Study and control of factors influencing casting shrinkage using DOE and numerical simulation

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Abstract. The purpose of this study is to predict the effect of various factors like alloying elements, inoculation and Carbon Equivalent (CEV) on green sand casting shrinkage defect in gearbox housing, without changing the casting methoding system. Foundries are prone to have defects related to feeding and gating system, sand and process parameters. In some engineering applications, it is very difficult to alter methoding system due to specific casting geometry requirements. If not controlled during development stage, the rejections may seriously affect the productivity. This research work involves the optimization of various factors by DoE and numerical simulation to reduce the shrinkage defect. Unlike the prototype or sample lot trial, mass production of gearbox housing castings has been done in a foundry to achieve the research purpose. Effect of these factors on final casting hardness and tensile strength has also been studied and found to be on positive side, as these parameters are important for satisfactory performance under dynamic loading. Outcome was the reduction in shrinkage porosity from 10.9% to 3.2% with overall saving of 41k USD over the period of 4.5 months. Implication of this study involves standardization of optimum range of alloy elements and inoculation for different grades of grey cast iron.

1. Introduction

For the purpose of power and speed transmission, gear box housing is an integral part of any automobile. The gear box housing not only provides rigid mechanical supports to high speed gears, but also provide needed lubrication to gears and protection from external surrounding. The gear box housing, which is normally of grey cast iron and made from green sand casting, needs to be sufficiently strong to avoid gears and shafts deflection under dynamic loading conditions.

Globally green sand casting is used for automotive housings due to process being economical, intricate profiles may be cast and high productivity. The normal grades of grey cast iron are FG260 and FG300. The casting process brings some inherent defects with them also, like blow holes, sand inclusion and shrinkage porosity. During machining of these housings, parts with visual defects like blow holes, pin holes, inclusion may be rejected. But hidden defects like shrinkage porosity pose a serious threat to housings, as they may not only cause leakage problem but also breakage at highly loaded points of gearbox housing. Shrinkage porosity defect poses a serious threat to performance and
reliability of the housing and its control is possible only through knowledge of source causing the porosity.

In practical terms, shrinkage is found to be deeply related with casting gating and feeding system, chemical composition, inoculation, pouring temperature and part geometry. Combination of any of these parameters causes the volumetric changes in casting during solidification process. Higher amount of alloying elements like phosphorus and molybdenum tend to increase the shrinkage porosity, whereas high pouring temperature also increases liquid shrinkage. Increasing carbon content may reduce shrinkage tendency and inoculation may help in increased level of nucleation.

2. Literature Review

In grey cast iron castings, the volumetric contraction is classified in three distinct forms, namely liquid shrinkage, liquid to solid shrinkage and solid shrinkage. High pouring temperature results in heat loss in liquid metal and results in liquid shrinkage, which is first shrinkage step. With decreasing temperature, molten metal viscosity decreases and feeding to isolated places becomes difficult. Due to dendrites formation, these voids get entrapped in dendrite arms. Solid shrinkage is related to pattern shrinkage allowance and may be controlled during pattern designing. Mould hardness (both horizontal and vertical) is also of importance to keep the mould stable due to volume change during solidification.

Metal composition has effect on freezing range and has role in porosity as well. Higher levels of inoculation reduces fading problem but may result in shrinkage. Although phosphorous helps in molten metal fluidity and feeding, yet higher levels results in formation of low melting point iron phosphide (steadite) and thereby enhancing shrinkage [1]. Phosphorus levels above 0.2% are found to be contributing towards shrinkage growth. Shrinkage increases with under-inoculation due to shortage of expanding graphite. It also increases with over-inoculation as large number of eutectic cells are formed early during solidification and causing lesser precipitated graphite [2].

Among alloying elements, silicon is most important alloy. It transforms carbon to graphite, resulting into softer iron, which results in lower strength but less shrinkage. High levels of sulphur causes short run defects and increase metal hardness. Manganese is added to counter harmful effects of sulphur by making manganese sulphide instead of iron sulphide. Alloys like titanium and zirconium are added to increase molten metal fluidity that eventually helps in reducing shrinkage as metal reaches far away voids. Molybdenum helps in graphite flakes refinement, reduction in carbides and matrix strengthening. Magnesium helps in improving flowability in ductile irons and thereby reduces shrinkage [3].

Cast iron inoculation changes the physicochemical state of the molten metal. Good control on the microstructure and properties of cast iron is achieved by inoculants through increase in nucleation sites for growth of graphite flakes in FG Iron and graphite nodules in SG Iron. The basic iron solidification mechanism tend to make chilled structure (carbide structures) in case of inadequate inoculation. This results in difficulty in part machining due to excessive tool wear or frequent tool breakage [4].

Casting solidification simulation software are widely used in foundries processing different materials like aluminium, copper, iron and steel. The processes adopted by different foundries include green sand casting, resin and shell-bonded sand casting to investment and gravity die-casting. With the help of metal and design data, both designer and foundry expert can help in effective utilization of simulation techniques for better quality castings [5]. Use of casting numerical simulation tools is providing a much needed support to foundry industry to reduce casting rejection by doing offline trials for parameters like gating and feeding system, chemical composition etc. In order to effectively predict casting defects, density and mass transportation calculations are linked with solidification simulation. Effect of various parameters like alloying elements, molten metal temperature and chemical composition needs to be considered to predict solidification behaviour for shrinkage control [6]. In simulation studies, formation and growth of porosity during solidification has been studied through multi-phase model, which is valid for both microporosity and macroporosity. The model predicted molten metal flow, melt pressure and location and percentage of porosity.
equation was derived by combining Darcy’s law (for fluid flow in mushy zone) and Stokes’ law (for flow flowing pure liquid) [7]. Solidification simulation is extensively used for detection of hotspots and predict the feed paths.

On the basis of filling results and solidification results, one can evaluate good options available to reduce defects. These good options can be converted to optimum option through use of optimization techniques like Taguchi techniques. DoE is a widely used tool to identify the most important process parameters, and to identify the levels at which these parameters to be kept to optimize the response. In addition, DoE helps in predicting significance of input variables as well as variables working in combination with each other [8].

3. Shrinkage porosity defect in Gearbox housing
During machining of the gearbox housing, shrinkage porosity was reported at the critical bearing bores and surfaces that are critical load carrying areas of the castings. Presence of sub surface shrinkage porosity, if goes undetected during machining at these areas, may adversely affect the field performance of the component also.

![Component Details]

Component Details
Casting wt.: 105Kg
Yield: - 80%, Cavity: - 1 cav.
Pouring Time: - 15.0sec
Pouring Rate: - 8.8kg/sec
Wall Thickness: - 6 mm
Liquid Metal Wt.: - 131.25kg

Figure 1: Gearbox housing detail

Shrinkage porosity defect was investigated with a scanning electron microscope (SEM) and energy dispersive spectrometer (EDS) was used for chemical characterization of the cavities.

![Figure 2](a): Shrinkage at Mag. 20x Macroscopic View, (b): Shrinkage at Mag. 32x Macroscopic View, (c): Shrinkage at Mag. 100x Macroscopic View

4. Research Methodology adopted for the work
The experiment for the research work is done at a foundry with automatic sand plant, high pressure moulding line and molten metal press-pour. Mass production tooling (patterns and core boxes) of gearbox housing are used for doing the casting.
Method adopted for the present work may be outlined in following way:

4.1. Pareto study for shrinkage porosity defects
Study done for quantity (% rejection) and concentration diagram for defects locations for castings with existing parameters.
4.2. Identification of potential causes responsible for shrinkage porosity

Following matrix was evaluated for validation purpose by taking in consideration all contributing parameters:

| Domain     | Cause             | Validation Tool                        |
|------------|-------------------|----------------------------------------|
| Design     | Feeding Modulus   | Feed Mod > Neck Mod > Casting          |
| Design     | Pouring Temp      | Temp. 1415-1425 deg C                  |
| Design     | Gating Location   | Bottom gate, Flow is proper            |
| Machine    | Pouring Temp      | Temp. 1430-1435 deg C                  |
| Machine    | Venting           | All machine vented                     |
| Machine    | Inoculation amount| (0.9 to 1 %) of Cast weight            |
| Material   | Inoculation amount| Composition (Ferro-silicon)            |
| Material   | Cr & Mo Optimize  | Influence in shrinkage defects         |
| Material   | Other alloys      | Graphitization retard influence        |
| Material   | Alloy composition | Added vs Customer Spec                 |

4.3. Numerical simulation for old and new casting system parameters

Simulation study was conducted as per following table through change in alloying elements (Cr and Mo), Carbon Equivalent CE and inoculation (supersede grade)

| Element | Previous  | Proposed  | Remarks                                           |
|---------|-----------|-----------|---------------------------------------------------|
| Carbon (%) | 3.35 - 3.50 | 3.35 - 3.45 | C less by 0.05 for maintaining Physical Prop       |
| Silicon (%) | 1.95 - 2.10 | 2.10 - 2.20 | Silicon increased to counter Shrinkage            |
| Manganese (%) | 0.60 - 0.90 | 0.60 - 0.80 | No Change                                         |
| Chromium (%) | 0.25 - 0.35 | 0.2 - 0.3  | Chromium less by 0.05 to counter Shrinkage        |
| Phosphorus (%) | 0.050 - 0.090 | 0.04 - 0.05 | Limits provided for P Content.                    |
| Sulphur (%)  | 0.070 - 0.10 | 0.070 - 0.10 | No Change                                         |
| Copper (%)   | 0.40 - 0.70  | 0.40 - 0.70 | No Change                                         |
| Tin (%)      | 0.040 - 0.070 | 0.040 - 0.070 | No Change                                       |
| Molybdenum (%) | 0.20 - 0.30 | 0.20 - 0.30 | Moly on lower side to counter Shrinkage           |
| Titanium (%) | 0.02 - 0.050 | 0.030 - 0.050 | Titanium up to Counter Nitrogen Fissure         |
| CEV (%)      | 4.02 - 4.22  | 4.06 - 4.20 | Narrowed down CE Value                           |
| Inoculation (SS) | 0.10% | 0.15% | No Change                                         |
| Pouring Temperature | 1420 – 1435 | 1420 – 1435 | No Change                                         |

4.4. Optimization of identified process parameters through DOE using Taguchi, with L9 orthogonal array

Different levels of alloying elements were taken for carrying 27 iterations.

| Element     | Designation | Level 1      | Level 2      | Level 3      |
|-------------|-------------|--------------|--------------|--------------|
| Chromium (Cr) | Cr          | Traces to 0.15 | around 0.2   | around 0.3   |
| Molybdenum (Mo) | Mo        | Traces       | around 0.2   | around 0.3   |
| Inoculation (SS) | SS        | 0.1 %        | 0.15 %       | 0.2%         |
| Expt No. | Level 1 | Level 2 | Level 3 | Iteration A | Iteration B | Iteration C |
|---------|--------|--------|--------|-------------|-------------|-------------|
| 1       | Cr-1   | Mo-1   | SS-1   | 1A          | 1B          | 1C          |
| 2       | Cr-1   | Mo-1   | SS-1   | 2A          | 2B          | 2C          |
| 3       | Cr-1   | Mo-1   | SS-1   | 3A          | 3B          | 3C          |
| 4       | Cr-2   | Mo-2   | SS-2   | 4A          | 4B          | 4C          |
| 5       | Cr-2   | Mo-2   | SS-2   | 5A          | 5B          | 5C          |
| 6       | Cr-2   | Mo-2   | SS-2   | 6A          | 6B          | 6C          |
| 7       | Cr-3   | Mo-3   | SS-3   | 7A          | 7B          | 7C          |
| 8       | Cr-3   | Mo-3   | SS-3   | 8A          | 8B          | 8C          |
| 9       | Cr-3   | Mo-3   | SS-3   | 9A          | 9B          | 9C          |

5. **Key Results**

On the basis of changes done in optimized identified process parameters, results were outlined as:

5.1. Elimination of shrinkage defect depends on CEV, inoculants and alloying elements
5.2. Tensile decreases with increasing CEV, and hence range was limited
5.3. High CEV (carbon equivalent) also give rise to Open-Grain Structure
5.4. CEV and Inoculation also promotes Graphitization and hence expansion and shrinkage reduction
5.5. Chromium and Molybdenum limits prescribed to reduce the effect of carbide formation and Inoculation limits to achieve graphitization

![Figure 3](image3.png) **Figure 3.** Temp less than liquidus temp upto 1223 deg

![Figure 4](image4.png) **Figure 4.** Temp less than liquidus temp upto 1210 deg

![Figure 5](image5.png) **Figure 5.** Velocity is 1.65 m/s

![Figure 6](image6.png) **Figure 6.** Velocity is from 0.33 m/s to 0.6 m/s

![Figure 7](image7.png) **Figure 7.** Fraction liquid result with old casting system

![Figure 8](image8.png) **Figure 8.** Fraction liquid result with new casting system
6. Conclusions
Casting process parameters like alloying elements, inoculants and CEV help in controlling the shrinkage porosity defects in areas, where profile or dimensional changes are not possible due to specific part requirements. Optimization of these parameters helped in achieving the hardness and tensile strength as per functional requirements. Improvement resulted in the reduction in shrinkage porosity from 10.9% to 3.2% with overall saving of 41k USD over the period of 4.5 months.

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