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Effects of gating design on structural and mechanical properties of high manganese steel by optimizing casting process parameters

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Abstract The impacts of gating design and riser system on structure-property relationship of high manganese steel specimens produced by CO_2 sand molding process were systematically examined. The designing of gating and riser system was done first using the traditional manual method and then by SolidCast simulation method. Confirmatory experiments were done to validate the obtained results. Castings were produced using both designs to verify the extent of defects. Their microstructural and mechanical properties were explored. Visual examination of castings designed by manual method showed major shrinkage defects, whereas software designed castings were quite sound showing no shrinkage (macro porosity) and micro porosity. Furthermore, optical microscopy and SEM analysis were performed to study microstructure of the specimens. It was found that the defect-free, software-designed castings with optimized parameters showed ~25 % improvement in yield strength, ~20 % in tensile strength and ~30 % in hardness.

1. Introduction

Steel is a widely used material in the construction of the world's infrastructure and industries [1-8]. Casting is a manufacturing process which is used to make intricate shapes of different materials. This process consists of two stages: filling process and solidification. Each process is very important for producing sound castings. The filling process is a metal guiding system, which is composed of pouring cup, sprue, runner and ingates. Whereas riser system is there to feed metal while shrinkage during solidification. Casting process is very important when better efficiency and production quality is required [1]. For casting, size of component can vary, based on size and shape from small to large. The manufacturing principle for casting involves first creating a cavity inside a sand mold and then pouring molten metal into it. Among several steps of the casting process, molding and melting processes are considered as most important stages. Better control of these processes gives better control of foundry productivity and casting quality. Generally, the foundry industry depends on skilled workers and it suffers in lack of process automation. Also, global buyers expect and demand castings which are defect free in strict delivery schedule, which is always challenge for the foundry industry [2]. Computer modeling/simulation of any engineering process is to make predictions about the effect of adjusting the controls of the process. By controlling pouring a mold with liquid metal and its subsequent solidification accurately and quickly simulated by software on computer, shrinkage cavities and other potentially harmful defects can be predicted. Modifying the gating system, position and volume of feeders and even change in the casting design can be simulated. The methodology of casting system can then be optimized before the design and methods of casting are finalized, resulting in avoiding the expense of time during casting trials stages [3].

Numerical simulation software for flow of metal and solidification simulation has been available since 1980. Several commercial softwares are now available which are being improved day by day. As turbulent and quiescent flow in intricate shaped castings is involved, therefore modeling the filling of castings is much more difficult. The purpose of modeling solidification is to predict solidification array and shrinkage cavity's location, calculate the sizes, volumes and weights of all feeders and gating system of the casting, compute the weights and sizes of all different materials in the solid model, provide a variety of quality of levels, letting the designer to highlight or ignore level of microporosity [3]. Some of the advantages of computer modeling & simulation are casting yield improvement, casting quality improvement, productivity of casting system development, data provision for given geometric model about volume, weight and surface, allowing fast cost estimation and permitting efficient rigging design, automated enmeshment for general purpose heat transfer simulators permits shorter design time, lesser trials leading to shorter lead time from design to product, and evaluation of engineering changes and implementation is easier [4].

The solidification behavior and temperature distribution of a casting are directly affected by the fluid flow pattern [9]. Speedy fluid flow shortens the solidification period, resulting in inferior mechanical characteristics. Changing the gating system design causes melt flow to deviate from the mold's parting line, resulting in a change in the mold filling pattern [10]. The change of metal head pressure at the opening of the mold cavity is also affected by gate geometry. Metal filling is affected by gate design, which has a direct impact on casting quality. The use of proper gating results in a uniform heat gradient and the prevention of mold erosion, resulting in smooth metal flow [11]. However, turbulence is created by improper gating design owing to the creation of oxide film, sand inclusion, dross, and air entrapment [12-18]. The entrance velocity of molten metal is controlled by precise gate shapes and sizes, which reduces air entrapment [19]. Mold filling can be controlled using various gating configurations in addition to solidification, flow pattern and design of gating system. Top, side, and bottom gating configurations are among the gating configurations described in the literature.

Even though various techniques and solutions have been proposed to improve gating system [20-31], the topic is still up for debate. Furthermore, it is evident that to manufacture every casting, a completely new gating system design is required, and a single gating system design cannot be used to develop the whole diverse range of castings for different applications. As a result, the gating system must be customized for each unique size, shape, alloy and wall thickness, etc. Also, previous studies revealed that there have been few investigations on the influence of gating configuration on mechanical qualities, particularly in the CO_2 sand molding technique. Moreover, more research into the specific behavior of gating design in CO_2 sand casting is required. Hence, in this study, the effects of gating design and riser system on structural and mechanical properties of high manganese steel were studied systematically produced by CO_2 sand molding technique. Moreover, no such exploration has been disclosed in literature.

2. Materials and methodology

In the present study, high manganese steel alloy ZGMn13Cr was utilized for CO_2 sand casting owing to its engineering importance [32]. The achieved chemical composition of the alloy is presented in Table 1.

First, the casting parameters were designed by traditional/manual method. Then pattern and mold for casting were prepared according to manual designed parameters and after preparing the molten metal according to the required steel standard, the liquid metal was poured into mold. Using Chvorinov rule (Eq. (1)), modulus of the casting "Mc" was calculated and found to be 2.21 cm. The ratio for calculating modulus of the riser "Mr" was kept 1.2 Mc and found to be 2.652 cm. Using

$$Mr = \frac{Vr}{Ar} = \frac{\pi R^2 H}{2\pi RH + \pi R^2} = \frac{RH}{2H + R} = \frac{DH}{4H + D}, \quad (1)$$

and keeping height to diameter ratio 1:2.3, cylindrical riser was calculated. Here, Mr = modulus of riser, Vr = volume of riser, Ar = area of riser and R = radius of riser. To fulfill the riser modulus, the dimensions of the riser were Ø110 mm with a height (H) of 250 mm. The number of risers was calculated by using the formula; number of risers = Lc/8Mc+Dr, where Lc= length of casting, Mc = modulus of casting and Dr = diameter of riser. Riser neck is used as riser connection to the casting. The ratio for calculating modulus of the neck is 1.1×Mc and found to be 2.21 cm. Width (Wn), length (Ln) and height (Hn) of the side neck were calculated according to following formulas: Ln maximum of D/3, Hn = 0.6-0.8 T, Wn = 2.5 Ln+0.18 D, where D = dia. of the riser and T = thickness of casting [33]. Length of the neck was kept sufficient to facilitate fettling and cleaning operation. A neck with dimensions 60 mm and 40 mm was placed between the casting and the riser.

The main elements of the gating system were down sprue, runner and ingates. Metal enters through the down sprue into the runner, which distributes the metal accordingly towards

Table 1. Achieved composition of steel grade ZG Mn13Cr.

C%	Mn%	Si%	P%	S%	Cr%	Ni%	Mo%	Cu%	Al%
1.10	12.00	0.64	0.085	0.010	1.60	0.30	0.05	0.18	0.042

ingates and eventually metal enters the mold through the ingates. The ratio of gating system was kept by area as 1:1.2:1.4 of down sprue to the runner and runner to the ingates. Sprue diameter 40 mm, runner with cross section of 35 mm * 40 mm and ingate cross section 25 mm * 40 mm were used.

SolidCast uses a thermal modulus which is more accurate than traditional VSA analysis. As necked simulation run casting modules had been calculated by the riser design calculator hazard modulus of the casting “Mc” was calculated and found to be 2.56 cm. The ratio for calculating modulus of the riser “Mr” was kept 1.2 Mc and found to be 3.1 cm, and the riser with height to diameter ratio 1.11 with cylindrical shape was selected; the riser with dimensions of diameter 180 mm and height 200 mm was calculated for 02 nos. of casting. Neck used was of dimensions 100 mm and 45 mm between the casting and the riser. The ratio of gating system was kept by area as 1:1.2:1.75 of down sprue to the runner and runner to the ingates. Sprue diameter 30 mm, runner with cross section of 30 mm * 30 mm and ingate cross section 15 mm * 30 mm was used.

Silica sand was used as molding sand SiO_2 (95 %), Fe_2O_3 (1 %) and clay content (4 %). Sodium silicate was used up to 7 % by weight as binding material. CO_2 gas was injected to make silica gel to make the mold hard. 3 ton electric arc furnace was used for steel making purpose. Estimated values of casting weight, melting and pouring temperature and mold filling velocities of gating system have been provided in Table 2.

After complete solidification to a specific temperature, the casting was knocked out from the mold and was fettled/cleaned

Table 2. Calculations for the casting parameters.

Parameters	Values
Net weight of casting (kg)	27
Melting temperature (°C)	1380
Pouring temperature (°C)	1460
Pouring rate (kg/s)	3.4
Pouring time (s)	30
Mold filling velocity of gate (mm/s)	885.8

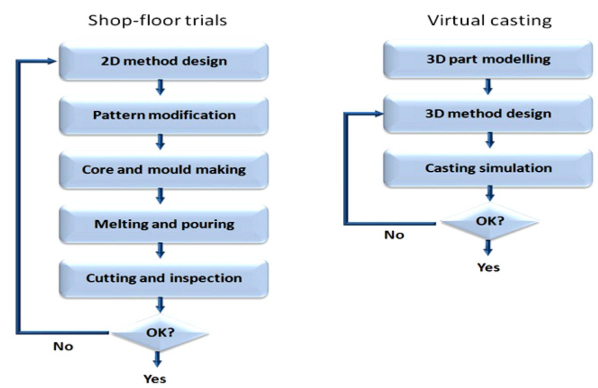

Fig. 1. The production steps in a typical sand-casting process.

by pneumatic chisels. Grinder cutting disc was used for removing the riser and gating from the casting.

Grinder was used to clean the surfaces of the casting. The casting parameters were designed using SolidCast simulation software and repeating all production process as shown in Fig. 1. Tensile and Rockwell hardness tests were performed following ASTM E8, and ASTM E18 standard, respectively.

3. Results and discussion

The manual method was used to design the casting technology. The risers were calculated by volume over surface area method using Chvorinov rule, and gating system was calculated manually. When the risers were taken from the castings, there was considerable shrinkage in the area next to the risers, shown in Fig. 2. This was due to the risers being fed insufficiently to the casting. Because of the section thickness difference on the junction of distinct casting surface regions, shrinkage occurred at the location where hot spots are likely to be located [34].

Further, this casting model having shrinkage adjacent to riser location was simulated through SolidCast to predict the shrinkage location. The same traditional design parameters were employed in SolidCast (that were originally employed to do the manual risering and gating method). The model was simulated, and the results were checked on the material density factor to diagnose defects.

Fig. 3 shows that almost the same amount of shrinkage detected adjacent to the riser as was reported in real casting (see Figs. 3(a) and (b)). Microporosity or secondary shrinkage was anticipated in the same way, and Fig. 3(a) depicted microporosity at various casting locations.

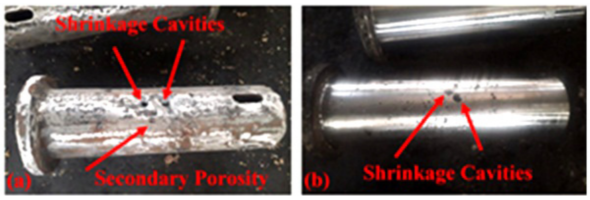

Fig. 2. (a) Casting made by manual method design shown shrinkage adjacent the risers; (b) shrinkage cavities and secondary porosity.

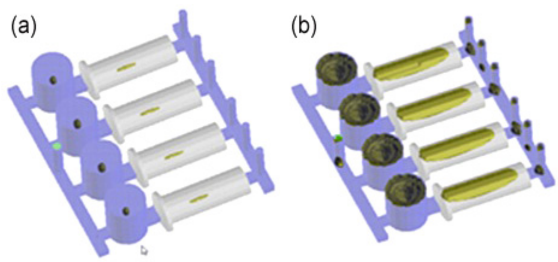

Fig. 3. (a) Secondary porosity; (b) shrinkage cavities were observed in the casting by SolidCast software.

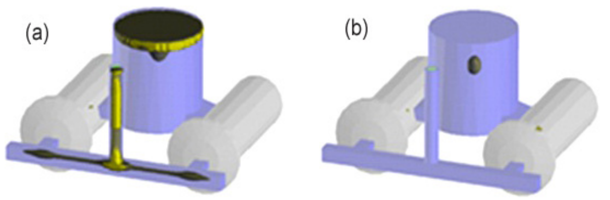

Fig. 4. (a) No shrinkage found after simulation; (b) minor dispersed micro-porosity was found.

Fig. 5. (a) Two castings with risers and gating system designed by SolidCast; (b) no shrinkage adjacent the riser location; (c) good surface after machining of the casting.

To reduce these defects for production of sound casting and improve casting quality, the casting model was redesigned through SolidCast [35]. For that, various parameters were studied, including riser and gating system design. Riser design wizard was run to design the optimized riser with maximum feeding ability. Gating design wizard was used to design the gating system maintaining the required velocity of metal flow within the mold. Two castings were put in one mold to distribute the equal flow and pressure of metal in the mold as shown schematically in Fig. 4. The redesigned model was again simulated, and flow of the metal was checked using the FlowCast module of the SolidCast. After simulation, the results were checked on material density factor for shrinkage using FCC criterion and the micro-porosity was checked on custom high. Figs. 4(a) and (b) illustrate that the modified simulated model works well. There is no shrinkage with minimal distributed micro-porosity.

To further validate these simulated results shown in Figs. 4(a) and (b), two castings were experimentally cast according to designed parameters using SolidCast software and shown in Fig. 5. It was revealed from the pictures that there was no shrinkage adjacent to the risers and no signs of micro-porosity as well. Thus, the results obtained through SolidCast had been validated.

To study the microstructure of the experimentally cast samples with optimized parameters, optical microscopy was done and shown in Figs. 6(a) and (b). Micrographs of the samples were taken at 500 μm and 100 μm resolution. The white matrix area and the black precipitate area are seen in the results. The austenitic structure is represented by white matrix, while the pearlite structure is represented by black precipitate.

Scanning electron microscopy was also used to further explore the microstructure of the experimentally cast samples with optimized parameters and results are in Figs. 6(c) and (d). It can be seen from Figs. 6(c) and (d) that the micrographs are

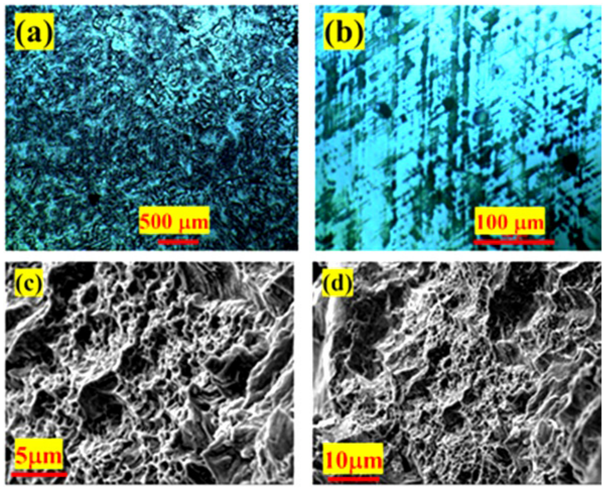

Fig. 6. (a) Micrograph taken at 500 μm; (b) micrograph taken at 100 μm; (c) SEM micrograph taken at 5 μm; (d) SEM micrograph taken at 10 μm.

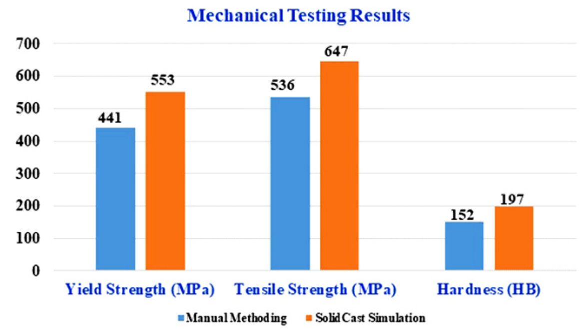

Fig. 7. Graph representing the comparison of yield strength, tensile strength and hardness.

uniform without any evident voids or micro-porosity. This hint towards the soundness of the cast samples without defects. From these observations, it is possible that good mechanical properties can be achieved in these samples.

A comparison of mechanical testing of manual as well as SolidCast simulated samples was performed and presented in Fig. 7. Yield strength is increased significantly from 441 MPa for specimen prepared by manual method to 553 MPa for specimen prepared by redesigned SolidCast. Similarly, tensile strength and hardness of the specimen obtained by using redesigned riser and gating system showed higher values. This enhancement in mechanical properties could be attributed to the void and defect free microstructure of the specimen (see Fig. 6) obtained by using redesigned riser and gating system. While observed poor mechanical properties for manually calculated riser and gating system could be ascribed to the shrinkage and micro-porosity observed by visual and SolidCast simulation (see Figs. 2 and 3). The results are well-matched with microstructural analysis and mechanical properties.

Fig. 8 shows the comparison of gross weight, liquid weight, riser and gating weight of the specimen cast by manual method and SolidCast simulation method. It can be observed that the riser and gating system design significantly affect the

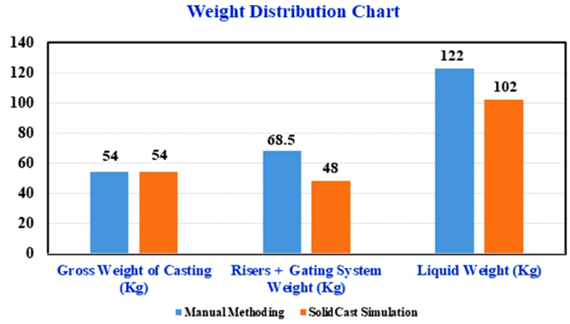

Fig. 8. Graph representing the comparison of gross weight, riser and gating weight and liquid weight by manual method and SolidCast simulation method.

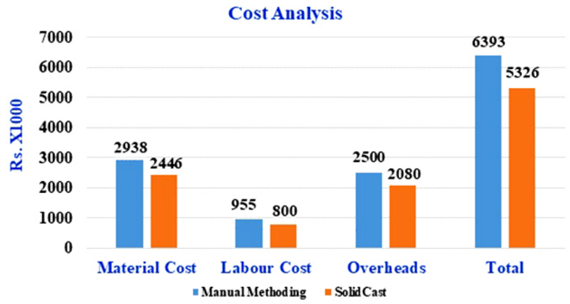

Fig. 9. Graph representing the comparison of cost by manual method and SolidCast simulation software method.

gross weight and liquid metal weight. The specimen cast through redesigned riser and gating system by using SolidCast simulation method consumed less amount of liquid metal that decreased the overall production cost. Liquid metal weight for one mold (02 specimen) was 122.5 kg. Total liquid metal weight poured through design by traditional/manual method was 2450 kg (20 specimen) and leading to a total liquid metal weight of 24500 kg (whole assembly) in which 2450 kg liquid metal was rejected due to shrinkage porosity and other defects during the trial production of manual method design parameters. When the casting parameters, i.e., riser and gating systems, were redesigned through SolidCast, the liquid metal weight for one mold (consisting of 02 specimen) was 102 kg and leading to a total liquid metal weight of 20400 kg (whole assembly) with no rejection by other means. By comparing both methods, around 4100 kg of the metal was saved by redesign, and development of casting parameters using SolidCast and the metal wastage through rejection was minimized to 3 % (12 specimens out of 400) from 100 % (20 specimens out of 20). The calculated casting yield was also increased from 43 % to 53 %.

Another crucial component is the process's cost analysis. A comparison of the cost analysis of specimen cast by manual method and SolidCast simulation software method is shown in Fig. 9. From the graph, the total cost (material, labor and overheads cost) is significantly reduced for the specimen cast by redesigned riser and gating system using SolidCast simulation method. Overall, manufacturing cost was reduced by 10 % in terms of materials, labor, and fixed and variable overheads.

4. Conclusions

The influence of gating design and riser system on mechanical properties of high manganese steel specimens produced by CO_2 sand molding technology were investigated. Gating and riser systems were designed using both classic manual methods and SolidCast simulation methods. The obtained results of calculations and simulations were validated by systematic experiments. Visual inspection of manual-designed castings revealed significant shrinkage problems, whereas software-designed castings appeared to be in good shape, with no shrinkage (macro porosity) and micro porosity. Optical microscopy and SEM analysis further confirm the soundness of software-designed castings with optimized parameters. The behavior of mechanical properties is well-matched with microstructural analysis. Void and defect-free software-designed castings with optimized parameters showed improved yield strength of about 553 MPa as compared to manual-designed castings of 441 MPa. A significant improvement of about 20 % in tensile strength and 30 % in hardness was also observed for defect-free, software-designed castings with optimized parameters. Moreover, sound casting significantly reduced the rejection rate, resulting in lowering of the overall production costs.

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