DESIGN AND DEVELOPMENT OF DIE CASTING DIE FOR REJECTION REDUCTION

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ABSTRACT

Product manufactured from every manufacturing process shows some defects. For supplying quality product to customer these defects must be reduced. In this work, an attempt is made to reduce the rejection due to the porosity defect of die casted part. Root cause of porosity defect is found out through why-why analysis technique. Process capability of current high pressure die casting manufacturing process is checked. Manufacturing process found capable to manufacture the components. Current problem of porosity is solved by making an improvement in design of die insert. Ingate directions are changed so as to obtain modified improved flow pattern. Then using Magma® flow simulation software existing and modified design is compared. It is found that, modified design shows superior results and using this, defect of porosity is minimized upto satisfactory level.

Keywords: die casting, rejection reduction, gas porosity, why-why analysis, finger gate.

http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=8&IType=5

1. INTRODUCTION

High pressure die casting (H. P. D. C.) is manufacturing process in which, molten metal is injected into the die cavity by means of external force. Die is defined as, a set of metal blocks having cavities use to reflect same impression on molten metal by forcing in to the cavity [1]. There can be defects in die casted product like porosity, blow hole, non-filling, etc. If they are within control limit then, product is acceptable; otherwise rejected. Every manufacturer tries to manufacture defect free components but practically it is not possible and some defects remains in the component and leads to rejection of the component. This rejection can be minimized upto certain extent. There are different methods that can be used to minimize defects, some of them are; by improving process parameters, by design modifications, or both.
1.1. Problem Statement
Porosity defect in the die casted product is major issue considered in this work. Figure 1 shows pareto chart for September 2016. Contribution of porosity in rejection is maximum. From trend chart for the months June 2016 to September 2016 that the rejection of product due to porosity is increasing month by month see figure 2. Objective is set to reduce the rejection of product due to porosity defect below 5%.

Figure 1 Pareto charts for September 2016.

Figure 1 Trend chart for porosity defect.

1.2. Causes of Porosity
Porosity is defined as void in casted part where there is absence of cast metal. Main cause for gas porosity is high velocity of metal injection [2]. Before proceeding to solve any problem of porosity, identification of the type of porosity is very essential to obtain optimum solution for minimization of defect. Gas porosity typically shows series of smooth pores in casting. As shown in figure 3, there are series of pores near gate region in final product. Therefore mentioned porosity is gas porosity.

1.3 Causes of Porosity
Once type of porosity is identified, next step is to find root cause for porosity. North American Die Casting Association (N.A.D.C.A.) has given some of the causes for gas porosity, some of them are, trapped air in plunger system, poor gate design, turbulent metal flow inside cavity, etc. Some secondary causes are coolant leakage in die, excess lubricant and die coat spray on die, etc. Figure 4 shows cause and effect diagram for porosity defect. By performing brainstorming on all obtained causes, we come to conclusion that mentioned porosity defect problem can be reduce by either modifying process parameters or by modifying gating system design.

Figure 3 Porosity defect in product.

Figure 4 Cause and effect diagram for porosity defect.
2. PROCESS CAPABILITY ANALYSIS

Initially, study was conducted on die casting process to check its process capability. A trial of 100 casting shots is taken. Standard values of Upper Specific Limit (U.S.L.) and Lower Specific Limit (L.S.L.) for respective process parameter are listed in table 1. 180 Ton die casting machine was used for these 100 shots (i.e. 200 castings) and defect concentration diagram for rejected castings is plotted, see figure 5. This diagram shows more porosity defects concentration area near the gate region.

<table>
<thead>
<tr>
<th>Process parameters</th>
<th>Upper Specific Limit (U.S.L.)</th>
<th>Lower Specific Limit (L.S.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low velocity ($V_1$) (m/s)</td>
<td>0.28</td>
<td>0.18</td>
</tr>
<tr>
<td>High velocity ($V_2$) (m/s)</td>
<td>4.3</td>
<td>3.3</td>
</tr>
<tr>
<td>$V_{rise}$ (sec)</td>
<td>0.025</td>
<td>0.15</td>
</tr>
<tr>
<td>Intensify pressure (kg/cm²)</td>
<td>300</td>
<td>260</td>
</tr>
<tr>
<td>$P_{rise}$ (sec)</td>
<td>0.065</td>
<td>0.15</td>
</tr>
<tr>
<td>Biscuit thickness (m)</td>
<td>0.025</td>
<td>0.005</td>
</tr>
<tr>
<td>Casting pressure (kg/ cm²)</td>
<td>850</td>
<td>750</td>
</tr>
<tr>
<td>Feed metal temperature (°C)</td>
<td>680</td>
<td>640</td>
</tr>
</tbody>
</table>

2.1. Process capability charts

Process capability chart is used to determine capability of process to manufacture components [3,4]. From numerical values obtained from machine setup run, process capability of each process parameter is checked by calculating values for process capability indices $C_p$ and $C_{pk}$ and normal distribution curve. A sample of curve for low velocity capability is shown in figure 6. Following values are calculated by using Minitab® software for low velocity parameter:

i. $C_p \geq 1.66$; hence process is satisfactory for low velocity.

ii. $C_{pk} \geq 1$; hence process is capable and centered between L.S.L. and U.S.L. for low velocity.

iii. $C_p > C_{pk}$; hence process is off-centered from midpoint of specified limits for low velocity.

Figure 5 Defect concentration diagram for existing design. Figure 6 Histogram for low velocity parameter
Rules given in table 2 are used to estimate process performance. Numerical values for process capability indices for all remaining parameters are calculated, see table 3. Analyzing table 3 values, all parameters except $P_{\text{rise}}$ time are capable to manufacture product within specified limits. $P_{\text{rise}}$ time control is not possible due to its very short time span. It can be stated that process is capable to produce die casted component. It directs to made design modifications for minimization of porosity defect.

### Table 2 Rules for process estimation based on the indices $C_p$ and $C_{pk}$ [3].

<table>
<thead>
<tr>
<th>Capability index</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p = C_{pk}$</td>
<td>Process is centered at midpoint of specification limits.</td>
</tr>
<tr>
<td>$C_{pk} &gt; 1$</td>
<td>Process is centered between U.S.L. and L.S.L. and capable for producing parts.</td>
</tr>
<tr>
<td>$1 \leq C_{pk} &lt; 1.33$</td>
<td>Process is adequate</td>
</tr>
<tr>
<td>$C_p \geq 1.33$</td>
<td>Process used is satisfactory</td>
</tr>
</tbody>
</table>

### Table 3 Process capability indices of other parameter

<table>
<thead>
<tr>
<th>Process parameter</th>
<th>$C_p$</th>
<th>$C_{pk}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High velocity</td>
<td>3.92</td>
<td>2.86</td>
</tr>
<tr>
<td>$V_{\text{rise}}$ time</td>
<td>1.31</td>
<td>0.9</td>
</tr>
<tr>
<td>Intensify pressure</td>
<td>4.62</td>
<td>3.06</td>
</tr>
<tr>
<td>$P_{\text{rise}}$ time</td>
<td>0.88</td>
<td>0.71</td>
</tr>
<tr>
<td>Biscuit Thickness</td>
<td>4.18</td>
<td>3.56</td>
</tr>
<tr>
<td>Casting Pressure</td>
<td>2.17</td>
<td>0.74</td>
</tr>
<tr>
<td>Feed Metal Temperature</td>
<td>2.25</td>
<td>1.69</td>
</tr>
</tbody>
</table>

### 3. DESIGN MODIFICATIONS

After obtaining CAD model (see figure 7) of existing design and shot details, flow simulation results using simulation Magma® software for air pressure and air entrapment are obtained. Figure 8 shows air entrapment results and air pressure results for existing design. From simulation results obtained from Magma® it is observed that, there is an air entrapment near gate section.

### Table 4 Shot detailing of existing design

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Name</th>
<th>Projected area (cm²)</th>
<th>Weight (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Casting (1 cavity)</td>
<td>30.75</td>
<td>184.98</td>
</tr>
<tr>
<td>2</td>
<td>Casting (2 cavities)</td>
<td>61.5</td>
<td>369.96</td>
</tr>
<tr>
<td>3</td>
<td>Runner</td>
<td>101.4</td>
<td>354.27</td>
</tr>
<tr>
<td>4</td>
<td>Overflow-1</td>
<td>30.73</td>
<td>48.01</td>
</tr>
<tr>
<td>5</td>
<td>Overflow-2</td>
<td>23.7</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>Overflow-3</td>
<td>22.93</td>
<td>52.28</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>134.86</td>
<td>864.52</td>
</tr>
</tbody>
</table>
Figure 7 Shot details of existing design

Figure 8 Magma simulation results for existing design a) air entrapment, b) air pressure.

Table 5 Why - why analysis for porosity defect.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Cause: Gas porosity</th>
<th>Why?</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gas porosity in gate region is observed.</td>
<td>Air entrapment in ingate.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Air entrapment in ingate</td>
<td>Gating directions are wrong.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Gating directions are wrong.</td>
<td>Poor feeding system design (Single gate).</td>
<td></td>
</tr>
</tbody>
</table>

Table 6 Shot details of modified design

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Name</th>
<th>Projected Area (cm²)</th>
<th>Weight (gram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Casting (1 cavity)</td>
<td>30.75</td>
<td>184.98</td>
</tr>
<tr>
<td>2</td>
<td>Casting (2 cavities)</td>
<td>61.5</td>
<td>369.96</td>
</tr>
<tr>
<td>3</td>
<td>Runner</td>
<td>101.4</td>
<td>384</td>
</tr>
<tr>
<td>4</td>
<td>Overflow-1</td>
<td>30.73</td>
<td>48.01</td>
</tr>
<tr>
<td>5</td>
<td>Overflow-2</td>
<td>23.7</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>Overflow-3</td>
<td>22.93</td>
<td>52.28</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>240.26</td>
<td>894.25</td>
</tr>
</tbody>
</table>

This results into gas porosity, known as flow dominated gas porosity. Analysis called why-why analysis is performed to get precise root cause for porosity problem. From why-why analysis, it is concluded that the gas porosity is occurring at gate section due to poor feeding system design, see table 5. Gating directions are modified so as to improve metal flow in die cavity.
Then modified CAD model is created and from that shot details for modified design are generated. The modified shot details are given in table 6 and figure 9 shows modified CAD model. From modified shot details, modified input parameters for Magma® are calculated as below:

3.1. Active Sleeve Length (A.S.L.)

\[ A.S.L. = (\text{Plunger stroke}) - (\text{Plunger penetration}) + (\text{Sprue - bush height}) - (\text{Diffuser height}) \]

\[ A.S.L. = 365 \text{ mm} - 150 + 148.61 - 30 \]

\[ A.S.L. = 333.61 \text{ mm}. \]

3.2. Active Sleeve Capacity (A.S.C.)

\[ A.S.C. = \left(\frac{\pi}{4} \times D_{\text{sleeve}}^2\right) \times A.S.L. \]

\[ A.S.C. = \left(\frac{\pi}{4} \times 60^2\right) \times 333.61. \]

\[ A.S.C. = 943260.05 \text{ mm}^3 = 943.26 \text{ cm}^3. \]

3.3. Shot Volume (\( V_{\text{shot}} \))

\[ V_{\text{shot}} = \frac{\text{Total shot weight}}{\text{Density of material}} \]

\[ V_{\text{shot}} = \frac{849.25}{2.71} \]

\[ V_{\text{shot}} = 329.98 \text{ cm}^3. \]

3.4. Metal fill Ratio (R)

\[ R = \left(\frac{\text{Shot volume}}{\text{Swept volume by plunger}}\right) \times 100 \]

\[ R = \left(\frac{329.98}{943.26}\right) \times 100 \]

\[ R = 34.98 \%. \]
3.5. Fast Shot Length ($S_2$)

$$S_2 = \frac{(\text{Total volume of metal to be filled after gate})^4}{\pi \times D_{\text{sleeve}}^2}$$  

(5)

Total volume of metal to be filled after gate = (volume of casting of 2 cavities) + (Volume of overflows for 2 cavities)  

(6)

Total volume of metal to be filled after gate = $136.5166 + 51.7675 = 188.2841$ cm$^3$.

$$S_2 = \frac{188.2841 \times 4}{\pi \times 6^2}$$

$$S_2 = 6.6591 \text{ cm} = 66.59 \text{ mm}.$$

3.6. Slow shot length ($S_1$)

$$S_1 = \text{A.S.L.} - S_2$$  

(7)

$$S_1 = 333.61 - 66.59$$

$$S_1 = 267.02 \text{ mm}.$$

3.7. Slow Shot Velocity ($V_1$)

$$V_1 = (22.8) \times \frac{100 - (\% \text{fill})}{100} \times \sqrt{\text{Dia. of plunger}}$$  

(8)

$$V_1 = (22.8) \times \frac{100 - (34.98)}{100} \times \sqrt{60}$$

$$V_1 = 114.83 \text{ mm/s} = 0.114 \text{ m/s}.$$

3.8. Fast Shot Velocity ($V_2$)

$V_2$ is determined by determining fill time and then using $V_2$ gate velocity is verified. Once gate velocity comes within limit specified, $V_2$ is finalized. According to NADCA, gate velocity should not less than 50 m/s. But, manufacturer sets limit for gate velocity less than 45 m/s; this is to avoid scoring of die and to get better die life.

3.9. Fill Time Required ($T_{req}$)

$$T_{req} = K \times \left( \frac{T_i - T_f + (S+Z)}{T_d^2} \right) \times T$$  

(9)

Where,

$T_i$ = Temperature of molten metal inside shot sleeve ($^0\text{C}$)

$T_f$ = Minimum flow temperature of metal ($^0\text{C}$)

$T_d$ = Surface temperature of die cavity before injection ($^0\text{C}$)

$S$ = % Solid fraction at end of filling (%)

$Z$ = Solids units conversion factor, $^0\text{C}$ to %, related to width of solidification range.

$T$ = Average wall thickness of casting (mm).

$$T_{req} = 0.03409 \times \left( \frac{650 - 571 + (0.3 \times 3.778)}{571 - 140} \right) \times 3.5$$

$$T_{req} = 0.02218 \text{ sec}.$$

3.10. Actual fill Time ($T_{act}$)

$$T_{act} = \frac{\text{Part weight+overflow weight}}{\text{density of material}} \times \frac{\pi}{4} \times (D_{\text{sleeve}})^2 \times V_2 \times 100$$  

(10)

$$T_{act} = \left( \frac{369.96 + 1440.29}{2.71} \right) / \frac{\pi}{4} \times (6)^2 \times V_2 \times 100$$
Now, as stated in this section, fast shot velocity, \( V_2 \) is determined and then gate velocity is verified. Now, for determining \( V_2 \) actual fill time is compared with required fill time.

\[
0.02218 = \left( \frac{369.96+140.29}{2.71} \right) / \left( \frac{\pi}{4} * (6)^2 \right) * V_2 * 100
\]

Hence,

\[
V_2 = \left( \frac{369.96+140.29}{2.71} \right) / \left( \frac{\pi}{4} * (6)^2 \right) * 0.02281 \times 100
\]

\[
V_2 = 3.0023 \text{ m/s.}
\]

### 3.11. Gate Velocity (\( V_{gate} \))

\[
V_{gate} = \left( \frac{\text{sectional area of sleeve}}{\text{gate area}} \right) \times V_2
\]

(11)

Sectional area of sleeve = \( \frac{\pi}{4} \times D_{sleeve}^2 \)

Sleeve area = \( \frac{\pi}{4} \times 6^2 = 28.2743 \text{ cm}^2 \).

\[
V_{gate} = \left( \frac{28.2743}{2.55} \right) \times 300
\]

\[
V_{gate} = 33.26 \text{ m/s.}
\]

If \( V_2 \) is not specifying this limit then we have to adjust \( V_2 \) so that gate velocity will come within specified range. But, in this case it is 33.26 m/s < 45 m/s. So, there is no need to adjust fill time and hence no need to rework for design. Updated feeding system design can be further used for tool design.

### 3.12. Machine Tonnage Calculation

\[
F = \left( \frac{\text{Projected area}}{100} \right) \times (\text{Casting pressure})
\]

(12)

According to NADCA standards castings are categorized into three categories based on their applications. For each application, casting pressure range is specified.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Casting type</th>
<th>Pressure ranges(kg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>General</td>
<td>400 to 600</td>
</tr>
<tr>
<td>2</td>
<td>Technical</td>
<td>600 to 800</td>
</tr>
<tr>
<td>3</td>
<td>Pressure tight</td>
<td>800 to 1000</td>
</tr>
</tbody>
</table>

Table 7 shows casting type and respective pressure ranges. As stated by manufacturer, this product comes under pressure tight category, taking casting pressure as 800kg/cm² = 80 MPa.

We get,

\[
F = \left( \frac{217.3}{100} \right) \times 80
\]

\[
F = 174 \text{ Tons.}
\]

Now as machine available has a capacity of 180 Tons. Casting pressure is taken as 70 MPa for ensuring safe operation. Hence, locking force,

\[
F = \left( \frac{217.3}{100} \right) \times 70
\]

\[
F = 168.182 \text{ Tons}
\]

This force is less than 180 Tons. So, with this design die can be operated at 180 Tons machine.
3.13. **Spare Force Ratio**

\[
\text{Spare force ratio} = \frac{\text{Actual machine tonnage} - \text{Calculated machine tonnage}}{\text{Actual machine tonnage}} \times 100\% \quad (13)
\]

\[
\text{Spare force ratio} = \frac{180 - 168.182}{180} \times 100\% \\
\text{Spare force ratio} = 6.56\%
\]

Spare force = 11.81 Tons.

4. **RESULTS**

After obtaining numerical values for above parameters, simulations for modified design are performed. Results for simulation are given in Figure 10. From simulation, it is observed that in the revised design due changes made in gating directions air entrapment near gate is drastically reduced and hence there are less chances for porosity to occur at gate. Hence modified gate design is further used for manufacturing of die. After manufacturing of modified insert, die is loaded on die casting machine of capacity of 180 Tons. At trial for 717 castings is taken and concentration diagram is plotted, see figure 11.

From above diagram, total rejections due to porosity is calculated as,

\[
\text{Total rejection due to porosity} = \frac{33}{717} \times 100 \\
= 4.06\%
\]

Figure 12 shows pareto chart for March 2017 month. From pareto chart it is seen that rejection quantity due to porosity is reduced. Table 8 shows porosity rejection data for cap manufactured by H.P.D.C. process for month March 2017.

<table>
<thead>
<tr>
<th>Quantity production (Nos.)</th>
<th>17092</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rejection due to porosity (Nos.)</td>
<td>526</td>
</tr>
</tbody>
</table>

From above table 8 percent rejections due to porosity are calculated as:

\[
\text{Total rejection due to porosity} = \frac{526}{17092} \times 100 \\
= 3.07\%
\]
5. CONCLUSION
In this work porosity defect found in cup manufactured by H.P.D.C. process was a major concern aimed to reduce below 5%. For this, existing gate design is changed to finger gate system and modified gate design reduced percentage of porosity defect. By modified design we achieved rejection reduction from 7.89% to 3.07% which is less than 5%.

REFERENCES
[6] Introduction to die casting, NADCA, Item #101 BK.