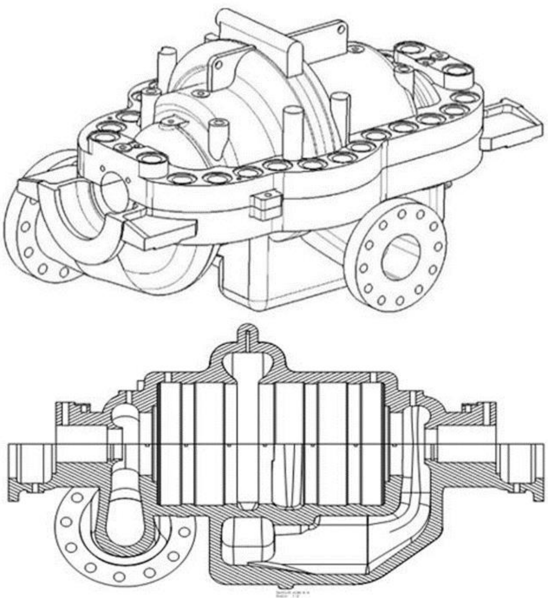

Figure 1. Schematic of designed pump casing for BB3-6x6

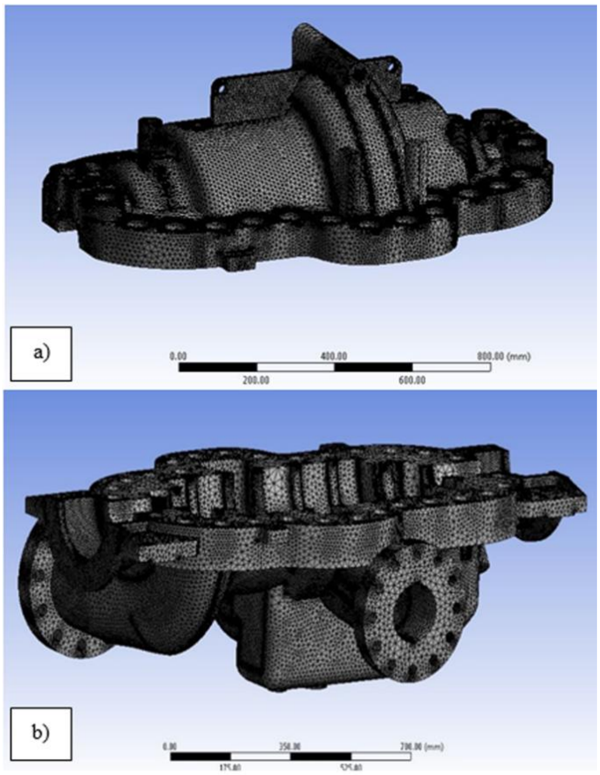

Figure 2. Finite element mesh for a) upper casing half and b) lower casing half

TABLE 1. Material properties of pump casing.

Material	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
EN 1.4517	480	850
EN 1.0619	250	460

MAWP shall be at least the maximum discharge pressure plus 10 % of the maximum differential pressure. The 10% differential pressure margin is intended to accommodate head increases, higher speed in variable-speed pumps and head (testing) tolerance. Maximum discharge pressure is maximum specified suction pressure plus the maximum differential pressure. The pump with the furnished impeller is able to develop when operating at rated speed with fluid of the specified normal relative density (specific gravity) [16]. Following equation presents MAWPE:

$$MAWP = P_{d\,\max} + 10\%\Delta P_{\max} = P_{s\,\max} + 1.1\Delta P_{\max} \quad (1)$$

where, P_{dmax} is maximum discharge pressure, P_{smax} is maximum suction pressure and $\Delta P_{\max}$ is maximum differential pressure. $\Delta P_{\max}$ is calculated as $\rho g H_{shutoff}$ where $H_{shutoff}$ is shutoff head. With considering shutoff head as 460 m and Psmaxas 14.8 bar, based on design requirements, MAWP was calculated as 60 bar. Viewing the counter plot of Von-Mises stress level in Figure 3 for upper and lower casing half respectively, the internal edges of hydraulic profile show highest stress value. Thus, the maximum Von-Mises stress values are equal to 184.99 MPa and 525.84 MPa for upper and lower casing half respectively. Although these data exceed 0.25 times the ultimate tensile strength for 1.0619 (115 MPa), as it is obvious from Figure 3-b, the area under the max stress is located in hydraulic channel edge and is very small and negligible. The edge can be modified by manual lathing which leads to elimination of stress concentration area. Stress concentration is one of the basic factors involves in accordance of fatigue failure in pumps, turbines, compressors, air craft and etc. [17]. Figure 4 presents deformation of upper and lower casing half based on MAWP (60 bar). Maximum deformations due to hydraulic pressure are equal to 0.0883 mm and 0.156 mm for upper and lower casing half, respectively which are minor and ignorable.

2. 1. 2. Stress and Deformation Analysis Based on Hydro Test Pressure To ensure the conformity of results, Von-Mises stress analysis was applied on internal surface of upper and lower casing using hydro test pressure of 90 bar (1.5 times of MAWP, according to API610) based on mechanical properties of 1.0619. Figure 5 presents counter plot of Von-Mises stress level for upper and lower casing half based on hydro test pressure, respectively.

Thus, the maximum Von-Mises stress values are equal to 262.45 MPa and 384.37 MPa for upper and lower casing half respectively.

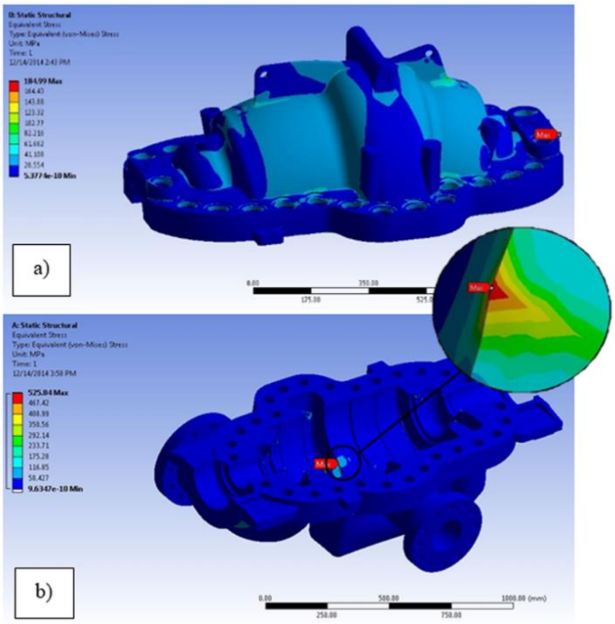

Figure 3. Counter plot of Von-Mises stress level for a) upper casing half and b) lower casing half based on MAWP

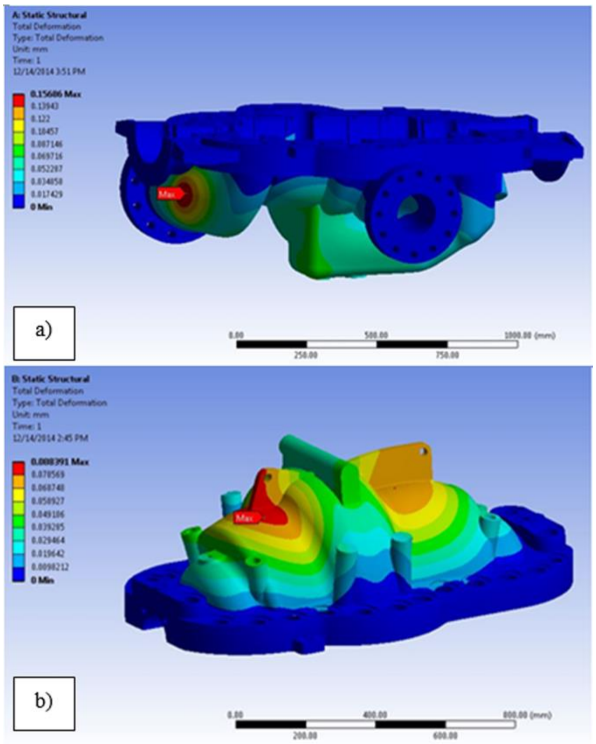

Figure 4. Counter plot of deformation for a) upper casing half and b) lower casing half based on MAWP

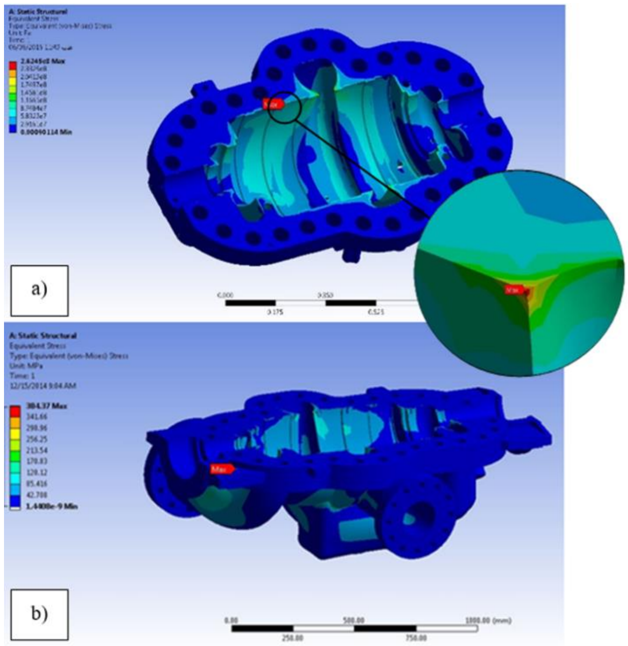

Figure 5. Counter plot of Von-Mises stress level for a) upper casing half and b) lower casing half based on hydro test pressure

Although these data exceed 0.25 times the ultimate tensile strength for 1.0619 (115 MPa), as illustrated in Figure 5-a, the area under max stress is located in hydraulic channel edge and very small and negligible. Modification of the edge will be performed manually to eliminate the stress concentration. Figure 6 present deformation of upper and lower casing half based on hydro test pressure (90 bar). Maximum deformations due to hydraulic pressure are equal 0.124 mm and 0.233 mm for upper and lower casing half, respectively which are small and ignorable. Considering all these data, minimum casing thickness was fixed as 35 mm.

3. GATING SYSTEM DESIGN FOR CASTING

Gating system is the assembly of channels which facilitates the molten metal to enter into the mould cavity. An ideal optimum gating system should fill the mold quickly with a minimum of turbulence, establish thermal gradients, which promote soundness, avoid reoxidation of metal in the gating system, remove slag and dross from the metal as it flows through the gating system, maximize casting yield and be economical to remove.

Figure 7 demonstrates required dimensions in a gating system design. Gating system ratio is defined as the ratio of sprue area to total runner area to total gating area which is described as S:R:G.

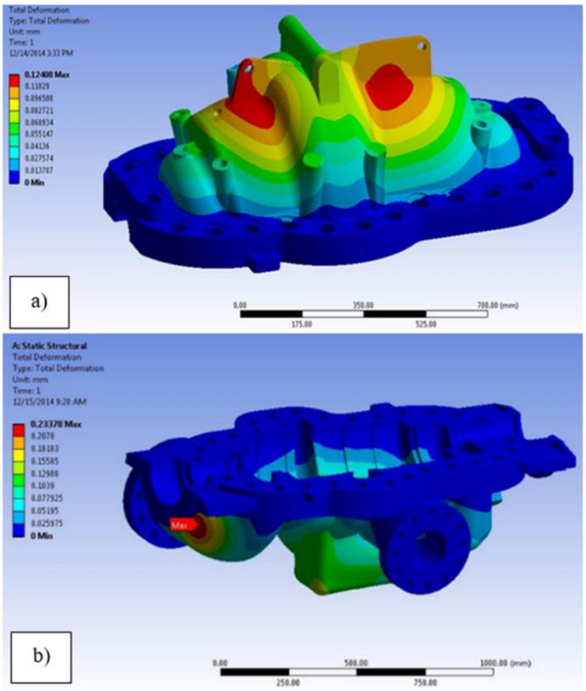

Figure 6. Counter plot of deformation for a) upper casing half and b) lower casing half based on hydro test pressure

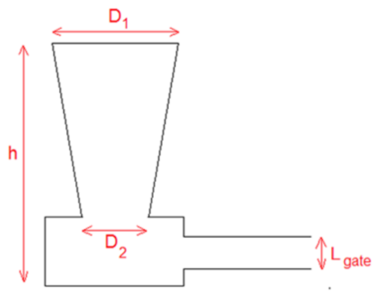

Figure 7. Required dimensions in a gating system design

There are two types of gating systems: non-pressurized and pressurized [18]. A non–pressurized gating system, has total runner area and gate area higher than the sprue area. In this system, there is no pressure existing in the metal flow system and thus it helps to reduce turbulence. In the case of pressurized gating system normally the gates area is the smallest, thus maintaining a back pressure throughout and generally flows full and thereby, can minimize the air aspiration even when a straight sprue is used. The volumetric contraction accompanying solidification of molten metal manifests in defects like shrinkage cavity, porosity, centerline shrinkage, corner shrinkage and sink. These defects can be minimized by designing an appropriate riser system to ensure directional solidification from thin to thick sections in the casting. Major parameters of a riser system include riser location and riser shape and size.

In this study, upper casing half was selected for numerical analyses. For this multistage pump casing, an unpressurized gating system with a gating ratio of 1:1.5:2.5 was designed based on dimensions presented in Table 2. Since the casing model was complicated, to avoid appearing any shrinkage defect, 20 risers with H/D=2 were considered on the model as illustrated in Figure 8. 3D CAD Model of gating system installed on pump casing was derived by Catia software.

3. 1. Numerical Method

Casting simulation of multistage pump casing was conducted by NovaCast (Nova Flow and Solid) software. 3D CAD model of casing including gating system and risers was imported to NovaCast as a .stp file. The model was meshed with a cell dimension of 15 mm and cell number of 1375700 (Figure 9). Mold minimum thickness was set at 25 mm and silica sand was selected as mold material. Initial temperature for melt and mold were considered as 1550°C and 25°C, respectively. Pouring type was set to ladle pouring from a height of 200 mm and flow rate of 1.14 kg/s.

The simulation was performed in Flow&Solid module of software and results of shrinkage were investigated.

TABLE 2. Utilized dimensions in gating system design.

D_1 (mm)	D_2 (mm)	h (mm)	L_{gate} (mm)
100	80	320	80

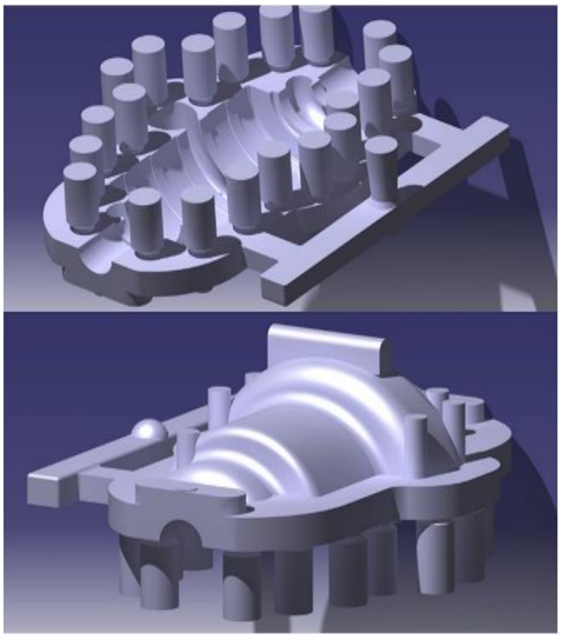

Figure 8. 3D CAD modeling of gating system installed on pump casing

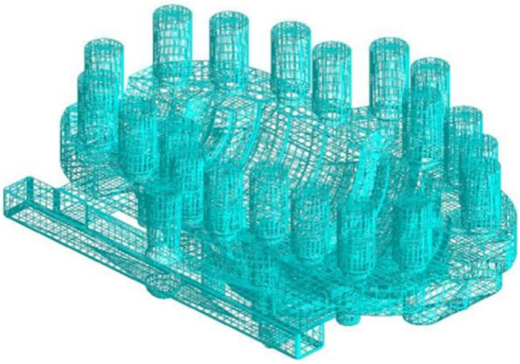

Figure 9. Mesh applied on upper casing half of BB3 pump

Figure 10 presents shrinkage distribution in upper casing half of multistage pump. The shrinkage defects (red areas) are dispersed into the main part after solidification which means that the gating design system and risers location is not suitable enough to prevent defects of shrinkage in part body.

To eliminate the shrinkage defects in pump casing, it was decided to change the gating system dimensions and risers location. Unpressurized gating system with new gating ratio of 1:1.6:2.8 was selected. New dimensions are listed in Table 3. Risers were located in opposite side with the same H/D ratio. 3D model was designed in Catia software and imported to NovaCast. Initial settings of NovaCast were remained unchanged. The number of meshes were calculated as 1581000.

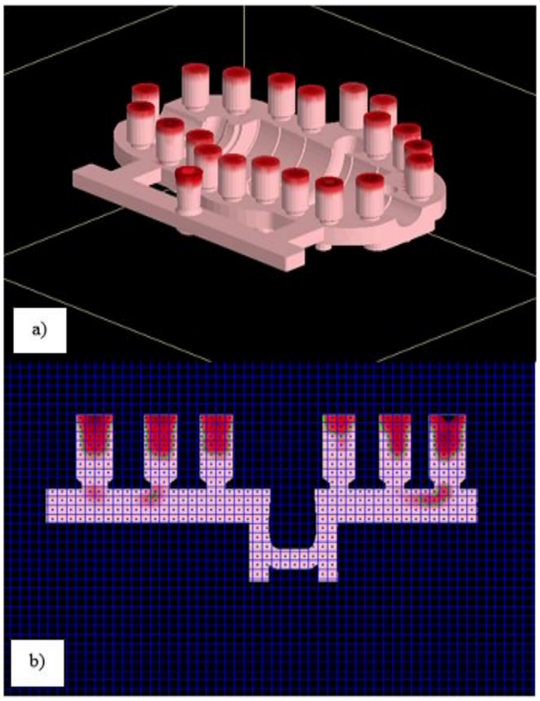

Figure 10. Shrinkage distribution in a) 3D model and b) section view of upper casing half of multistage pump

TABLE 3. Utilized dimensions in improved gating system design.

D_1 (mm)	D_2 (mm)	h (mm)	L_{gate} (mm)
110	80	630	80

Figures 11 and 12 illustrate 3D model of improved gating design and results of simulation on shrinkage, respectively. Figure 12 results that shrinkage only happens in risers and pump casing body is free from any defect. It can be revealed that gating system and riser location have a major effect on defects occured during sand casting.

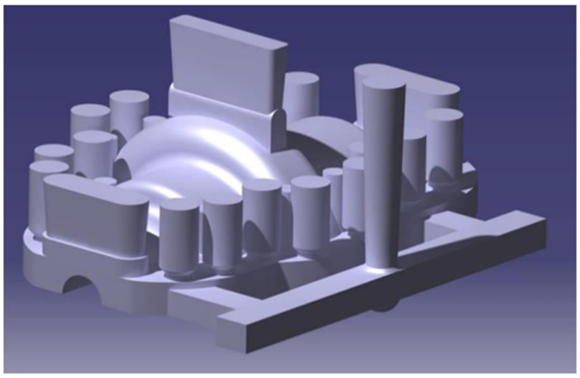

Figure 11. 3D CAD modeling of improved gating system installed on pump casing

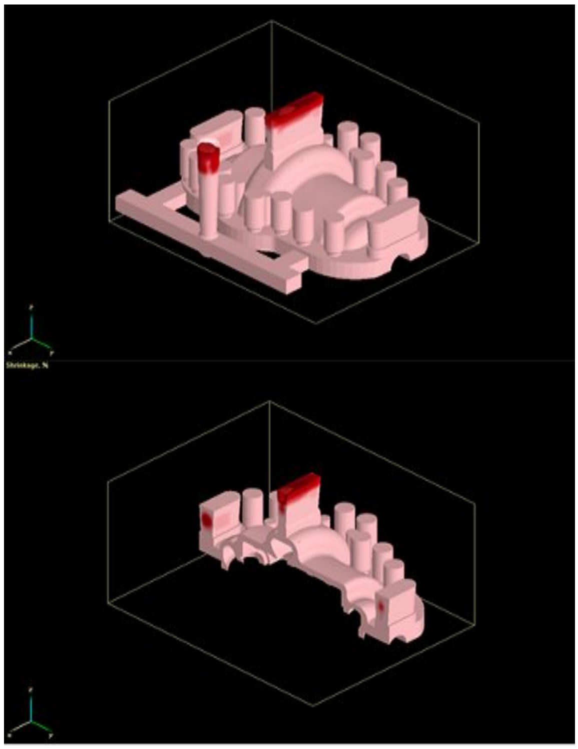

Figure 12. Shrinkage distribution in improved design of upper casing half of multistage pump

4. CONCLUSION

The effect of gating system design and riser location on shrinkage of a multistage BB3-6×6 pump casing was the aim of this research. To ensure casing reliability, stress and deformation analysis were performed on pump casing via Ansys software. When casing was validated, an unpressurized gating system with gating ratio of 1:1.5:2.5 and risers with H/D=2 were designed and assembled on pump casing. Results of FEM simulation of casting via NovaCast software showed defects dispersion in main body which emphasized on inappropriateness of gating system design and riser location. To avoid shrinkage, gating system size and riser location were changed and simulation was repeated until a part free from any defect was obtained. This study revealed that using simulation process before production, decrease total cost of part production obviously due to the high cost of experimental research on casting mold design.

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چکیده

پمپ‌های طبقاتی فشار قوی که مورد مصرف نیروگاه‌ها، صنایع نفت و خطوط انتقال فرآورده‌های نفتی هستند تاکنون بیشتر از کشورهای خارجی تامین می‌شدند. اما به تازگی در ایران بومی‌سازی شده و اجرای تمام مراحل طراحی تا ساخت آنها بعنوان یک پروژه ملی از سوی کارشناسان ایرانی محقق شده است و می‌توان گفت که قابلیت رقابت با نمونه‌های خارجی خود را دارند. تحقیق حاضر، بخشی از پروژه ملی طراحی، ساخت و نصب اولین پمپ API طبقاتی BB3-6×6 تولید داخل را ارائه می نماید. در مرحله اول با توجه به نیازمندیهای پروژه، بدنه پمپ طراحی گشته و توسط نرم‌افزار Ansys تحت تحلیل استاتیکی قرار گرفت. پس از تایید کارکرد آن، سیستم راهگاهی و تغذیه مناسب بر روی بدنه پمپ تعبیه شده و فرایند ریخته‌گری نیمه بالایی محفظه پمپ مذکور توسط نرم‌افزار NovaCast شبیه‌سازی شد. بررسی عیوب انقباضی در قطعه نشان داد که با بهبود سیستم راهگاهی و تغذیه می‌توان به قطعه‌ای عاری از تخلخل انقباضی دست یافت. نتایج تحقیق، موید این مطلب بودند که شبیه‌سازی فرایندهای تولیدی پیش از تولید تا چه میزان بر کاهش هزینه‌ها موثر است.

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