# ANALYSIS OF CENTRELINE SHRINKAGE IN STEEL CASTINGS WITH GRATE-SHAPED GEOMETRY

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# ANALYSIS OF CENTRELINE SHRINKAGE IN STEEL CASTINGS WITH GRATE-SHAPED GEOMETRY

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## Abstract

Numerical simulation is very necessary for predicting the process of freezing castings on gravity casting methods. Centreline shrinkage is often found in casting with a special form of grate-shaped defect due to the presence of an isolated liquid area. This study aims to get a gating system that can minimize the occurrence of centreline shrinkage defects in steel castings using the numerical simulation. Simulation results from several gating system designs show the minimum shape, position and size of centreline shrinkage. The analysis involved a critical fraction solid time, a Niyama criterion and a thermal modulus factor for each casting design. The position of the gating system from this research can be used as a reference for cast steel castings.

Keywords: Centreline shrinkage, Gating system, Grate shaped steel casting.

## 1. Introduction

Steel casting manufacturing allows the production of steel-related material with high integrity and monolithic structural steel components. For some cases, steel castings relate to the complex geometry of metal products, while each geometry correlates to the final performances of material [1]. From the traditional perspectives, there are many parameters affecting the heavy steel ingots. One of the most typical defects that are often ignored is centerline shrinkage. This is because centerline shrinkage is related to porosity contained in the material [2]. To have an effective performance of steel castings, there needs to be a suitable geometry so that optimum castings can be obtained. This study; however, implements one of the geometry shapes, which is considered effective and efficient, namely grate-shaped geometry [3].

Many papers have reported how to manage geometry. However, they still have disadvantages. Palumbo et al. [4] reported a numerical simulation of rectangle-shaped cast steel products without grating using a Magmasoft. They analysed the evolution of microporosity along with the longitudinal pieces of the plate or bar. Beckermann [5] states that porosity can be formed in parts that are not covered by the riser zone and the end zone on steel plate or bars. Hsu et al. [6] made a multiple gating system in L shaped resulting in excellent casting for simple shaped design. However, the system is not applicable for grate shaped casting, particularly for solidification direction where there are many solidification fronts. In fact, the grate shape is one of the most controversial geometries [7]. The correlation of directional solidification and casting design is not similar to the simple form of casting.

Here, the purpose of this study was to understand the grate shape in a gating system, in which, specifically, the present study was focused on how to minimize the occurrence of centreline shrinkage defects in steel castings using the numerical simulation. This study was done based on Beckermann [5] method, which stated that centerline shrinkage can be identified if the distance between end zone length and the riser zone length appears. This area cannot be covered by the riser as a metal liquid reservoir. Then, due to the directional solidification caused by the end zones extending from the side edges of the casting section, solidification in the front will go from the side edges toward the centreline. This solidification would meet at the centreline. The feed metal from the riser zone to the end zone extending from the right edge of the casting was cut off. To minimize centreline, the shrinkage was predicted by making intersections of the end zones that lied within or intersect the riser zone. The centreline shrinkage defects are often found in cast steel with a grate shape due to more complex freezing morphology compared to the simple form of cast steel [8]. To analyse the best possible casting design, this study presented a simulation using SOLIDCast 8.1.1. software tools. The study focused on understanding the most minimal centerline shrinkage. Then, the analysis was supported with a trial at the workshop and the result was compared by foundry engineers in designing a grate shaped casting.

Here, several alternative casting designs were tested, including laying position and number of risers and gating systems. To make the optimum condition, the process was fixed using velocity by 20.07% at the mould cavity of the steel castings. These testing were done to get an optimal design. The optimum condition was then tested and implemented in the metal casting workshop to produce the product.

## 2. Methods

The research used a numerical and simulation method to obtain centerline shrinkage prediction, in which, the algorithm is shown in Fig. 1. The simulation used SOLIDCast cast simulation technology, in which, this is done by analysing the presence of centerline shrinkage in cast products via iterations. To support the analysis, commercially available machines and tools were used.
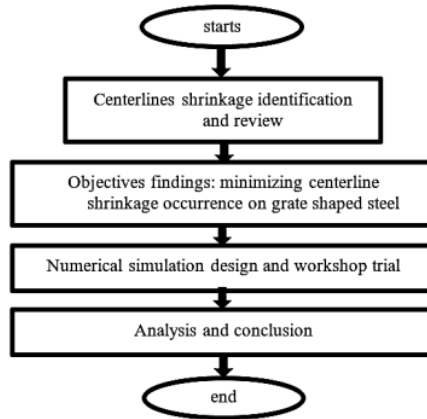
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**Fig. 1. Research flow chart.**

In short, the research procedure in this study was divided into two main parts namely simulation and experiment. Each step of the procedure in both parts are the same. Each part has the following parameters: (1) critical fraction solid point; (2) Niyama point; (3) solidification shrinkage; (4) initial temperature; and (5) freezing range material.

For the simulation procedure, we used SOLIDCast 8.1.1. software tools. Several parameters were set in this specific condition by 20.07% of the velocity at the mould cavity of the steel castings.

For the experimental procedure, we implemented the results of the simulation procedures. First, we prepared equipment made of ceramics. The ceramics were designed at purchased from PT Rumah Publikasi Indonesia, Indonesia. Then, the designed equipment was used for the casting of steel by pouring the mixture of heated liquid (melted material). As a model of melted material, we used stainless steel balls (8 mm; AISI 4140), which were melted at the temperature of 2,000 °C. The melted materials were poured into the designed equipment and kept in it for several minutes. Then, they were frozen at a specific degree to acquire a maximum quality of steel castings.

Finally, the produced material from the metal casting process went to other tests, including the testing for the materials' quality and performance. The results gained from numerical and metal casting product were also compared.

## 3. Results and Discussion

Out of a series of analyses performed in this study, the first one is an analysis of stainless-steel ball raw material. This analysis is used to understand the nature and composition of the materials used in this study.

The composition of the supporting elements in stainless steel ball as raw materials for the grate shape production is shown in Table 1. The analysis focused on supporting elements only. We did not analyse the composition of core elements such as iron, nickel and oxygen. This is because the AISI 4140 has been well known as iron-based material [9]. We also did not analyse the metal oxide elements (e.g., $FeO$, $Fe_2O_3$, $Fe_3O_4$, $Al_2O_3$, $SiO_2$, $K_2O$, $Cr_2O_3$ and $NiO$) since we assumed that all components in the material stay at their individual elements.

The results showed several existing components, including carbon, mangan, silica, chromium and molybdenum, in which, the compositions of the elements reached about 0.40, 0.80, 0.20, 0.90, and 0.20 respectively. Some impurities were detected to be less than 0.025%, such as phosphor and sulphur. This result is in a good agreement with other literature regarding the stainless steel-related material [9-12].

The material can be classified as a corrosion-resistant material. The existence of chrome component is also good and gives benefits as a corrosion-resistant agent. Chrome can create passive layers, which can prevent the metal oxidation process and avoiding the formation of iron oxide [9]. Further, due to the less amount of impurities such as silica, phosphor and sulphur in the material, this material can be classified as a good model for steel casting [13]. The impurities can sometimes interfere with the process of metal utilization, including in cutting, thawing and solidification processes in the steel castings.

One of the most important elements in steel castings is the design of riser. It is well known that the riser is a reservoir in the casting process, which serves as a source of liquid metal, compensates for shrinkage during solidification (liquid metal into solid metal) and represents a way to separate waste metal (from the cast part and re-melted to make subsequent castings) [14]. Because it is the source of liquid metal, the temperature should be more than 1,500 °C. This way, the liquid will be in the best condition to fill in the casting's equipment. This is also to prevent failure prior to the solidification process.

**Table 1. Composition of supporting elements in AISI 4140 steel.**

| Element | Percentage (%) |
|---------|----------------|
| C | 0,36 – 0,43 |
| Mn | 0,75 – 1,00 |
| Si | 0,15 – 0,30 |
| P | Max. 0,025 |
| S | Max. 0,025 |
| Cr | 0,80 – 1,10 |
| Mo | 0,15 – 0,25 |
| Al | n.i. |
| K | n.i. |

Note: n.i. means not identified

Based on the analysis, the design of the riser must be through several different calculation methods. This analysis is useful for determining the most effective and efficient calculation method to design riser for grate-shaped casting. The calculation began with riser dimension, including head diameter and height (see Fig. 2). This figure shows the analysis must be performed in a cylindrical form. This is because the form is the most stable form in comparison with the other ones during the solidification.

To make sure the analysis of dimension of riser head, there are three alternative risers and the results are shown in Table 2. The main dimensions that are calculated are diameter and height. The calculation showed the diameters (D) must be set between 11 and 16, whereas the heights (H) must be between 7 and 16. If the dimensions (either the diameter or the height) are not in that range, the steel castings will not be optimum.

In the series of steel castings processes, solidification takes one of the most important parts. In solidification, freezing modulus gradation should be taken into consideration. Using the optimum condition of steel castings including riser dimensions, the direction of the freezing modulus gradation based on the simulation results data of zero casting design is presented in Fig. 2. Naturally, the direction of metal freezing will lead to several zones. The blue arrow is the direction of the colour modulus of freezing.

There are colour gradations, in which, the purple is the zone with a smaller freezing modulus and the yellow is the zone with a greater freezing modulus. The calculation showed that the largest freezing modulus is 2.34 cm, which is shown as a bright yellow zone pointed by number 1 and 2. Other yellow zones, shown as area number 3, 4, 5, 6 and 7 are also classified to receive freezing modulus. However, freezing modulus in these zones is lower than that in zone 1 and 2.

Based on the simulation results, in the grate shaped section, the colour gradation is in the opposite direction, which is in a good agreement with the literature [6]. The gradation section is flanked by two parts, which have a larger freezing modulus. They also have experiences in the freezing sequence in different directions. As shown in the left side of Fig. 3, the grate-shaped plate has four areas namely area numbers 4, 5, 6 and 7. Those four areas have the same function as they reveal the same vertical direction. However, there are constant horizontal directions in between each area. Detailed information about the direction is marked by the two-way arrows in the figure.

On the right side of Fig. 2, there are three areas divided into area number 1, number 2 and number 3. These three areas show different temperature degradation of the plate. It has been proven that area number 1 has the highest temperature followed by area number 2 and number 3. These analyses were in good agreement with previous studies [15, 16].

**Table 2. Alternative of dimension of riser head.**

| No. | Alternative-n | Riser 1 | | Riser 2 | | Riser 3 | |
|-----|---------------|---------|------|---------|------|---------|------|
| | | D | H | D | H | D | H |
| 1 | Alternative-1 | 16,0 | 16,0 | 15,0 | 15,0 | 11,0 | 11,0 |
| 2 | Alternative-2 | 13,0 | 13,0 | 14,0 | 14,0 | 12,0 | 12,0 |
| 3 | Alternative-3 | 12,3 | 7,5 | 12,3 | 7,5 | 12,3 | 7,5 |
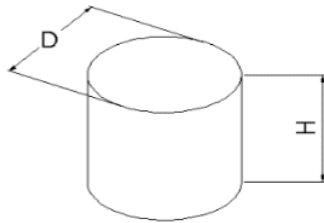
Remarks: D: riser hear diameter (cm), H: head riser height (cm)
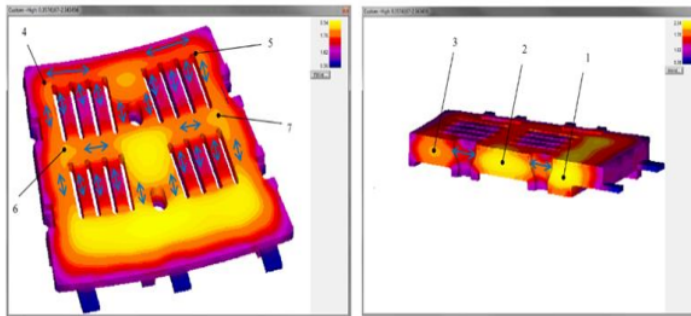
**Fig. 2. Dimension analysis of riser.**



**Fig. 3. Direction of solidification modulus gradient.**

In addition to the analyses of heat direction and temperature degradation, flow velocity in the gating system needs to be performed. To indicate different velocity, the analysis uses colour gradation as shown in Fig. 4. As explained in the Method section, the analysis was calculated based on the data velocity at 20.07% of filling the mould cavity (to perform optimum steel castings). This analysis was varied by applying the angular ingate and the flow velocity gradation in each gate.

There are several conditions obtained, which are shown by different colour gradations. Red indicates the highest velocity (which reaches 2 m/s). The color grades into yellow (which values at 1 m/s), green (reaching 0.50 m/s) and blue (0 m/s). The colour gradation occurs due to the gating system. It is the basic design, which needs to be added in the castings process for making the smooth and proper filling of the mould cavity [17]. The results showed that uniform liquid flow could be obtained when implementing a designed gating system.

Applications of the simulation analysis to the real condition of steel castings are shown in Fig. 4. The realistic equipment is shown in Fig. 5(a). This equipment is designed based on simulation analysis as shown in Figs. 2 to 4. Whereas, the equipment after processing is presented in Fig. 4(b). Shrinkage phenomena were

obtained, which was confirmed by cutting the equipment (See Fig. 5(b). The illustration model for the shrinkage phenomena is shown in Fig. 5(c), in which, the illustration is the movement of heat in the equipment during the casting process. Some heats are trapped on the top of the casting moulding, whereas the other is inside the equipment.

The variety of heat existence (whether it is trapped, released, or transferred) in the steel castings is undeniable. This is in line with the literature [18]. The equipment used in this study can be classified as effective as it has the criteria for optimum steel castings process.
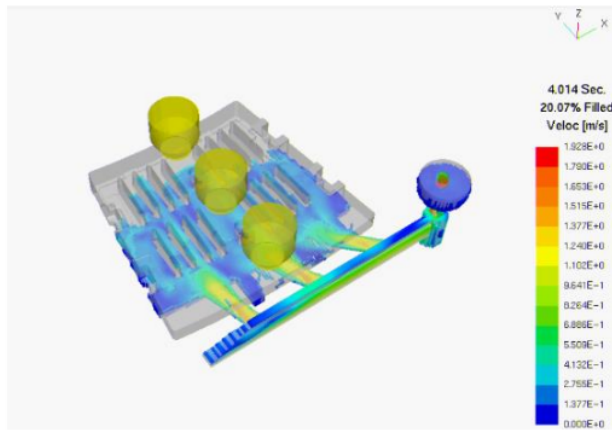


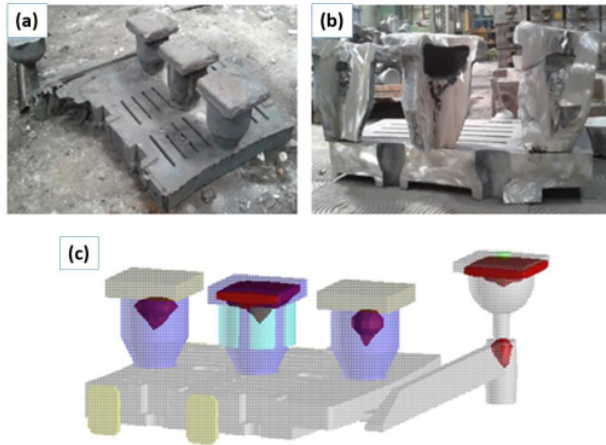**Fig. 4. Analysis of flow velocity in gating system.**



**Fig. 5. Results of cutting products and risers with their simulation results.**

To ensure the analysis, several analyses for the shrinking phenomena during the process of steel castings are characterized using several methods (see Table 3). The characterizations included critical fraction solid point, Niyama point, solidification shrinkage, initial temperature and freezing range for the materials. All characterization analyses (based on experimental results) are in a good agreement with simulation analyses.

The first parameter in the characterization is a critical fraction solid point. It is defined as the point at which, the melted material is solid enough that liquid feed metal can flow no longer. In a good solidification direction, the areas within the steel castings cannot be fed by risers. In this study, the analysis of the critical fraction solid point was 60%, which is higher than that of the simulation analysis. This indicates that the solidification using grate-shaped geometry has a good critical fraction solid point leading to effective and optimum steel castings [19].

The second parameter is Niyama point. This point plays an important role in steel castings. This is due to the fact that Niyama point is capable fo predicting the leakage possibility in the macro and/ or micro centerline shrinkage [20]. The results showed that the Niyama point in the experimental process was higher (60%) than that in the simulation (20%). This means that the present method is effective for steel castings.

The next parameter is the solidification shrinkage. This parameter influences the cavity formation is the casting of metal, including steel. This shrinkage is formed due to unavailability of molten metal during solidification. Within this process, the hot spots (melted material that will be solidified) were surrounded by metal with lower temperature. When too rapid solidification happens, the shrinkage has impacts on the internal part (formation of brittle material) [21]. In this case, the solidification shrinkage has the percentage by -5% on the experimental result and that by -3.5% on the simulation result. These values were near 0%, informing that there is almost no shrinkage phenomenon in the whole processes of steel casting using this method (grate-shaped geometry).

The next parameter is the initial temperature. This temperature is important to ensure that the raw material to be completely melted and ready to be solidified into the steel casting equipment. The experimental result showed that the temperature was 1550 °C, in which, this is higher than that of the simulation (1520 °C). This fact is in agreement with the literature [22].

The last parameter is the freezing range material. Freezing raw material affects the solidification process of the liquid (or melted) material. The too low temperature usually leads to the formation of brittle material because of a drastic shift of temperature (from too high to too low) cause inhomogeneous temperature degradation. Consequently, the too hight temperature is good for the formation of the material as long as there is a proportional freezing process. Therefore, if the temperature is too high, there needs to be a cooling process to balance things out [23]. The simulation showed that the freezing temperature should be at 45 °C. Thus, the experimental result is set to be near the simulation result. However, we cannot control the result of the experiment (50 °C). The difference between the experimental and simulation results show no significant influence. In other words, this can be classified as ideal freezing range material in steel castings.

In addition, the results of the experiment and simulation were not the same (as shown in Table 3). The main reason is that the need for some properties of the materials that are not added to the simulation analysis.

**Table 3. Calibration result for simulation parameter.**

| No. | Parameter | Default by experimental | Calibration by simulation |
|-----|-----------|-------------------------|---------------------------|
| 1 | Critical fraction solid point (%) | 60 | 20 |
| 2 | Niyama point (%) | 65 | 25 |
| 3 | Solidification shrinkage (%) | -5 | -3.5 |
| 4 | Initial temperature (℃) | 1550 | 1520 |
| 5 | Freezing range material (℃) | 50 | 45 |

## 4. Conclusions

The application of castings design carried out in numerical simulation and experimental can be obtained by predicting the position, size and shape of centreline shrinkage in the grate shaped casting product. Modification of the gating system can provide lower temperature gradient distribution so that the formation of centreline shrinkage can be suppressed. Numerical simulation is very necessary to predict and control the formation of these defects.

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