Defect Analysis and Process Improvement in Sand Casting

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ABSTRACT

A common process used to create metal, sand casting is known for producing intricate shapes with both ferrous and non-ferrous alloys, having low tooling expenses, and being flexible in design. However, regardless of its wide application, the process is susceptible to a series of casting defects that undermine the final product's mechanical properties, surface finish, and accuracy in terms of dimensions. These defects, such as inclusions of sand, cold shuts, blowholes, and shrinkage cavities, are most often due to variations in process parameters, improper mold design, or insufficient control over material characteristics.

The different types, reasons, and prevention of defects encountered in a green sand casting setup are systematically discussed in this research. To find out the most important factors for causing defects, data on defects was collected through three months of production and analyzed using quality control techniques such as Pareto charts, Fishbone (Ishikawa) diagrams, and process flow mapping. Poor operator procedures, poor gating and riser design, high moisture content of molding sand, and improper pouring temperature are the primary culprits identified. Therefore, following the investigation, remedial actions were implemented, including standardization of pouring procedures, training shop floor personnel, redesigning gating and riser system by means of casting simulation software, and improving the composition and moisture control of the sand. These improvements resulted in a significant reduction in the overall defect rate, which was reduced by as much as 46%. Besides demonstrating the worth of defect analysis in enhancing product quality, the study indicates how effective an integrated approach incorporating statistical tools, process simulations, and actual shop floor interventions can prove.For foundries interested in improving casting quality through a problem-solving system and continuous process improvement methods, this research provides as a reference model.

1. INTRODUCTION

One of the oldest and most versatile metal casting methods is sand casting, often called green sand casting. It is used extensively in the manufacturing industry to create detailed metal components with minimal material loss and relatively low-cost tooling expenses. To make a part, molten metal is poured into an excavation in a sand mold and let solidify. For components such as engine blocks, pump housings, and gearboxes, this process is particularly popular among the heavy industrial, automotive, and aerospace sectors [1].

Sand casting has numerous advantages, but owing to the complex interactions among the mold material, metal flow, and solidification heat gradients, it is highly susceptible to a variety of defects.Some of the widespread casting defects include blowholes, shrinkage porosity, sand inclusion, cold shuts, and misruns. These defects have the potential to increase rework, scrap rates, and manufacturing expense by degrading the ultimate product's mechanical integrity, dimensional tolerances, and surface finish [2], [3].

Some studies identified inconsistent mold appearance, poor gating and riser design, inadequate process control, and unsuitable pouring temperature as common causes of casting defects [4], [5]. As an illustration, excess moisture in green sand can form steam and seal it during pouring, which may lead to the development of blowholes [6]. Similarly, limited riser size or location results in an insufficient feeding rate during metal solidification, thus causing shrinkage porosity [7].Hence, enhancing the overall yield and quality in sand casting processes necessitates successful defect analysis and control.To detect surface and subsurface defects, conventional quality control techniques such as visual inspection and non-destructive testing are commonly applied. However, these approaches do not check the root causes of defect generation and are often reactive in nature [8].To effectively detect, quantify, and eliminate process inefficiencies ahead of time, current techniques involve integrating statistical quality tools such as Pareto analysis, Fishbone (Ishikawa) diagrams, and Design of Experiments (DOE) with modern simulation techniques [9]. To detect defect-prone areas prior to production and enhance gating systems, computer-aided simulation software such as MAGMASOFT® and ProCAST is increasingly being utilized [10].Exploring the root causes of casting defects in an industrial green sand casting environment and proposing viable, cost-effective solutions to reduce defect occurrences are the primary objectives of this research. To develop an improvement framework that can be sustained in the long term, the research integrates simulation-based optimization, process standardization, and quality control technologies. To demonstrate the implementation and effectiveness of these interventions in a real-world manufacturing environment, a comprehensive case study is presented. The productivity, reliability, and competitiveness of small- and medium-sized foundries with budgetary constraints and quality compliance needs are enhanced by the systematic and data-driven approach of this research.

2. LITERATURE REVIEW

Although sand casting is extensively practiced and cost-effective, it is prone to various quality issues induced by inhomogeneous materials, human factors, and poor process control. Typical defects in castings have been grouped by researchers into three categories: dimensional defects (e.g., warpage, mismatches), internal defects (e.g., shrinkage porosity, gas porosity), and surface defects (e.g., blowholes, sand inclusions) [1]. Typically, poor mold design, lower-quality sand composition, inadequate venting, or uneven pouring methods are the root causes of these defects. Desai and Patel [2] report that optimization of process factors such as moisture control, permeability, and pouring temperature would prevent over 70% of casting defects encountered by industry foundries.

Today's foundries rely increasingly on quality control technologies to identify and eliminate these root causes. Kumar et al. [3] were able to reduce shrinkage-related defects by 35% in a ferrous foundry by applying the Six Sigma DMAIC (Define-Measure-Analyze-Improve-Control) methodology. Their study demonstrated the effectiveness of statistical methods, including cause-effect diagrams and control charts, in identifying significant contributing factors and instituting lasting improvements.

Moreover, simulation-based methods have proven effective in predicting and minimizing defects at the initial stages of casting design. To reduce internal shrinkage and misruns, Ravi and Srinivasan [4] optimized the gating and riser systems through casting simulation software. Simulation allows foundries to foresee problem areas by seeing the metal flow and solidification patterns. Several researchers have applied Taguchi-based experimental design as well. For instance, Nian et al. [5] optimized sand casting conditions, i.e., mold hardness, grain fineness number (GFN), and pouring rate, through the Taguchi method, resulting in a reduction in cold shuts and inclusions. The role of moisture in green sand and its relation to the formation of blowholes was thoroughly studied in another publication by Vasudeva and Dhakad [6], which concluded that moisture content greater than 6% greatly degrades the quality of casting. In addition, Rodrigues et al. [7] implemented countermeasures that reduced rejection rates by 40% after using FMEA and cause-effect matrices to systematically prioritize the variables that induce defects in aluminum castings.Scientists have also emphasized the value of standard operating procedures and operator training as a frequently neglected element of process control. Jain and Mehta [8] had advocated the use of comprehensive operator certification and inspection protocols, and highlighted that despite the use of advanced simulation tools, human action in ramming and pouring often leads to avoidable defects. It is therefore clear from the literature that the foundation for effective defect reduction in sand casting processes lies in the integration of statistical analysis, simulation, material control, and employee training. To reduce defect levels and increase casting reliability in a green sand foundry environment, this study builds on these conclusions and proposes a holistic strategy that integrates process improvement with practical shop-floor interventions.

3. METHODOLOGY

To identify and reduce casting defects in a green sand casting operation, this research employs a systematic, data-intensive technique. Data collection, fault categorization, cause identification, corrective action implementation, and post-intervention assessment are the five key phases of the method. The research was conducted within a medium-scale foundry producing grey cast iron components such as valve bodies and bearing housings.

In the initial stage, there were three months of incessant manufacturing line defect data gathering. A total of 500 cast parts were visually inspected and examined with the help of non-destructive testing (NDT) methods, including radiographic inspection and dye penetrant testing. Defects were observed, inspected, and grouped into typical categories, including blowholes, sand inclusion, cold shuts, shrinkage porosity, and misruns.

Each part had its position, type, and number/percentage of defects documented and stored in a defect data base.The most frequent and significant flaws were prioritized with a Pareto analysis once the data had been gathered.
These, the investigation revealed, generated more than 60% of the total defects due to blowholes (26%), shrinkage porosity (18%), and cold closes (15%). A Fishbone (Ishikawa) diagram was subsequently employed in analyzing the causes to identify the likely root causes of such high-priority defects. Five categories were employed to categorize significant contributing factors: Material (e.g., moisture content and sand quality), Method (e.g., pouring temperature and gating design), Machine (e.g., furnace stability and molding machine condition), Manpower (e.g., operator skill level), and Environment (e.g., humidity and ventilation).Key process variables were monitored and recorded in order to investigate these factors more intensively. The lab tested sand samples to establish its moisture content, clay content, permeability, green strength in compression, and grain fineness number (GFN). Thermocouples were employed to check the pouring temperature at intervals, and the riser dimensions were checked to confirm they met acceptable feeding distance ratios. Gating and riser systems were simulated virtually using simulation software (MAGMASOFT®) to help identify areas susceptible to shrinkage and turbulence. A set of corrective actions were developed and implemented on the work floor after analyzing the problem.These comprised the uniforming of the pouring temperature of metal to 1350 ± 20 °C, modification of riser sizes and locations, enhancing venting within mold cavities, and controlling the moisture content of molding sand within the optimal range of 3.5%–4.0%. To ensure strict adherence to revised standard operating procedures (SOPs), training sessions for operators were also conducted. Lastly, to test the effectiveness of the improvements, a post-intervention test was conducted after one manufacturing run (approximately two weeks).To quantify the decline, defect levels were again recorded and compared against pre-intervention data.The total fault frequency reduced by nearly 46%, reflecting significantly better casting quality.By integrating shop floor observation with laboratory testing and simulation analysis, this systematic approach ensured guaranteed that fault diagnosis extended beyond the symptoms to the root causes using both empirical and analytical approaches.

Table 1: Key Process Steps and Tools Used

Phase	Description	Tools/Techniques Used
1. Data Collection	500 components analyzed over 3 months using visual & NDT inspection	Dye penetrant test, Radiography, Inspection checklist
2. Defect Categorization	Grouping into blowholes, shrinkage, inclusions, cold shuts, misruns	Defect log sheet, IS standard coding
3. Prioritization	Identification of most frequent & critical defects	Pareto Chart (80/20 Principle)
4. Root Cause Analysis	Investigation of defect causes under main process categories	Fishbone (Ishikawa) Diagram
5. Process Variable Monitoring	Testing of sand properties, pouring conditions, riser geometry	Moisture meter, Thermocouple, Sand testing (AFS methods)
6. Simulation and Design Review	Virtual analysis of gating & riser system	MAGMASOFT®/AutoCAST® simulation software
7. Corrective Actions	Moisture control, gating redesign, temperature regulation	Venting adjustment, SOP implementation
8. Training & SOPs	Educating workforce on standard practices	Visual work aids, On-floor demo sessions
9. Post-Intervention Evaluation	Re-analysis of defect rates after improvements	Statistical comparison, Re-inspection

Table 2: Summary Table of Sand Test Results (Before vs. After)

Parameter	Before Improvement	After Improvement	Optimal Range
Moisture Content (%)	5.5–6.2	3.5–4.0	3.2–4.5
Green Compressive Strength (g/cm²)	90–100	120–130	110–130
Permeability (AFS units)	70–75	85–90	80–100
Grain Fineness Number	70	85	70–90

4. RESULTS AND DISCUSSION

The performance of sand-cast parts was significantly enhanced by the use of a systematic defect analysis and process improvement strategy. A detailed inspection of 500 grey cast iron parts before intervention yielded high defect rates, which were blowholes (26%), cold shuts (15%), sand inclusions (12%), shrinkage porosity (18%), and a miscellaneous category that included rough surfaces, fusion defects, and misruns (29%). All of these shortcomings together reduced yield and require high rates of rejection or rework. Subsequent production of 500 parts was evaluated following corrective measures, which involved regulation of the sand's moisture content, the designs of the risers and gating optimized using MAGMASOFT® simulation, improvement of venting in the mold, and standardization of pouring temperature.Defect frequencies in all the main categories were drastically reduced following improvement. Blowholes fell from 26% to 14%, the primary reasons being excessive moisture content and poor mold ventilation. Due to enhanced feeding through changed risers and directional solidification research, shrinkage porosity defects fell from 18% to 10%. Reconfigured gating design and uniform pouring velocity reduced cold shuts significantly, which are attributed to poor metal flow and turbulence. In the same way, by improving mold surface smoothness and increasing sand permeability through correct control of clay-water ratio, sand inclusions were minimized. The overall defect rate decreased by approximately 46%, which enhanced the quality index and reduced rework hours and material loss.

These improvements validate the effectiveness of controlled shop-floor processes and simulation-driven design changes. Also, process reliability maintenance was facilitated by operator training and compliance with updated Standard Operating Procedures (SOPs). The following table shows the improving trends:

Table 3: Comparative Defect Analysis Before and After Improvement

Defect Type	Pre-Improvement (%)	Post-Improvement (%)	Percentage Reduction (%)
Blowholes	26	14	46.15
Shrinkage Porosity	18	10	44.44
Cold Shuts	15	7	53.33
Sand Inclusions	12	6	50.00
Misruns & Others	29	17	41.38
Total Defects	**100**	**54**	**46.00**

Table 4: Sand Property Comparison (Before vs. After Improvements)

Sand Property	Pre-Improvement	Post-Improvement	Standard Range	Remarks
Moisture Content (%)	5.5 – 6.2	3.5 – 4.0	3.0 – 4.5	Reduced blowholes
Green Compressive Strength (g/cm²)	90 – 100	120 – 130	110 – 140	Improved mold strength
Permeability (AFS Units)	70 – 75	85 – 90	80 – 100	Enhanced gas escape
Clay Content (%)	12 – 13	8 – 9	7 – 10	Controlled bonding and flowability
GFN (Grain Fineness Number)	65 – 75	85 – 90	70 – 95	Better surface finish

Table 5: Key Process Parameters Before and After Correction

Parameter	Pre-Improvement	Post-Improvement	Target/Recommended Value	Impact on Casting
Pouring Temperature (°C)	1430 – 1460	1380 – 1400	1380 – 1420	Reduced cold shuts & misruns
Pouring Time (sec)	18 – 22	12 – 15	10 – 15	Improved metal flow & fill
Riser Design	Cylindrical, static	Optimized (Tapered)	Simulation-based	Better feeding, reduced shrinkage
Gating Ratio	1:4:4	1:2:2 (pressurized)	1:2:2 or 1:3:3	Reduced turbulence & cold shuts
Venting Channels	Inadequate	Redesigned & added	As per cavity size	Reduced gas defects

Table 6: Casting Performance Indicators

Metric	Pre-Improvement	Post-Improvement	Change (%)	Interpretation
Total Components Produced	500	500	-	Batch size remains constant
Defective Components	147	72	↓ 51.02%	Significant quality improvement
Casting Yield (%)	68.4	85.6	↑ 25.00%	Higher productivity and material utilization
Rework Hours (Total)	126 hrs	58 hrs	↓ 53.97%	Labor and machine time savings
Scrap/Rejection Rate (%)	8.2	3.6	↓ 56.10%	Cost-effective production

5. CONCLUSION

The quality and productivity of sand casting operations can be significantly enhanced by bridging data-driven process modifications with systematic fault finding, as this research effectively demonstrated. Focused corrective actions were implemented in mold preparation, gating system design, riser set-up, and pouring methods once fishbone analysis and process audits to identify the root causes of casting defects like blowholes, shrinkage porosity, cold shuts, and sand inclusions were employed.

To guarantee directional solidification and reduced turbulence, simulation tools such as MAGMASOFT® played a key role in the refinement of the riser and gating design. Moreover, adjustments in moisture content, permeability, and green strength of the sand directly contributed to the reduction of mechanical and gas-related defects.

When pre- and post-improvement information was contrasted, the overall defect rate fell by 46%, the casting yield improved by 25%, and rework time and scrap were decreased by over 50%. These results prove how effectively traditional foundry practices can be integrated with modern diagnostic and optimization techniques. The approach facilitates enhanced cost-effectiveness and customer satisfaction along with enhanced product quality and reduced operational waste. To further automate quality monitoring and enhance decision-making in foundry operations, future studies can focus on real-time defect prediction based on machine learning models.

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