

OPTIMIZING SHRINKAGE DEFECTS IN GREY CAST IRON BUTTERFLY VALVE CASTING: A SIMULATION AND EXPERIMENT-BASED APPROACH

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Abstract

The study focused on addressing casting defects in green sand casting that have negatively impacted the quality of the butterfly valve body. By employing various methods such as observation, interviews, numerical experimentation, and simulation, the researchers aimed to develop and evaluate a sand-casting technique for the butterfly valve body. Solidworks software was used to model the component and its gating system, while ProCAST software enabled mold filling and solidification analyses. The goal was to minimize shrinkage porosities in the cast butterfly valve body by optimizing process parameters through numerical experiments and the Taguchi technique. Analysis of variance (ANOVA) using Minitab 18 software analyzed the results. Through this research, the sand mold-related defect was reduced from 10% to 3%, and the special shrinkage defect was reduced from 26% to 2% by using a simulation of casting.

Keywords: ANNOVA; Butterfly Valve Body; Casting; ProCAST; Shrinkage Defect; Simulation

Introduction

Analytical methodologies and mathematical simulations revolutionize metal casting by accurately analyzing mold filling, phase transformation, heat transfer, and predicting internal defects. They enhance quality control, optimize processes, and minimize reliance on trial-and-error methods (Ravi, 2019). Simulation methods have revolutionized casting units, replacing trial-and-error methods with systematic simulations in product development. This shift allows investigators and foundries to study the casting process comprehensively and understand its complex behavior under actual working conditions (Acharya *et al.*, 2016).

Understanding physical processes design, location, solidification rate, heat transfer rate, molding sand type, filling time, riser design, metal/alloy type, pouring height, distance, and temperature is essential for an effective casting simulation software. (Acharysyah *et al.*, 2020). Casting simulation programs need mass, energy, and momentum conservation mathematical models. The program must specify cast alloy and mold materials and their physical properties. This ensures casting process simulation accuracy. (Nimbulkar *et al.*, 2016). Math solves casting equations. FVM, FEM, etc. Simulation needs to drive the strategy (Bagale *et al.*, 2020). Multiple methods may

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simulate casting. Finite element methods combine. Hybrid finite difference-finite element methods may model casting processes. Simulation accuracy and requirements dictate the method (Bočkus *et al.*, 2005; Barot *et al.*, 2020). Pre-casting simulation software decreases shop floor trial-and-error, cutting production costs (Azhar *et al.*, 2016). Auto Cast, ProCast, MAGMA, Solid Cast, Nova Cast, and Flow Cast employ distinct simulation methods (Gaware *et al.*, 2017) MEGMA software may reduce mass production casting faults by developing the gating system (Jezierski *et al.*, 2018).

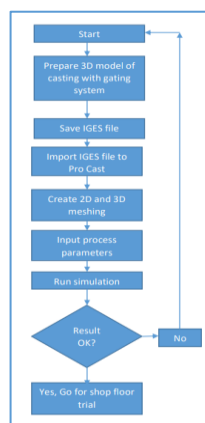
Auto Cast shows alloy plate casting temperature distribution and hot spot location (Hirigo *et al.*, 2019). Flow casting tools may also clear an increased temperature and solidifying region (Tian *et al.*, 2021). NOVACAST calculates casting product filling time and flow velocity (Mehta *et al.*, 2018).

Important Observations in Simulation

ProCast simulation software may enhance impeller casting yield and reduce shrinkage faults (Liu *et al.*, 2023). ProCast modeling software examined how bottom and top gates affect shrinkage faults in brass meter shell castings (Zheng *et al.*, 2020). The ProCast program analyzed the gate velocity design percentage of solid design,



Figure 1. Shrinkage defect in butterfly valve body



**Figure 2. Flow chart for simulation in ProCast
Details of the casting part**

shrinkage porosity technique, and casting flaws for rotary adapter investment casting (Kumar *et al.*, 2020). The Auto Cast program improved the LM6 contact wheel casting yield and eliminated shrinkage flaws (Hodbe *et al.*, 2018).

Casting simulation reduced propeller shrinkage (Riazi, 2022). Green sand mold casting simulation enhanced mild steel process parameters (Tiwari *et al.*, 2016). Quartz investment powder thermally expands to offset alloy shrinkage. (Chomsaeng *et al.*, 2021)

This work designs a gating method to decrease shrinkage errors in casting a grey cast iron butterfly valve body, as demonstrated in Figure 1.

The ProCast software is being used for the simulation of the existing gating design, and simulation was carried out. The results of the simulation were validated, a new gating system was designed and simulated, and a physical trial was carried out, which resulted in a reduction of the shrinkage defect from 26% to 3%.

Materials and Methods

Materials

The butterfly valve body component casting uses cast iron for its particular properties. This cast iron alloy is compressive and vibration-dampening despite its low tensile strength. It has good machinability, castability, thermal conductivity, wear resistance, and low ductility. It's corrosion-prone, however. Cast iron is cheap. Butterfly valve body castings are typically made of FG 250 grey cast iron.

This study evaluated shrinkage, simulated the current gating system, and observed the simulation outcomes. After simulation, physical testing advised improved gating and riser designs.

After simulating the existing gating design, shrinkage faults were analyzed. After that, Pro Cast software simulated alternative gating designs and examined shrinkage faults. The ideal gating design was chosen, which had the lowest shrinkage and porosity in simulations. Based on it, 800 butterfly valve body castings were tested using the revised gating design and pattern design. To identify shrinkage or porosity in the casting, ultrasonic testing was done on a set sample size.

The flow diagram for simulation by Pro CAST is shown in Figure 2.

Details of The Casting Part

- Part Name: Butterfly Valve Body
- Alloy: grey cast iron
- Designation: EN-GJS-250
- Mould: green sand

The present charge proportion is shown in Table 1. Existing sand composition details are presented in Table 2.

The chemical composition of butterfly valve body casting using a spectrometer is shown in Table 3.

Table 1. Charge materials proportion

Sr. No.	Material	%
1.	Pig Iron	21.05
2.	Mild steel scrap	4.2
3.	Foundry return	15.78
4.	Machining return	26.31
5.	Automobile Scrap	32.63
Total		100%

Table 2. Green sand composition

Sr. No.	Content	%
1.	Recycled sand	83.85
2.	Fresh sand	9.3
3.	Bentonite	2.79
4.	Coal dust	0.93
5.	Water	3
Total		100%

Table 3. Chemical composition of casting

Sr. No.	Content	%
1.	Carbon	3.3
2.	Silicon	2
3.	Manganese	0.703
4.	Phosphorous	0.104
5.	Sulphur	0.088
6.	Chromium	0.072
7.	Nickle	0.031
8.	Copper	0.075
9.	Iron	Reminder



Figure 3. Existing gating system



Figure 4. Shrinkage defect in butterfly valve body casting

Other Parameters

- Pouring height: 580 mm
- Pouring ladle size: 68 Kg
- Pouring time: 16 seconds
- Pouring Temperature: 1350°C

The present gating system in the casting of butterfly valve bodies is shown in Figure 3:

The existing problem of shrinkage in butterfly valve body casting is shown in Figure 4. The average rejection was reported at 26% due to a shrinkage problem in the casting unit.

Research Methodology

The following techniques have often been used in the research process in order to achieve the intended objectives: personal observation, interviews, discussions, assembling secondary data, analyzing cause-and-effect diagrams, doing numerical experiments, and modeling methods.

Data Collection

For this study, primary as well as secondary information was collected using a mix of both quantitative and qualitative information-gathering techniques. Various data collection methods have been employed to ensure comprehensive research, including:

Observation

Surveys and direct observation in the foundry's production areas have provided practical data. Molding, melting, pouring, and composition testing were seen. This observation identified prospective production parameters and recorded operator-induced production variable changes.

Executives, casters, molding designers, pattern creators, and quality control supervisors were interviewed. These meetings covered product and process development plans and other quality challenges. Based on the study, these interviews and conversations were thoroughly analyzed, and significant material was retrieved. Books, manuals, journals, websites, and visual observations of the operating section casting unit provided secondary data.

Cause-Effect Diagram

Casting the butterfly valve body included mold, metal, sand, shake-out, and machine-related variables. Ishikawa's cause-and-effect diagram revealed the production factors that affect butterfly valve body quality. Product development and defect prevention employ the Ishikawa diagram to identify potential reasons. Figure 5 shows how each source of variation causes an imperfection. This figure

shows the many process factors affecting butterfly valve body quality.

Numerical experimentation uses the Taguchi design-of-experiments technique. This method is excellent at determining the appropriate process parameter settings to prevent rejection due to faults in new and old butterfly valve body castings. The cause-and-effect diagram determined that moisture level, permeability, and pouring temperature would impact mold cavity filling and butterfly valve body castings.

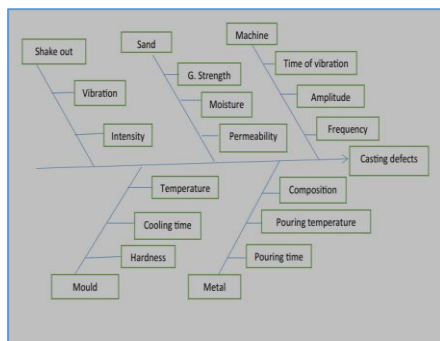


Figure 5. Cause effect diagram

Numerical Experimentation

Three experimental zones were chosen for each process parameter. The organization's foundry specialists' expertise and accepted criteria for butterfly valve body component castings defined these levels. Every parameter had low, medium, and high levels. Orthogonal arrays, the signal-to-noise (S/N) percentage, and analysis of variance were employed in Minitab 18.0 to determine how the factors affected the replies.

The Taguchi technique adjusted butterfly valve body sand casting parameters in the following phases:

- Identifying sand, mold, and solidification-related flaws in butterfly valve body castings. By modifying the process parameters, a goal of "lower casting defects" was established.
- Selection of the most significant parameters that substantially influence butterfly valve body casting defects.
- Figuring out the variables and their appropriate values. Using the Taguchi approach, experiments were carried out by the Design of Experiments (DoE) principles.
- Applying statistical methods to analyze the data that was obtained. An analysis of variance (ANOVA) was used to evaluate the parameters' statistical significance. To determine the optimal amounts of the factors taken into consideration for testing, mean plots were constructed.

- Confirmation experiments are run after choosing the ideal values for the control parameters. Based on the conclusions and suggestions made throughout the optimization process, the action plan was put into place.

By following this methodology, the aim was to minimize casting defects and achieve improved outcomes in the sand casting process for the butterfly valve body component.

Analysis of Data from Physical Observation and Interviews

The data were analyzed quantitatively and qualitatively using capabilities in the Minitab program after being acquired through various approaches. The outcomes of this data evaluation were used to reduce sand casting flaws. In order to evaluate the critical casting process variables for butterfly valve bodies and determine the root causes of the faults, talks, and interviews with foundry specialists in the pattern groups, molding portions, and melting sections were also carried out. The information gathered from those interviews and conversations showed that various problems may happen during the casting of the butterfly valve body owing to equipment failures, process variances, incorrect sand characteristics, insufficient gating systems, labor concerns, and inappropriate process operations. To further analyze the casting defects that arise during butterfly valve body castings, the elements involved in the process have been identified.

Manufacturing of butterfly valve bodies

The manufacturing process of the butterfly valve body was carried out while taking into consideration the design requirements of the valve body material. The butterfly valve body has been designed with specific specifications. These include a final mass of 9.615 kg, dimensions of 280 mm in outer diameter, 140 mm in inner diameter, and 45 mm in height. Using Solidworks software, a 3D model of the butterfly valve body was created based on these specifications. Using its tool for material mass characteristics, the program calculated the butterfly valve body's net weight, density, total volume, and total surface area to be 9.614 kg, 7150.00 kg/m³, 0.0135 m³, and 0.157 m², respectively. The geometry of the butterfly valve body is depicted in Figure 6. The required foundry allowances were taken into account while preparing the pattern measurements.

Clay analysis

In molding sand, clay refers to particles that remain suspended in water for an extended length of time without settling. These particles typically have

a diameter of less than 20 microns. In order to verify the clay content, all extremely fine materials must be examined, including fine green mold and clay minerals. The amount of clay in each sample of the green mold sand used to create the molds for the butterfly valve body casting process has been identified.

The equation 1 has been used to calculate the percentage results of each sample test that was performed, and Table 4 shows those findings.

$$\text{Clay content}(\%) = \frac{M_{sb} - M_{sa}}{M_{sb}} \times 100 \quad (1)$$

By correlating the amount of sand prior to washing (M_{sb}) to the mass of sand following washing (M_{sa}), in accordance with Equation (1), the percentage of clay content for the initial sample was calculated. For example, the precise computation is as follows:

$$\text{Clay content}(\%) = \frac{50 - 43.16}{50} \times 100 = 6.84$$

Similar results were obtained for samples 2, 3, 4, and 5 (7.68, 5.29, 6.17, and 8.44, respectively).

The average amount of clay from the five samples in Table 4 has been used to calculate the clay amount of the molded green sand utilized for butterfly valve body casting. By multiplying the total number of samples by the sum of the clay percentages in each sample, one can calculate the average. The average amount of clay detected as a result is 6.88%. This value falls within an acceptable range, indicating that the sand is suitable for use and that its impact on the casting process is minimal.

Determination of The Gross Mass of Casting

The total weight of the metal that's in the mold cavity and all of the gating system's components are taken into account when calculating the gross weight of a casting. This comprises the net weight of the valve body pattern casting as well as the surplus weight of the components that were eliminated by machining and grinding, such as risers, hot wells, sprues, pouring basins, runners, and ingates. In this study, the highest casting yield for grey cast iron material was 90%. Equation 2 is used to get the casting's gross weight. (Dev *et al.*, 2017)

$$M_g = \frac{\text{net weight of valve body casting}}{\text{maximum yield}} \quad (2)$$

Where M_g = gross weight of casting

$$M_g = \frac{9.614}{0.9} = 10.614 \text{ Kg}$$

The valve body's required weight of 9.6144 kg is attained with this weight, and it also sufficiently fills the chambers of the gating system used in the casting process of the butterfly valve body casting, and the gross weight of valve body casting along

Table 4. Clay content analysis

Sample	Mass before wash (g)	Mass after was (g)	Clay content %
I	50	43.16	6.84
II	50	42.32	7.68
III	50	44.71	5.29
IV	50	43.83	6.17
V	50	41.56	8.44
Average clay content % is 6.88			

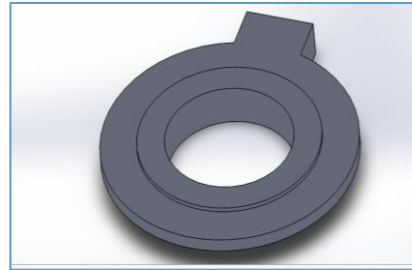


Figure 6. 3D model of butterfly valve

with the runner, ingate, runner, and riser i.e., foundary return, is 10.614 kg against the maximum yield of 0.9.

Pouring Time

The amount of time needed to pour molten grey cast iron into the mold cavity to cast the valve body has been estimated, and the results have been compared to the actual amount of time the mold actually filled with pouring material. The fluidity factor of grey cast iron (k) and the material's pouring temperature of 1350°C are both taken into consideration when calculating the filling time. Using the empirical formula in Equation 3, the pouring time is determined for grey cast iron masses under 450 kg as follows:

$$t = k \left(1.237 + \frac{P}{16.66} \right) \sqrt[3]{M_g} \quad (3)$$

$$t = 0.608 \left(1.236 + \frac{85}{16.65} \right) \sqrt[3]{10.614} = 8.47 \text{ sec}$$

This is the minimum pouring time necessary to guarantee that the 10.614 kg of metal completely fills the system of gates and mold cavities.

Gating Design

The parts and channels that the molten metal travels through as it enters the mold cavity are collectively referred to as the "gating system." (Nimbalkar *et al.*, 2016)

A downward-tapered sprue prevents air input during sand casting. The straight, cylindrical shape creates a low-pressure region around the metal in the sprue. The tapered shape allows molten metal to flow without agitation to the ingate and into the mold cavity through the gate. The sprue was built on



Figure 7. CAD model of sprue

the continuity of mass concept, which states that liquid mass flow velocity remains constant at any cross-section. Equation 4 calculates the sprue area using the correct diameter at the entry cross-section, 30 mm.

$$\text{Area} = \frac{\pi \times D^2}{4} \quad (4)$$

Where D= Cross-section diameter of spue at inlet

$$\text{Area of sprue at inlet} = \frac{\pi \times 30^2}{4} = 707 \text{ mm}^2$$

The sprue height in valve body casting is determined to be equal to the height of the mold, which is 50 mm. The actual diameters of the sprue used are 30 mm at the top and 25 mm at the exit, with a fillet radius of 1 mm. CAD model of sprue as illustrated in Figure 7. As a result, the entering and leaving areas of the sprue were measured and determined to be, 707 mm² and 491 mm², respectively.

Because of this, the sprue displays a frustum-like form. The frustum's formula, Equation 5, is used to calculate the amount of metal enclosed inside the sprue.

$$V_s = \frac{1}{12} \times \pi \times h (D^2 + d^2 + Dd) \quad (5)$$

Where Vs=volume of sprue, d=diameter of sprue at outlet=25 mm,

$$\begin{aligned} V_s &= \frac{1}{12} \times \pi \times 50 (30^2 + 25^2 + 30 \times 25) \\ V_s &= 29780 \text{ mm}^3 \\ V_s &= 2.978 \times 10^{-5} \text{ m}^3 \end{aligned}$$

The amount of weight of the hot metal in the sprue is calculated using Equation 6 by multiplying the volume of the sprue by the weight per unit area of the sprue substance, which is 7130 kg/m³.

$$\text{Mass of sprue} = \text{Mass density of sprue} \times \text{Volume of sprue} \quad (6)$$

$$\text{Mass of sprue} = 0.212 \text{ kg}$$

Design of hot well

Hot wells have a metal reservoir at the bottom of the sprue. This well slows the metal flow to avoid mold erosion.

Valve body casting uses grey cast iron for the hot well. This design is 134 mm. by 15 mm. by 40 mm. The hot well cavity, which conducts molten metal from the sprue exit to the entrance ingate, is designed for this.

$$\text{Volume of hot well} = 134 \times 40 \times 15 = 80400 \text{ mm}^3$$

$$\text{Mass of hot well} = \text{density of hot well} \times \text{volume of hot well}$$

$$\text{Mass of the hot well} = 0.57 \text{ kg}$$

Hence, the mass of a hot well of 0.57kg is required in the gating system design.

Design of pouring cup

Within the gating system, the sprue is a tapered, hollow vertical component. It accomplishes the task of first guiding the molten metal toward the mold cavity by feeding it via the gating system.

The conical-shaped pouring cup has an inlet diameter of 40 mm and an outlet diameter (Which is equal to the inlet diameter of the sprue) of 30 mm, with a 25 mm height.

The volume of the pouring cup can be determined by equation 6.

$$\text{The volume of the pouring cup} = \frac{1}{12} \times \pi \times 25 (40^2 + 30^2 + 40 \times 30) = 24216 \text{ mm}^3$$

Therefore, the mass of the pouring cup = density of pouring cup material × volume of the pouring cup.

$$\text{Mass of pouring cup} = 7130 \times 24216 \times 10^{-9}$$

$$\text{Mass of pouring cup} = 0.172 \text{ kg}$$

Total Ingate Area Design

To regulate the flow rate of molten grey cast iron into the mold cavity during the valve body casting process, the quantity of ingates may be changed. The design of the gating systems utilized in valve body casting follows the principles of an unpressurized gating system.

The gating ratio for the cast iron unpressurized gating system was derived from Equation 7. (Adefuye *et al.*, 2019)

$$A_s : A_r : A_g = 1 : 2 : 2 \quad (7)$$

Where A_s is the area of the sprue at the outlet, A_r is the area of the runner, and A_g is the total gate area. From Equation 7, the area of the gate:

$$A_g = 0.5 \times A_s = 491 \times 0.5 = 246 \text{ mm}^2$$

The minimum area in question represents the combined area of all the ingates that are constructed at the entrance of the valve body mold cavity.

Number of Ingate

Depending on the casting's size and complexity, the number of ingates needed to fill a cavity within a reasonable amount of time may be calculated. (Yokesh Kumar *et al.*, 2016)

Based on the geometry of the valve body, two ingates are required.

Riser design

Current Design of The Riser:

Let d = diameter of the cylindrical riser which is 10 mm. And h = height of cylindrical riser = 80mm

$$A_r = \text{Surface area of cylindrical riser} = \left(\pi d h + 2 \frac{\pi}{4} d^2 \right) = 2670.35 \text{ mm}^2$$

$$V_r = \left(\frac{\pi}{4} d^2 h \right) = 6283.18 \text{ mm}^3 \quad (8)$$

Where V_r = volume of cylindrical riser

The ration of the surface area of the cylindrical riser to its volume is

$$\frac{A_r}{V_r} = 0.4249 \text{ mm}^{-1} \quad (9)$$

Mass properties obtained from the solid-cast 3-D model are as follows:

The surface area of casting $A_c = 157184.85 \text{ mm}^2$

The volume of Casting $V_c = 1344679.31 \text{ mm}^3$

$$\frac{A_c}{V_c} = 0.166 \text{ mm}^{-1} \quad (10)$$

From (9) and (10),

$$\frac{A_r}{V_r} > \frac{A_c}{V_c} \quad (11)$$

From result (11) we can say the riser solidified first, which is undesirable for sound casting and may lead to a shrinkage defect.

Proposed Design of Cylindrical Riser:

The volumetric shrinkage of grey cast iron is 0.1%. (Rajput, 2007), So the required volume of the riser (V_r) is:

$$V_r = 3 \times \text{volumetric shrinkage of gray cast iron} \times \text{volume of casting}$$

$$V_r = 3 \times 0.1 \times 1344679.309 = 403403.8 \text{ mm}^3 \quad (12)$$

Now, the design of the riser is at a minimum ratio of surface area to volume of the riser.

$$\frac{\partial A}{\partial d} = 0$$

$$\frac{\partial}{\partial d} \left(\pi d h + 2 \frac{\pi}{4} d^2 \right) = 0 \quad (13)$$

From A, we have (h) = $\frac{4V}{\pi d^2}$ Substituting the above value of h in equation 13

$$\frac{\partial}{\partial d} \left(\pi d \frac{4V}{\pi d^2} + 2 \frac{\pi}{4} d^2 \right) = 0$$

$$\frac{\partial}{\partial d} \left(\frac{4V}{d} + 2 \frac{\pi}{4} d^2 \right) = 0$$

$$\left(-\frac{4V}{d^2} + \pi d \right) = 0$$

$$\text{Thus, } V_r = \frac{\pi}{4} d^3 \quad (14)$$

$$\text{But we have, } V_r = \frac{\pi}{4} d^2 h \quad (15)$$

From Equations 14 and 15, we have $d=h$ for a cylindrical riser. From Equations 14 and 15, we have $d= h = 73 \text{ mm}$.

So, the proposed diameter and height of the cylindrical riser are 73 mm, which satisfy the following criteria:

$$\frac{A_r}{V_r} \leq \frac{A_c}{V_c}$$

Riser Volume

By using equation 6, the riser volume was calculated as 305533.23 mm^3 . The mass of the riser can be calculated as 2.17 kg.

The additional cavity for metal shrinkage causes the riser cavity's slight overflow of molten metal. The casting yield exceeded expectations.

Process Parameter Selection

Control factors significantly affect valve bias component rejection. These standards were established and maintained via discussions with foundry managers, casters, mold manufacturers, and pattern designers. Noise includes operating environment changes. According to casting industry data, 70% of rejections occur from molding sand parameters, 20% from metal pouring parameters, and 10% from melting, pattern shops, and cores (Weldeanenia *et al.*, 2016).

Sand and metal pouring settings are studied to solve this issue. Blow holes, pin holes, etc., result from poor process parameter selection.

These elements impact solidification, which affects grey cast iron formation. Ishikawa diagrams (cause and effect diagrams) identified the most essential and quantitative traits.

To demonstrate the impact of parameters on sand casting defects in valve body production, the following parameters have been chosen: permeability (ranging from 110 to 140), pouring temperature (ranging from 1320°C to 1380°C), and moisture content (ranging from 1.5% to 2.5%). These parameters will be examined to visualize their effects on the occurrence of defects in the casting process.

Experiment Design

To build the experiment, identify factors, interactions, and levels. This study employed the Taguchi technique, which recommends two to five component levels. Three factors were studied using the L9 three-level orthogonal array. A foundry's valve body data was analyzed using Minitab 18. The process's most influential variable was identified.

Variable and level selection

This study focuses on moisture content, permeability, and pouring temperature, which may impact valve body quality. Studying each control parameter required a three-level strategy. The company's foundry's valve body manufacturing process and production crew interactions determined factor values. Table 5 shows the set parameters and their level for the experimental trial.

Experimental result and SN plot

As per the taguchi design, nine experiments were conducted. For better accuracy, each experiment was conducted three times. Comparative observations were taken for each trial, and with the

help of MINI TAB 9 software, the main effects plot for SN ratios was taken. The AOM is plotted from experimental data as per taguchi design, as shown in Figure 8.

ANOVA

Using Minitab 18 software, numerical experiments were conducted, and the results were subjected to ANOVA analysis. This approach assisted in determining the important variables and how they interacted. Graphs were generated to represent different trial conditions, and through careful examination, the factors that significantly affected.

Process Variable Selection

After performing the taguchi design of the experiment and ANOVA, the author found that permeability (no) is set at the A3 level, pouring temperature is at the B2 level, and moisture content is at the C2 level in order to minimize rejection due to sand mold-related defects the average and range of the rejection percentage were identified. The result of the analysis is shown in Table 6.

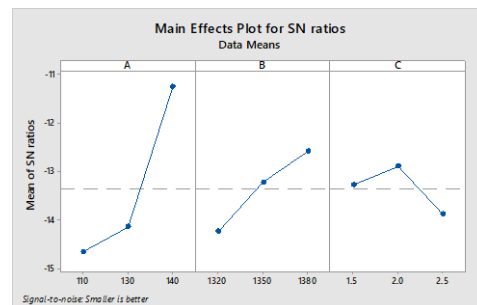


Figure 8. AOM for SN ratio

Table 5. Variables and set parameters

S. No.	Name of variable	Factor symbol	Low level I	Medium level II	High level III
1.	Permeability (no)	A	110	130	140
2.	Pouring temperature°C	B	1320	1350	1380
3.	Moisture content (%)	C	1.5	2.0	2.5

Table 6. Analysis of variance

Source	DF	Adj SS	Adj MS	F-Values	P-Value	Content
A	2	5.362	2.6811	6.93	0.028	59.58
B	2	1.182	0.5911	0.761	0.606	22.53
C	2	0.3356	0.1678	6.14	0.875	3.99
Error	2	4.3201	2.3867			
Total	2	11.1997				100

Table 7. Experimental conformation

Experiment No	Number of sample cast	Number of Rejected casting	% Rejection
1.	100	3	3
2.	100	4	4
3.	100	2	2
Total	300	9	3
Average % Rejection			3

Experimental Conformation

Based on the above-mentioned analysis, three experiments were conducted, and in each trial, 100 butterfly valve body cases were used.

The results of three experiments, along with the percentage rejection caused by sand mold, are shown in Table 7.

Simulation of casting

ProCAST is an invaluable tool used by the industry for various purposes, such as developing new casting processes, optimizing existing processes, solving problems, and designing dies. Typically, simulation software like ProCAST consists of three main components: pre-processing (during which the software reads the CAD geometry and creates the mesh), main processing (during which boundary conditions, material data, and calculations relating to filling and temperature are added), and post-processing (during which the results are presented and evaluated).

To simulate the casting process, the following steps were undertaken using ProCAST software: Firstly, a geometric model created in SolidWorks software was utilized as input for ProCAST. This 3D model was imported into ProCAST in IGES format. The model was then repaired and assembled in the visual mesh module.

If any issues were identified, modifications were made to the CAD design. Then, a 2D surface mesh was created by specifying the edge group's element size and being verified as accurate. A 3D volume mesh was also produced. Silica sand and

grey cast iron were chosen as the molding materials for the volume manager, and an alloy element with an initial operating temperature range of 30°C to 1350°C was established.

Table 8 presents the temperature ranges used for the casting process simulation. In the interface manager, the coincident option was chosen; moreover, $h=1000 \text{ W/m}^2\text{K}$ was chosen as the interface condition. With a heat-air cooling boundary condition and an intake mass flow rate of 1 kg/s, the process condition manager took into account thermal and fluid flow features. The TH-Module could be used to the simulation process parameter, which also used gravity casting and activated thermal and porosity models.

To initiate the simulation, four cores were selected, and the program generated output files made up of video and graphic picture files. After the simulation was successfully completed, these results were examined to identify any possible flaws. The valve body's mesh shape, including the gating mechanism, and change in riser location, and sprue, hot well and runner design is employed as calculated earlier in new gating design is shown in Figure 9.

Shrinkage porosity analysis

Shrinkage porosity defects manifest as voids within components, leading to potential material degradation. They may have a detrimental effect on attractiveness and corrosion resistance if they are surface-based. Shrinkage porosity arises during the solidification phase of material, commencing with the mold filling process until the complete



Figure 9. 3D mesh geometry of valve body

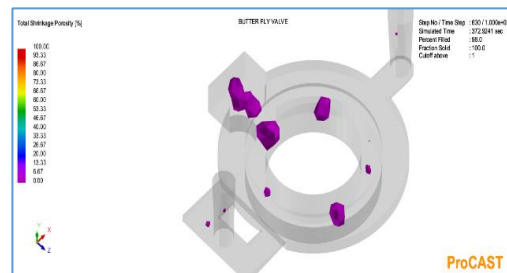


Figure 10. Total shrinkage porosity in existing casting

Table 8. Process parameter inputs for simulation

Input parameter	Value	Description
Alloy	Grey Cast iron	EN-GJL-250
Mold	Green sand	
Initial temperature of alloy	1380°C	
Initial temperature of mold	30°C	
Heat transfer coefficient between mold and alloy	1000 W/m ² /K	
Pouring temperature	1350°C	
Boundary condition for mold	Air cooling	
Mass flow rate	1 Kg/S	

solidification of all material parts. The root cause of this porosity is the contraction of the material during the solidification process. The following Figure 10 shows shrinkage porosity in the existing mold design of butterfly valve body casting.

Niyama Criterion

As shown in Figure 11, it is clear that the value of Niyama at the thickest section of casting is 7, which is less than the critical value of Niyama of 45 for cast iron. (Ignaszak, 2017) Therefore, there are the strongest possibilities of shrinkage at the thickest section of valve body casting.

Experimental Validation

According to Figure 12, demonstrates that the findings of the experiment about the gating design of the existing mold match with the findings of the simulation regarding shrinkage flaws. These findings were discovered as a consequence of the experiment.

The shrinkage issue in the product contributes to the relatively high rejection rate of the unit, which is about 26%.

Proposed Gating Design

In this paper, proposed gating designs based on sprue design, pouring basin design, hot well design, and riser design as calculated riser design were implemented. Furthermore, the location of the riser is changed.

The following Figure 13 shows a 3D mesh model of the proposed gating design.

Simulation Result of Proposed Gating Design

Shrinkage Porosity Analysis

The following Figure 14 shows the total shrinkage for the proposed gating design of butterfly valve body casting.

As per Figure 14, there is no shrinkage porosity found in across casting, but shrinkage is found at the runner and riser inlets, which is acceptable.

Niyam Criterion

As depicted in Figure 15 the entire region of casting is above the critical value of Niyama 45, so therefore there are no strong chances of a shrinkage defect present in the casting.

Experimental Validation

As per the proposed gating design trial taken for 500 pieces of valve body casting, only 10 pieces were rejected due to a shrinkage defect. Hence rejection due to shrinkage defect reduced from 26% to 2%, and productivity and quality of casting improved.

Figure 16 shows experimental validation of the proposed gating design.

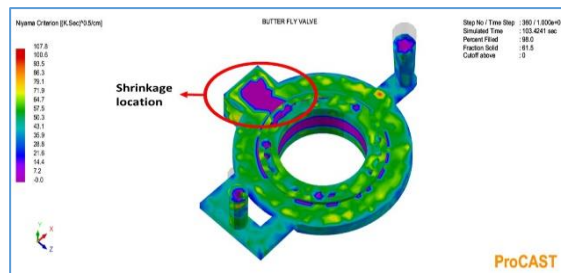


Figure 11. Shrinkage location as per Niyama Criterion



Figure 12. Experimental validation

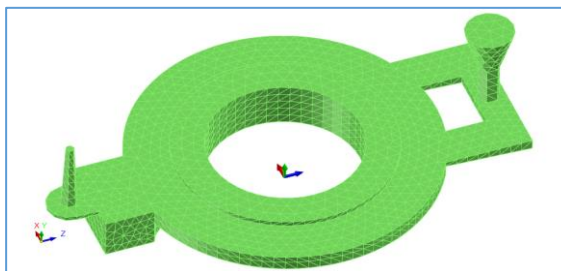


Figure 13. 3D meshed model of proposed gating design

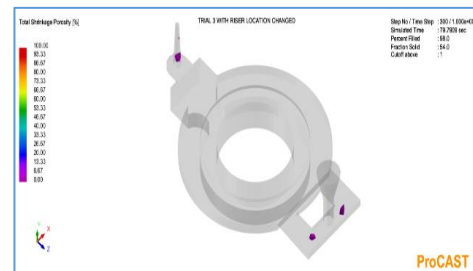


Figure 14. Total shrinkage porosity in the proposed gating design

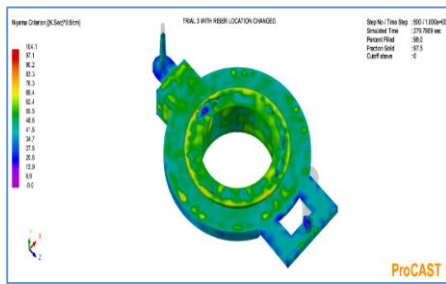


Figure 15. Niyama criterion for proposed gating design



Figure 16. Valve body casting after new gating design



Figure 17. Ultrasonic testing of valve body casting



Figure 18. Shrinkage before in the old gating design and after in the new gating design

Non-Destructive Testing of Proposed Casting

Castings are evaluated using non-destructive testing techniques such as ultrasonic testing, magnetic particle testing, and penetrant testing. (Gao *et al.*, 2019). The EPOCH 6LT digital ultrasonic flaw detector is used to conduct ultrasonic testing on cast valve pieces with a higher incidence of casting flaws. A longitudinal wave dual crystal probe with a frequency of 4.0 Hz is employed for the testing, and the ASTM A609 standard is used for flaw detection.

The standard quadrilateral cast steel joint is subjected to ultrasonic non-destructive testing in order to get interior fault pictures. Based on waveform analysis, attempts are made to identify the problem type. The findings reveal significant defects in the valve body, particularly a sizable shrinkage defect near the riser inlet, which is acceptable. The following Figure 17 shows ultrasonic testing of the valve body casting.

Results and Discussion

The case study involved examining a valve body product made of grey cast iron with dimensions of 280 mm. × 140 mm. × 45 mm. for its external diameter, internal diameter, and height. The analysis focused on specific model elements within the valve body. The casting process is constructed using SolidWorks software, incorporating all the relevant elements and their corresponding positions within the

mold. The obtained numerical, experimental, and simulation results have been thoroughly analyzed and compared to existing literature, taking into account the available data and actual occurrences.

Clay Content

Based on the experimental results in Table 4, the molding sand used has a determined clay content of 6.88%. A comparison with the standard clay content range of 5-10% for “grade A” foundry molding sands was made. The literature suggests that this sand type exhibits a high sintering temperature resistance of 1350-1450°C, surpassing the pouring temperature of the liquid metal (1350°C). To further enhance resistance, additional materials like dolomite powder and zirconium are added to the sand mixture. These materials effectively reduce heat transfer, preventing sintering issues with the green mold sand. Consequently, this sand, with its clay content, does not cause mud-related problems in the mold, making it suitable for use with older sand.

Gating System

The size of the gating system components in the valve body casting has been established using the unpressurized gating ratio rule for grey cast iron castings. The sprue area, runner area, and total ingate area are the main subjects of the selected gating area ratio. the chosen ratio of “1:2:2” to prevent shrinking during volumetric solidification.

Table 9. Experimental conformation

Experiment No	Number of sample cast	Number of Rejected casting	% Rejection
1	200	6	3
2	200	4	2
3	200	2	1
4	200	4	2
Total	800	16	2
Average % Rejection			2

Signal-To-Noise Analysis

The primary focus of this research is on the valve body defect resulting from sand casting. Minitab-18 software was utilized to analyze the impact of process parameters on the occurrence of casting defects in the valve body. The mean values and signal-to-noise ratio (S/N ratio) were calculated for each control factor to evaluate their influence, as presented in Table 5. The criterion “smaller is better” was adopted to select the S/N ratio.

The primary impact charts for the S/N ratio of casting flaws in valve bodies are shown in Figure 12. Based on the data in the table and figure, it can be said that the moisture content has a comparatively lower influence than the permeability of the sand mold on decreasing the percentage of casting faults. According to the major effects plot for both mean values and S/N ratios, the lowest frequency of valve body problems is found at the third level of permeability (140), the second level of pouring temperature (1350°C), and the second level of moisture content (2.0%).

ANOVA result

In process analysis, the analysis of variance (ANOVA) approach is often used to calculate the percentage contribution of each parameter

Table 6 presents the results obtained through the analysis of variance for the signal-to-noise (S/N) ratios related to valve body casting defects. According to this investigation, the analysis of variance results indicates that permeability contributes the most to the casting defects, accounting for approximately 59.58%. Poring temperature contributes 22.53%, followed by moisture content with a contribution of 3.99%, as indicated by both the mean values and S/N ratios.

Experimental validation

The goal of the confirmation experiment is to identify the values of certain control parameters that provide findings that are superior to those from the standard experiment. The foundry shop performed a total of four confirmation trials, with the process parameters adjusted to their ideal values as described in the ANOVA result. In these tests, it was discovered that the typical valve body casting fault rate was 3%. The usual approach, on the otherhand,

produced a fault rate of 10%. Thus, it may be inferred that the values of the parameters that were chosen and their significance in reaching the intended result

As demonstrated in Figure 18(a), in the case of the old gating design, rejection due to the shrinkage was 26%; however, as shown in Figure 18(b), by this research, rejection due to the shrinkage in the case of the new gating design was decreased to 2%.

Based on the new gating design, four experiments were conducted; in each trial, 200 butterfly valve bodies were cast.

The results of four experiments, along with the percentage rejection caused by a shrinkage defect, are shown in Table 9.

Conclusions

The successful application of statistical techniques in reducing sandcast valve body defects has been demonstrated. It is evident from Section 4.3 that nearly all the parameters have an impact on both the mean and variance of casting defects. Drawing upon the analysis conducted through experiments and simulations, the following conclusion can be drawn:

I. The utilization of Taguchi’s method in the sand-casting process for valve bodies has resulted in the following benefits:

- Enhanced productivity of the valve body.
- Increased stability of the casting process for the valve body.

II. The defect due to sand mold-related problems decreased from 10% to 2%, furthermore shrinkage defect decreased from 26% to 2%.

III. Through the design of the experiment, the optimal factors and corresponding levels for the sand casting of the valve body have been determined. These optimal factors and levels are as follows:

- Permeability: 140 (no)
- Pouring temperature: 1350°C
- Moisture content: 2.0%

IV. The numerical calculations have revealed that the occurrence of misrun and volumetric solidification shrinkage defects in the valve body

castings can be attributed to improper utilization of the gating system element patterns.

V. By utilizing casting simulations, it is possible to assess the impact of various casting parameters, including total solidification time, fill time, and mold configuration, on the production of defect-free castings. Accurately predicting these defects during the design stage can significantly contribute to the production of sound castings and help minimize casting defects in valve bodies.

VI. To sum up, simulations are an excellent tool for visualizing the filling and solidification processes without wasting time, effort, labor, or money. The simulations' findings showed that porosity and volumetric solidification shrinkage flaws might be minimized in the casting of the valve body.

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