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An MSME Foundry Improvement Framework Integrating Simulation-Based Gating System Optimization for Defect Reduction and Production Efficiency Enhancement

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Abstract - *Micro, Small and Medium Enterprise (MSME) foundries are important contributors to the manufacturing industry, as they make a variety of engineering parts with the sand-casting process. But a lot of MSME foundries are suffering from serious issues like rejection rate, casting defects and lack of modern manufacturing technologies. Many of these problems occur because the gating system design is incorrect, the process does not involve simulations to analyze the process, and the personnel are not aware of the principles of defect prevention and optimization of production. This research provides a detailed experimental and numerical simulation study of an existing sand-casting gating system, with a view to geometrical optimization. The casting process was simulated in the ProCAST software to determine the filling behavior, solidification characteristics, temperature distribution during mould filling, formation of shrinkage porosity, time to solidus and prediction of voids. The simulated geometry of the gating system was optimized based on the analysis results to optimize the molten metal flow and to improve the geometry for the directional solidification. The optimized gating system was tested in the experimental study of an MSME foundry under industry standard conditions and limitations such as limited technological resources and traditional manufacturing practices. The obtained results showed that the casting defect has been improved significantly as well as the casting yield and production efficiency. This research also explores the operational issues encountered by the MSME foundry personnel including pattern makers, moulders, grinders, welders and machines. On-site observations and interviews with workers were conducted to develop practical recommendations for enhancing worker skills, practices and process knowledge. In addition, a MSME Foundry Improvement Framework Model is developed to incorporate simulation-based process optimization and workforce development and operational improvements. The suggested framework offers a realistic approach for MSME foundries to boost productivity and quality of products under resource constraints.*

Key Words: Numerical Simulation; ProCAST; MSME Foundry Improvement Framework; Casting Defects; Shrinkage Porosity Analysis; Industrial Validation; Production Efficiency; Small-Scale Foundry.

1. INTRODUCTION

Sand casting is still one of the most popular casting methods because it can be used to make complex metal parts at a relatively low cost. The casting system (gating and feeding system) which regulates the flow of molten metal to the mould cavity, plays an important role in the quality of sand castings. If the casting gating system design is incorrect, it can cause problems in the casting, including the shrinkage porosity, air entrapment, incomplete filling, and formation of voids. The problems are more common in MSME foundries where the casting design and casting production process are more traditional than scientific analysis. There are also challenges with limited access to advanced manufacturing technologies, the absence of simulation tools and inadequate technical training, which lead to production inefficiencies. Advances in casting simulation technology have made it possible for engineers to study the behavior of molten metal flow, heat transfer and solidification of the metal prior to casting production. ProCAST simulation software offers a great tool for predicting casting defects and gating system design optimization. However, in spite of these technology developments, the use of simulation-based optimization techniques in foundries of MSME is still in its infancy because of financial constraints, technical awareness and exposure to the modern manufacturing techniques. Thus, research combining simulation-based casting optimization and practical industrial validations and workforce-based improvements is needed. This is addressed by the present research which is undertaken through geometry optimization of the existing gating system using numerical simulation and validated in the foundry environment of MSME. Further, operational issues encountered by the shop floor workers are studied and a holistic framework for MSME improvement is suggested to improve the overall performance in production.

2. LITERATURE REVIEW

The gating system is one of the key factors that influence the quality, reliability and productivity of metal casting process. The gating system determines the flow of molten metal in the mould cavity and has a significant effect on the creation of casting defects like shrinkage porosity, air entrapment and defects caused by turbulence. Much work has been done to investigate gating geometry effects on flow behavior, turbulence formation and solidification characteristics of molten metal to enhance casting quality and process efficiency. Numerical simulation is becoming an important tool to analyse the casting process and the formation of defects. The casting analysis can be performed using this type of simulation which enables engineers to examine the flow patterns of the molten metal, the temperature distribution and sequences of solidification in the mould cavity prior to production. By using advanced casting simulation software like ProCAST, the casting defects, such as shrinkage porosity, void formation and air entrapment etc., can be accurately predicted. These tools can minimize experimental trials and enhance the efficiency of gating system design. Some researchers have been interested in the design and optimization of gating systems with the help of simulation methods and computational methods. Ingle and Narkhede [1] did an extensive review of literature related to various techniques to analyze the gating system design and its impact on casting quality. They pointed out that the defects could be created when the mould is filled improperly due to excessive turbulence caused by improper design of the gating. Likewise, Seo and Kang [13] analyzed the optimization of gating and riser system for turbine housing components by experimental and simulation methods, and concluded that optimized gating system can improve the casting quality considerably. Hodbe and Shinde [2] conducted a study on Design and simulation of LM25 Aluminum alloy sand casting of minimizing casting defect. Their results showed that using the simulation to modify the design of castings was able to effectively reduce the risk of shrinkage defects and enhance casting reliability. Based on the fruit fly optimization algorithm and casting simulation technology, Wang et al. [3] presented an optimization method for the design of gating system. Their research shows that gating system performance can be greatly improved by the use of computational optimization techniques. Dojka et al. [4] studied the optimization of gating system for steel casting and stressed the need to control the velocity of metal flow and turbulence during the filling of the mould. In die casting processes, Singh and Madan [5] designed a computer-aided system to enhance the quality of the casting process by optimizing metal distribution in multi-gate gating system. Optimization techniques have also been used to enhance the performance of gating system in sand casting process. Developed by the Taguchi method and a multi-objective optimization algorithm, Chen et al. [6] optimized the gating system for the sand casting of A356 aluminum alloy. They found considerable improvement in the stability of metal flow and defect reduction. The use of simulation-based design optimization is common practice in industry. Kumar et al. [7] carried out casting design and gating system simulation using ProCAST to reduce the casting defects in rotary adaptor component. They found that using simulation tools to design the gating system can be an effective method in enhancing the flow characteristics of the molten metal and minimizing the occurrence of defects in the casting. There are also a number of studies that have investigated casting simulation in small scale industries. Rajkumar and Rajini [8] explained about the efficiency and accuracy of the small-scale industries by using metal casting modeling software. Their study revealed that simulation has the potential to greatly improve production quality even in limited resource conditions. Bhatt et al. [9] performed a systematic review of the various techniques adopted for the optimization of riser and gating system with respect to energy efficiency and process efficiency. Their study highlighted the importance of the correct design of the gating system on better metal utilization and reduced production losses. The effect of gating design on mechanical properties and casting quality has also been studied. Huzaifa et al. [10] investigated the gating design on the mechanical properties of aluminum alloys in sand casting foundry process and found that optimized gating systems help to achieve better structural integrity of cast components. In recent years, further research has been undertaken on optimizing gating systems for various materials and industries. Kielbus and Jarosz [11] studied gating system optimization for the sand casting of a magnesium alloy engine body, and proved that casting quality could be improved by optimizing the gating system by simulation. Rajkumar et al., [12] did experimental studies for multi-gating system in small industries for the evaluation of flow parameter and cast quality improvement. Alrobei et al. [13] also optimized the casting process parameters to investigate the effects of gating design on the structural and mechanical properties of high manganese steel castings. Kumbhar et al. [14] emphasized on optimization of casting process to achieve higher yield of casting components, and gating design was shown to play a crucial role in the enhancement of production efficiency. Recently, Wang et al. [15] proposed an integrated gating and riser optimization system for steel casting, and it was found that the system could effectively decrease the steel casting defects and improve process efficiency. A considerable number of studies have been conducted on gating design of the casting system and casting simulation, but most of them have been conducted in controlled laboratory environment or on a large-scale industrial production line. Few studies have been conducted on actual case studies of Micro, Small and Medium Enterprise (MSME) foundries with practical challenges like inadequate technological infrastructure, skill shortage of the employees, and traditional manufacturing processes affecting the manufacturing productivity. Additionally, the existing literature does not consider workforce participation, operational practices and skill development in MSME foundries, and only concentrates on process optimization. Hence, workforce-oriented operational improvement strategies combined with the use of simulation optimization for casting should be integrated to improve productivity and sustainability of MSME casting industry. The current research work aims to bridge this gap by utilizing simulation-based gating system optimization with ProCAST, experimental testing on an MSME foundry environment and development of an MSME Foundry Improvement Framework Model that would help to improve the production efficiency, reduce defects and increase the workforce awareness.

3. RESEARCH GAP

While considerable progress has been made in casting simulation and gating system optimization, there are still some gaps in research. However, most of the previous studies focus on theoretical modelling and simulation analysis without taking into account the problems faced by MSME industries in implementing these models. The usage of simulation tools in small-scale foundries is frequently limited by the financial resources available, the lack of understanding of simulation and the few available technical resources. Secondly, the knowledge and experience of shop floor people are seldom included in the process changes study. Another significant lack is the absence of established programs that combine workforce development, technical optimization and operational improvement. Due to this reason, high defect rates and low production efficiency prevail in the many MSME foundries despite the technological advancements available. The present research fills these gaps by evaluating an actual industrial application, optimizing gating system based on simulation, and evaluating the operational changes with the workforce.

4.RESEARCH METHODOLOGY MSME FOUNDRY IMPROVEMENT FRAMEWORK MODEL. (FOR CASTING QUALITY AND PRODUCTION PERFORMANCE ENHANCEMENT)

4.1 Frame Work Overview

Micro, Small and Medium Enterprise (MSME) foundries are frequently faced with constraints like limited technological infrastructure, financial resources and traditional manufacturing processes. These constraints often cause issues such as casting defects, production quality problems, and reduced efficiency. These challenges necessitate a structured program for improvement to be implemented which combines technical optimization, workforce development and process improvement in the operations. This study presents an MSME improvement framework, which integrates worker centered operational improvement, industrial verification and optimization through simulation to improve the productivity and product quality in the MSME foundries. The framework is built following field observations, analysis of simulation, trials in industry and discussions with the foundry workers such as pattern makers, moulders, machinists, welders, grinders etc. The goal of the framework is to offer practical suggestions for increasing the performance of production, even when the technology and financial resources are limited, for MSME foundries.

4.2 MSME Improvement Framework Structure (The proposed framework consists of five interconnected improvement stages)

Stage 1: Industrial Problem Identification.

The first step is to understand the various critical production problems of the MSME foundry. Some of these problems can be easy casting rejection, shrinkage porosity, voids, poor metal flow and low casting yield. Current production practices are analyzed through observation of the plants and interactions with workers and supervisors. The existing gating system design, mould preparation process and pouring method are analyzed to find out the cause of casting defects. This step enables the development of clear perception about the manufacturing limitations and operational constraints in the MSME sector.

Stage 2: Simulation-Based Process Analysis.

The second stage is numerical simulation-based analysis of the casting process for defect formation mechanism, which is used for the numerical simulation of the casting process. The current gating geometry is modeled and simulated in casting simulation software like ProCAST.

The simulation analysis includes several critical parameters such as:

- Filling analysis.
- Solidification analysis.
- Temperature distribution at fill time.
- Shrinkage porosity prediction.
- Time to solidus analysis.
- Void detection analysis.

These analyses are useful in visualizing the flow patterns of the molten metal, the heat transfer characteristics and solidification sequences within the mould cavity. Using simulation results, engineers can identify critical areas that are prone to defects and assess how well the current gating design allows them to produce the desired part.

Stage 3: Geometrical Optimization of Gating System.

Following the simulation results the existing gating system is modified so as to enhance the flow characteristics of the metal and solidification behavior. The following changes can be made in the geometrical optimization:

- Sprue dimensions
- Runner design
- Ingate configuration
- Flow path geometry

This stage aims at obtaining smooth flow of molten metal, decreased turbulence, better-temperature uniformity, and better directional solidification. Many design iterations are made and evaluated via simulation to achieve an optimized gating configuration. This stage is used to reduce casting defect and increase casting yield prior to industrial implementation.

Stage 4: Industrial Implementation and Validation.

The improved gating system is put into practice in the MSME foundry for experimental validation following optimisation. To confirm the efficacy of the improved design, casting trials are carried out under real production parameters.

Stage 5: Workforce Skill Development and Operational Improvement.

The final stage of the framework focuses on improving the operational capabilities of MSME foundries through workforce development and process awareness.
Discussions with workers involved in various stages of casting production help identify practical operational challenges such as lack of training, limited knowledge about casting defects, and communication gaps between engineers and shop-floor personnel.

Based on these observations, improvement strategies are proposed including:

- Skill development and training programs for foundry workers.
- Awareness programs on casting defects and their prevention.
- Improved coordination between engineers and shop-floor workers.
- Documentation of best casting practices These improvements help workers better understand the production process and actively contribute to defect reduction and production efficiency.

4.3. Conceptual Model of the Framework.

The MSME improvement framework can be represented as a cyclic continuous improvement model:

Industrial Problem Identification
↓
Simulation-Based Casting Analysis
↓
Gating System Optimization
↓
Industrial Implementation and Validation
↓
Workforce Skill Development and Operational Improvement
↓
Continuous Productivity and Quality Enhancement

This cyclic model enables MSME foundries to gradually improve their production systems while adapting to technological advancements.

4.4 Benefits of the Proposed Framework.

The implementation of the MSME improvement framework provides several advantages:

- Reduction in casting defects.
- Improved casting yield.
- Enhanced production efficiency.
- Better utilization of available resources.
- Increased workforce awareness and skill development.
- Sustainable technological improvement in MSME foundries.

By integrating simulation-based optimization with workforce participation and operational improvements, MSME industries can significantly enhance their manufacturing capabilities even under limited technological and financial constraints.

5. SIGNIFICANCE OF THE FRAMEWORK FOR MSME INDUSTRIES.

The proposed framework serves as a practical guideline for MSME foundries aiming to improve casting quality and production performance. Unlike purely simulation-based studies, this research incorporates real industrial validation and workforce engagement, making the framework highly applicable in small-scale industrial environments.
The framework also encourages gradual adoption of modern manufacturing technologies such as casting simulation tools while maintaining compatibility with existing MSME operational conditions.

Practical Guidelines for MSME Foundries.

To improve production efficiency and product quality in MSME foundries, several practical guidelines are proposed based on the findings of this study.

First, simulation-based process analysis should be gradually adopted for gating system design to reduce production trials and minimize casting defects. Second, workforce training programs should be implemented to improve understanding of casting defects and proper mould preparation techniques.

Third, better communication between design engineers and shop-floor workers should be encouraged to ensure effective implementation of process improvements. Finally, MSME industries should adopt systematic documentation of casting parameters and best manufacturing practices to maintain consistency in production processes.

5. CONCLUSIONS

This research presents a comprehensive investigation into the optimization of sand-casting gating systems and production improvement strategies in MSME foundries. Simulation analysis using ProCAST enabled detailed evaluation of molten metal flow behavior and solidification characteristics, leading to the development of an optimized gating system design.

The experimental validation conducted under real industrial conditions confirmed the effectiveness of the optimized design in reducing casting defects and improving casting yield. In addition to technical optimization, the research highlights the importance of workforce involvement and operational improvements in achieving sustainable productivity enhancement in MSME industries.

The proposed MSME Foundry Improvement Framework Model provides a practical roadmap for small-scale foundries to integrate simulation-based optimization with workforce development and process improvement strategies.

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