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Effects of Process Related Variations on Defect Formation in Investment Cast Components

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Abstract

Castability of thin-walled castings is sensitive to variation in casting parameters. The variation in casting parameters can lead to undesired casting conditions which result in defect formation. Variation in rejection rate due to casting defect from one batch to other is common problem in foundries and the cause of this variation usually remain unknown due to complexity of the process. In this work, variation in casting parameters resulting from human involvement in the process is investigated. Casting practices of different groups of casting operators were evaluated and resulting variations in casting parameters were discussed. The effect of these variations was evaluated by comparing the rejection statistics for each group. In order to minimize process variation, optimized casting practices were implemented by developing specific process instructions for the operators. The significance of variation in casting parameters in terms of their impact on foundry rejections was evaluated by comparing the number of rejected components before and after implementation of optimized casting practices. It was concluded that variation in casting parameters due to variation in casting practices of different groups has significant impact on casting quality. Variation in mould temperature, melt temperature and pouring rate due to variation in handling time and practice resulted in varying quality of component from one batch to other. By implementing the optimized casting instruction, both quality and process reliability were improved significantly.

Keywords: Investment casting, Casting defects, Process variations, Foundry practices

1. Introduction

All foundry processes generate a certain level of rejection that is closely related to the type of casting, the processes used and the equipment available. However, in most foundries a substantial proportion of rejection results from poor control of CTQ (critical-to-quality) parameters which typically exist in a non-automated casting process [1]. These variations in CTQ parameters are often overlooked while analyzing the cause of rejections. Rejected products resulting from casting defects are re-melted which results in loss of value-added made during the complicated manufacturing process [2]. It is common in foundries that there is a level of uncertainty in determining specific causes of rejections due to the complexity of the manufacturing process and the manual nature of the work.

For thin-walled castings, the significant casting parameters which influence the castability are the casting temperature, the mould pre-heat temperature, and the pour rate [3]. Fluctuations in the set values of these parameters due to variation in casting practices or equipment response can lead to unexpected casting results. It is reported [4] that fluidity length decreases with an increase in fill time as little as 0.4s to 0.8s, especially if less superheat is available. Similarly, an increase in mould temperature from 900˚C to 1000˚C is reported to result in a 10% increase of filled area for a 1.3mm thick test blade and up to 20% increase in filled area for 2.5 mm thick test blade [3]. Variation in metallostatic pressure also effects the fillability as reported previously [3] where fluidity dropped significantly at metal head less than 127 mm for a test where Al alloy was poured in a 1.8mm diameter tube. Fluctuations in targeted value of casting parameters also limits the use of simulation in casting process, which has become an important tool for foundries to aid in casting process design during recent years. In order to get meaningful results from the simulation, the boundary conditions defined in the model must be reproduced in the foundry [5]. Control of CTQ process parameters is important as failing to replicate simulated condition in the casting process can lead to bad decisions when interpreting the simulation results [6].

It is reported that the variation in casting parameters can be attributed to operator skill and practice as well as wear on casting equipment [7], however the effect of these variations on defect formation, especially in thin-walled casting has not been reported previously.

The aim of this study is to develop an improved casting procedure and instructions to reduce rejection rates. The procedure is developed by identifying process variation originating from manual casting operations and resulting effect on targeted values of casting parameters. By establishing a relation between fluctuations in targeted values of casting parameters and the reject/re-work rate, the significance of variations in casting operation is determined. Standardized operation instructions were implemented to minimize the process variations, focused on casting parameters appeared to be critical in terms of their effect on quality of castings. After the implementation of the instructions, the improvement in quality is evaluated and discussed.

2. Materials and methods

This study is based on observations made during casting in air using a high frequency (HF) induction furnace. Fig. 1 shows the casting setup comprised of a pre-heat furnace, intermediate casting ladle and melting furnace.

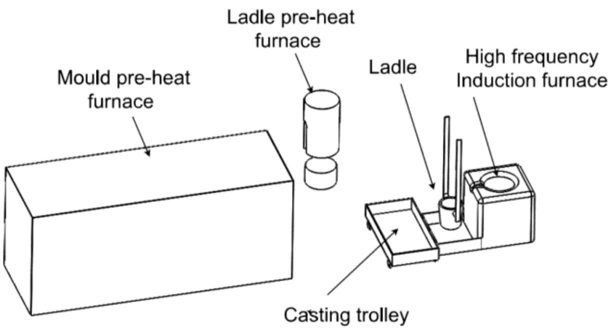

Fig. 1. Casting furnace and set-up for evaluating effects of variations originating from casting practice

In the first stage of the study, the number of rejected components produced by four groups of casting operators were obtained from the statistics reported in the ERP (enterprise resource planning) system of the foundry for production lots of a specific component. Each production lot consisted of 25 cast trees, where each tree consisted of 20 components. Each group consisted of one casting operator and one support person. In the second stage of the study, the casting practices of each group were monitored by recording their routine and execution time for 5 trees in row.

During the casting process, variations in 5 casting operations, i.e. pouring time, lead pouring time, ladle idling time, slag generation and slag removal time were evaluated as significance of these casting parameters in relation to casting defects has been reported previously [9]. Pouring operations were timed with a stopwatch and filmed for further analysis of casting practices. The process variation originating from practices of different casting groups were identified. A link between variation in casting practices of different casting groups and the resulting fluctuations in values of casting parameters was established. Improved casting procedures were developed and implemented in the form of visual instructions and operator training to minimize the process variations. The percentage of rejected components before and after the implementation of the process improvement were used to validate the effectiveness of the process change.

3. Results and discussion

It was observed that 80% of the rejections, reported in ERP system resulted from fill related defects, i.e. misruns for the product examined in this study. Other types of defects leading to rejection were internal porosity, inclusions and surface defects. While evaluating the casting practices of different casting groups, it was observed that the casting operation varies for each group significantly. The casting operator groups are designated as A, B, C and D in the Fig. 2. Figure shows variation in ladle idling time for each group. It shows the time elapsed between removal of the ladle from the ladle heating station to when the ladle is poured with melt. Average idling time for the ladle varied from 19 seconds to 27 seconds for different groups. The error bars show variation in time for each group. The variation in ladle idling time, as shown in Fig. 2 directly resulted in melt temperature variations. Fig. 5 shows loss of temperature in the ladle over the time. Once the ladle is removed from ladle pre-heat furnace, the temperature in the ladle drops rapidly as shown in Fig. 5, and may decrease by 100°C in 17 seconds and up to 150°C in 27 seconds. This resulted in a drop of melt temperature and thus less superheat available at the time of casting.

Fig. 3 shows variation in lead pouring time for different groups. Lead pouring time is the total time from removing the mould from pre-heat furnace to completion of the pouring in to the mould. It is shown in the figure that lead pouring time varies from an average of 11 seconds up to 25 seconds. The time also varied within each group as shown in error bars. The variation in lead pouring time, as shown in Fig. 3 resulted in variation of the mould pre-heat temperature. Fig. 5 shows drop in mould temperature over the time. As seen in the figure, the variation in lead pouring time from 10 seconds to 25 seconds resulted in a temperature drop between 25˚C to 75˚C.

Fig. 4 shows the variation in pouring time for different groups. Pouring time is the time it takes for filling the mould with molten metal. The average pouring time varied from average 4 seconds to 8 seconds for different groups. Error bars show variations in pouring time within each group. The variation in pouring time had significant effect on the empirically assessed pouring rate which varied from 3kg/s to 1.25kg/s when pouring time increased.

Fig. 6 shows variation in slag generation time for different groups. It refers to time allowed for the slag to form on the surface of molten metal in HF furnace. It can be seen that average slag generation time varied between 3 seconds to 10 seconds for observed groups. Similarly, the variation in time within each group is highlighted with the error bars.

Fig. 7 shows variation in slag removal time for different groups. The average duration of the slag removal operation was between 14 seconds to 32 seconds. Error bars shows variations in time within each group. The variation in slag generation and slag removal time highlights the uncertainty in melt cleanliness due to lack of a standardized process.

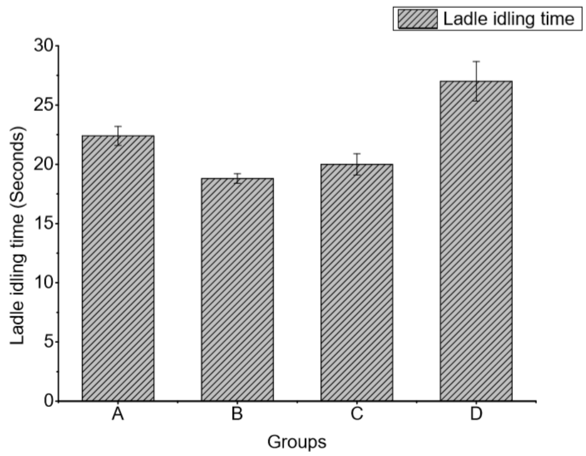

Fig. 2. Ladle idling time for different groups

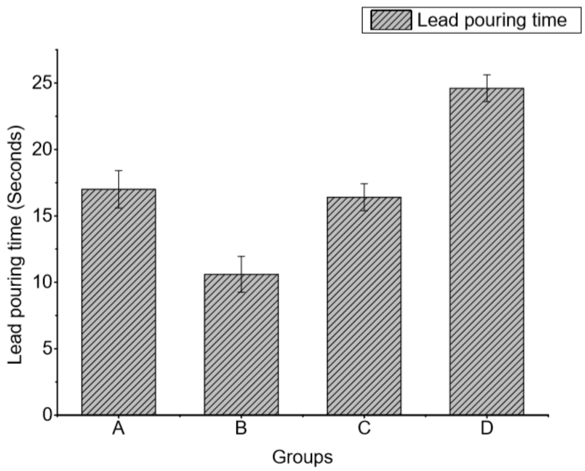

Fig. 3. Lead pouring time for different groups

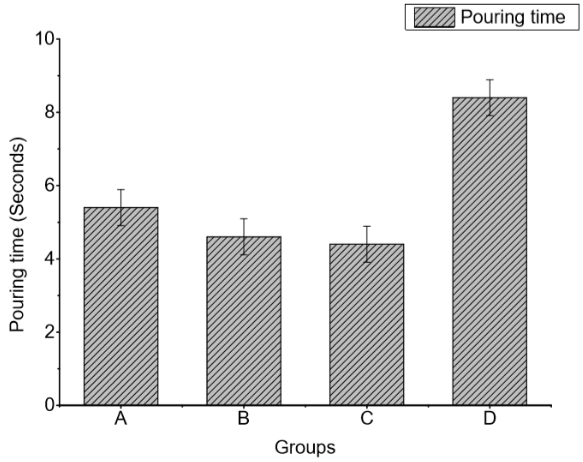

Fig. 4. Pouring time for different groups

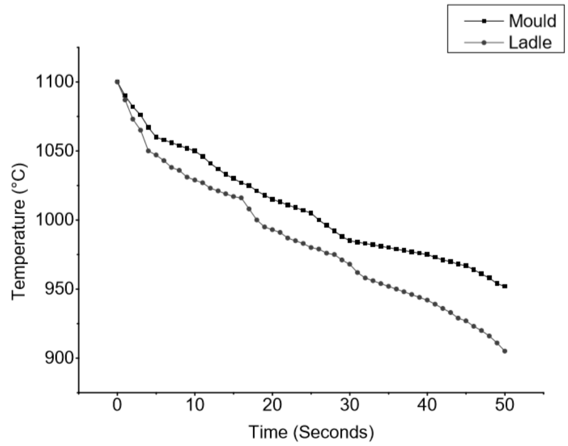

Fig. 5. Temperature drop in the mould and ladle during transportation

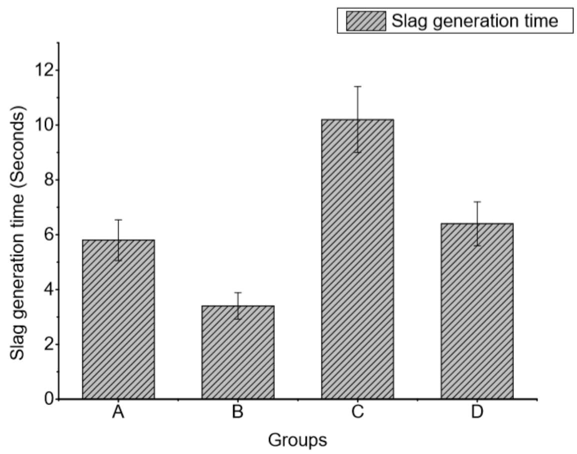

Fig. 6. Slag generation time for different groups

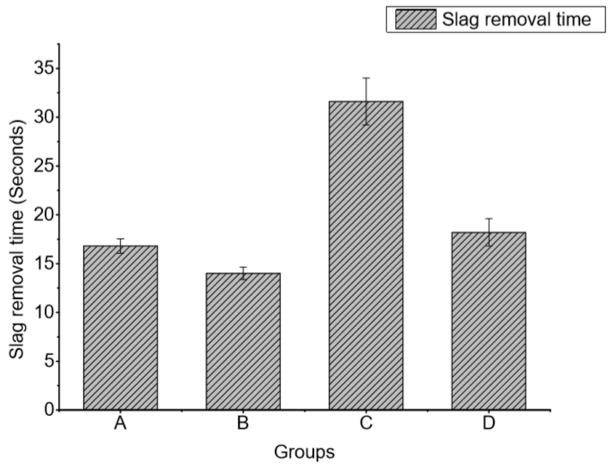

Fig. 7. Slag removal time for different groups

The reject/re-work statistics are shown in Fig. 8. It is noted that group D which has the longest lead pouring time, prolonged pouring and long crucible idling time has most rejected components. Major source of rejections was misrun which can be attributed to lower superheat and drop in mould temperature due to delay in handling operations. A lesser degree of superheat and a larger drop in mould temperature resulted in significantly reduced fluidity both in terms of fillability and flowability [10]. Similarly slow pouring rate due to prolonged pouring operation resulted in drop in fluidity [11]. The effect of melt temperature, mould temperature and pour time is in agreement with previous work [12]. Although, it is reported that melt cleanliness is important to avoid inclusions [13], it was difficult to distinguish between rejections due to slag related defects and mould related defects in data reported in ERP system. Due to uncertainty in nature of defects, the effect of variation in slag generation and removal time on rejections is not discussed in this work.

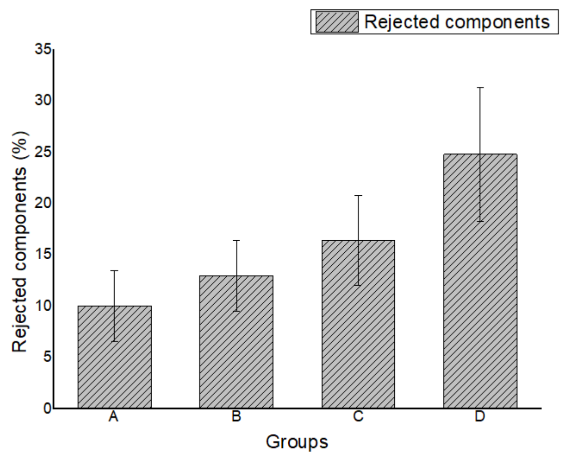

Fig. 8. Percentage of rejected components for different groups

Additionally, mould tilting also appeared to have significant impact on quality of castings due to the asymmetry in melt flow. Due to the tilt of the mould in relation to the melt stream, the melt flows along a preferred path depending upon gravity and thus preferentially fills mould cavities favored by the tilt angle. This alters the fill rate and pattern in the cavities that are disadvantaged due to the tilt and thus do not get a continuous supply of melt during the mould filling process. This is indicated in Fig. 8, where group B, despite having faster filling, shorter lead time and shorter ladle idling time, shows a higher percentage of rejection compared to group A. It was observed that group B, in an attempt to minimize the casting time, were unable to ensure that the moulds were placed vertically upright in the casting trolley before start of pouring. This resulted in higher rejections compared to group A, which placed the mould in the vertical position. The results suggest that although, pour rate, lead time and ladle idling time are important, uneven placement of the mold can result in uneven melt flow and thus unpredicted casting results. The effect of mould tilt on the fill behavior is in agreement with previously reported results [1].

Based on these findings, a standardized instruction card was developed to reduce the variation in process. To minimize loss of superheat and mould temperature, a minimum lead pour time and ladle handling time were suggested in the instruction card. Similarly, to maintain an un-interrupted smooth flow of the melt into the mould, a proper vertical position was recommended. An improved de-slagging and cleaning procedure for the foundry returns used as charge material was proposed to achieve required melt cleanliness. Fig. 9 shows the instruction card develop to minimize process variations in order to avoid fluctuation in mould temperature, melt temperatures, pouring rate as well as cleanliness of melt. Training sessions were conducted to ensure that operator groups adopt to the new practice. To verify the effectiveness of the instruction card the historical data on rejection/re-work before the implementation of instructions was compared with 10 production lots after the implementation and was followed-up in the foundry. The effect of implementation of standard instructions is shown in Fig. 10.

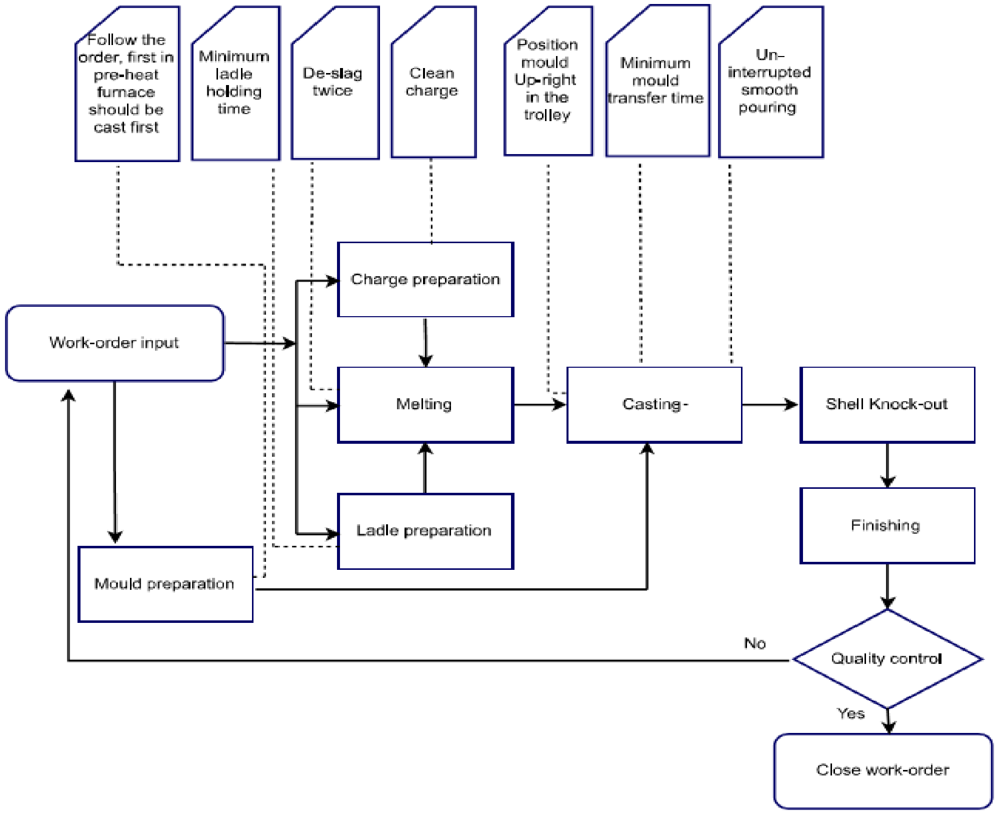

Fig. 9. Instruction card for casting operation at HF induction furnace

Firstly, it can be seen that the variation in rejection percentage was significantly reduced as is illustrated by the error bars in Fig. 10. Secondly, a tendency towards reduced rejection was seen after the introduction of the instruction card. The rejections dropped from 15% to 8%. Although, the effect of variation in casting parameters on fluidity has been reported previously, the effect of variations in casting practices and resulting fluctuations in casting parameters is reported here.

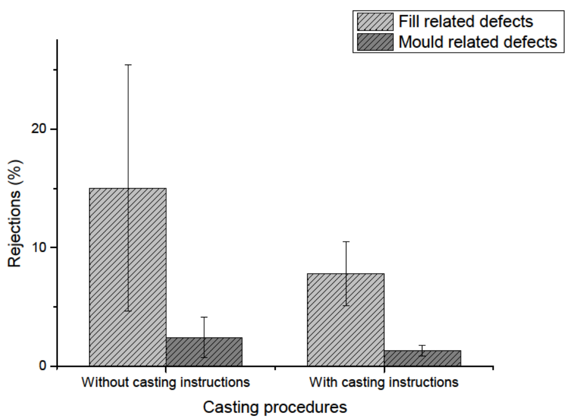

Fig. 10. Rejection percentage before and after implementation of casting instructions presented in Figure 9

4. Conclusions

Casting quality varies in the foundry due to variations in the process originating from human involvement and semi-automated equipment. These variations result in ill-defined variations and confunding with other casting parameters that effect the process stability. Optimized casting process instructions to maintain a minimum variation and to achieve the favourable casting condition can result in significant improvement in casting quality and minimize the uncertainty in component quality. The implementation of process instruction resulted in reduction in fill related foundry rejections from 15% to 8%. Mould related defects also decreased from 3% to 1.5 %. Although, it is suggested in the literature [7] that process conditions vary depending upon the foundry environment and equipment, variation in process parameters due to human involvement is reported in this work. The results not only provide better understanding of the casting process but are also helpful in defining accurate boundary conditions when simulating casting process.

Acknowledgements

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