A Review of the Reliability Techniques Used in the Case of Casting Process Optimization

Amit Chaudhari and Hari Vasudevan

Abstract Foundry industries nowadays face problems, such as poor quality of the castings produced as well as wrong practices followed, which finally lead to decrease in productivity. Castings with minimum production cost and no defects have emerged as prime requirements in this vital manufacturing industry. This includes improving productivity and reducing cost by minimizing rejections. To achieve these improvements, various process parameters are necessary to be optimized. Simulation of casting process has become an irreplaceable tool in the production of cost-effective and high performance castings. Most of the casting simulation is based on a purely deterministic approach, in which shop floor iterative trial and error methods are replaced with iterations on computer. Optimization in casting process lacks consideration of reliability of casting production process and casting model. Reliability-based design optimization (RBDO) is an approach for the development of components, which aims to minimize the cost, while constraining the probability of failure. This study provides for a review of the casting process optimization through a reliability approach and concludes that the future studies could develop a comparative analysis of reliability with conventional techniques used in casting process optimization.

Keywords Casting process optimization · Reliability

A. Chaudhari (✉)
Department of Production Engineering, Dwarkadas J. Sanghvi College of Engineering, University of Mumbai, Mumbai, India
e-mail: amit_durlabh@yahoo.com

H. Vasudevan
Dwarkadas J. Sanghvi College of Engineering, University of Mumbai, Mumbai, India
e-mail: principaldjs@gmail.com

H. Vasudevan et al. (eds.), *Proceedings of International Conference on Intelligent Manufacturing and Automation*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-4485-9_32

1 Introduction

1.1 Casting Process and Optimization

Quality of any manufactured product depends largely upon the type of manufacturing process used. Casting, as a manufacturing process is widely used to obtain complicated shapes of metal parts, with little or no machining involved, in a very economical way. It is amongst the most common processes of manufacturing. In order to maintain good quality production, cast parts must be defect free (internal as well as external). Quality and strength of the castings depend on various parameters. Reliability of casting depends generally on parameters, such as quality of the mould cavity, parting line, holding time, pouring temperature and the skills of the personnel involved. In casting, conservative design rules are formed due to immeasurable factors, such as mould shift, cold shut, shrinkage, blow holes and porosity inclusion. Unquantifiable factors are the ones with an unknown state of defect. Standardization of production techniques and close control on various parameters can lead to preparing foolproof castings. Due to a wide range of possible factors, reasonable classification of casting defects is considered difficult to achieve.

Simulation of casting process can be worked as a collaborative tool, between the design department and production department to reduce lead times, so as to produce defect free castings and to develop simplified component designs for casting. In the simulation approach, the skillset and knowledge of the simulation personnel determines the effectiveness of the simulation software used to develop the best casting process. There is ample of literature to show that the ability and efficiency of the casting process can be forecast through reliability. It is also known that the redundancies play an essential role in increasing the reliability characteristics of systems [1]. Efficiency of the production can be increased through high reliability of the system [2]. Reliability measures are amongst the primary concerns, while planning, designing and operation of any system or equipment.

1.2 Reliability Approach

Reliability provides the method for assuring that a product or service function, when it is required to do so, by its user. These methods consist of the technique for determining what can go wrong, how can that be prevented from going wrong, and, if something goes wrong, how can it quickly recover and minimize the consequences.

The reliability of an item is the probability that the item will perform a specified function under specified operational and environmental conditions, at and throughout a specified time.

Reliability prediction is the combination of the creation of a proper reliability model, together with estimating the input parameters, like failure rates for a particular failure mode or event and the mean time to repair (MTTR) the system for a particular failure for the model and finally to provide a system-level estimate for output reliability parameters (system availability or a particular function failure frequency). Requirements are specified using reliability parameters. The most common parameter of reliability is mean time to failure (MTTF). Reliability increases as the MTTF increases. Reliability modelling is the process of predicting or understanding the reliability of a component or system prior to its implementation. Two types of analysis, often used to model a system's reliability behaviour are fault tree analysis and reliability block diagram. Reliability must be designed into the system and during the system design, top-level reliability requirements are allocated to subsystems by design engineers, maintainers and reliability engineers working together. Reliability design begins with the development of a (system) model. Reliability model use block diagram and fault trees to provide a graphical means of evaluating the relationship between different parts of the system [3].

2 Literature Review

In the current situation with respect to industry practices, reliability theory has become the most challenging and demanding. During the last 40 years, the reliability theory and the methods of reliability analysis have evolved considerably and have also been acknowledged in a number of publications. These studies have shown a multidisciplinary approach of the reliability. Earlier, the casting process optimization was a focused area for many researchers, wherein they used different traditional and simulation techniques for improvement in the casting process. This section on literature review comprises of two sections, process optimization using reliability and casting process optimization.

(a) **Process Optimization using Reliability**:

For practical optimization studies, reliability-based techniques are getting increasingly popular, due to the uncertainties involved in realizing the design variables and stochastic ties involved in various problem parameters. This section highlights the extant research work done in the process optimization with the help of reliability theory used by various authors.

Gupta and Sharma [4] studied reliability and MTTF evaluation of a two duplex-unit standby system, involving two types of repairs; namely cheaper and costlier. Procurement for a new unit was done immediately, if the costly repair was found in inspection. The unit under repair was replaced by a new unit, if it was delivered before the repair, otherwise, the order for the new unit would be cancelled. The system was analyzed for MTTF, availability, steady-state probability and variance by using the supplementary variable technique (SVT).

Ram [5] discussed the mathematical modelling of a highly reliable complex system, which included three states, i.e. normal, partial failed (degraded state) and complete failed state. The system, "partial failed" was due to the partial failure of internal components or redundancies and "completely failed" was due to the catastrophic failure of the system. Repair rates were general functions of the time spent. All the transition rates were constant, except for one transition, where two types of repair, namely exponential and general were possible and could be tackled with the help of a COPULA approach. By employing the supplementary variable technique, Laplace transformation, various transition state probabilities, availability and cost analysis (predictable profit) were obtained along with the steady-state behaviour of the system. Inversions were also carried out, so as to obtain time dependent probabilities, which find out the availability of the system at any instant.

Park and Yang [6] worked on an automated die-casting process. The authors proposed a linear programming (LP) model for solving the number of products to be cast. They found that the proposed model provided the minimum usage of casting time, i.e. the average time, the efficiency was optimized.

Kumar and Ram [7] worked on the reliability and sensitivity analysis of a coal handling unit of a thermal power plant using a probabilistic approach. The transition state probabilities, availability, reliability, MTTF, sensitivity analysis and cost-effectiveness of the system were evaluated using Laplace transforms and differential equations. The authors concluded that the system failure rates depend on sensitivity of the system, i.e. sensitivity of the system can be reduced by controlling the failures. With this, the reliability model parts or units, which affect the system, could be identified.

Yourui et al. [8] worked on reliability modelling and die-casting process optimization. Firstly, simulation of die-casting process was carried out using finite element analysis (FEA). The multidisciplinary optimization model of die-casting process was generated using the quadratic response surface. Also, the epistemic uncertainty was signified using the evidence theory. Later, a reliability-based multidisciplinary optimization (RBMDO) technique was proposed for die casting. Results confirmed the high computational efficiency with epistemic uncertainty through the RBMDO technique.

Kumar t al. [9] investigated a casting system and used the supplementary technique. System's MTTF was most crucial and sensitive for failure rates of the mould shift. They also found that the failure rate of shrinkage and blow holes were highly sensitive for the reliability of the system.

Hardin et al. [10] integrated the casting simulation with a reliability-based design optimization software tool (RBDO). Uncertainties in input variables and model were considered in this methodology. The outcome of the methodology comprised of the confidence level in design along with the reliable optimum design. Design of riser was optimized by considering the uncertainties in fill level, riser diameter and depth. It was observed that the RBDO provided a different overview for the design than in the case of a traditional approach.

(b) **Casting Process Optimization**:

Due to globalization, short lead time is a challenge for casting set up and foundries. Castings with no defects and minimum production cost have turn out to be the necessity for this indispensable manufacturing industry. Rejection of casting is caused due to defective components. These defects depend on various process parameters, which need to be improved upon, using various methods in optimization. The IT industry in collaboration with manufacturing industry, have come up with various simulation software packages, which could identify the parameters affecting the casting through simulation. This simulation also helps to forecast the defects and provides for the corrective measures to minimize these defects.

Tai and Lin [11] optimized the techniques used to design a runner in a die-casting process. The entire process was mathematically modelled using abductive network technique. This helped them to optimize the runner design in the making stage, by ruling out various discrepancies in the system in the development stage itself.

Tai [12] optimized the control of accuracy of the component which was made using a metal die-casting process. In order to locate the correct gate position of the design mould, a finite element method was used. On the basis of the results obtained from finite element analysis, an abductive network was designed, which could predict important process parameters, such as the injection angle and sectional ratio of the runner and gate and injection positions. Optimizing these process parameters leads to more accurate components.

Rohallah and Davami [13] carried out design optimization of an automatic feeder used in the steel casting process. The design process of the feeder consisted of factors, such as determination of the feeder-neck connection point on the casting surface, initial feeder design and optimization of feeder shape and feeder topology. Process optimization was eventually achieved by introducing an automatic feeding system to the existing process, which helped in increasing the productivity by reducing the process time.

Feng et al. [14] carried out a generalized study on various optimization techniques used for solidification during heat transfer of continuous slab casting. Prior to the study, it was observed that there was a lot of heat loss in this system due to which, this problem was taken into consideration for further research. Numerical simulation tools were used to calculate the optimal cooling rate of the continuous slab casting process, which results in efficient solidification of the slab components.

Dabade and Bhedasgaonkar [15] analyzed various defects in the process of metal casting process and optimized the performance of the system using the design of experiments (DOE). The entire process of metal casting was simulated virtually using a commercial computer-aided engineering (CAE) package MAGMASOFT. The virtual simulation helped to narrow down on defects, such as hot tears and shrinkage porosity. The design of experiments (DOE) model was used to improve the feeding system design and gating locations, which helped them to achieve a reduction in shrinkage porosity by 15% and improved the yield strength by 5%.

Choudhari, Narkhede and Mahajan [16] reduced the defects caused in the casting process by simulating the casting process. The process was simulated using the computer-aided engineering (CAE) package "Auto CAST X", which pointed out major casting defects in the system. The defects, such as shrinkage cavity, porosity and sink were identified in the simulation. A new feeder was designed to reduce the defects, which were detected by "AutoCAST X", which was then performed experimentally. The values attained from the experiment were similar to that simulated by the software, hence validating the process improvement.

Jie et al. (2014) [17] studied on the TiB2/A356 aluminium base composite to be used for investment casting and carried out numerical simulation to optimize the process. Process simulation was performed using a commercial computer-aided engineering (CAE) casting package "Pro Cast". Numerical simulations obtained from "Pro Cast" pointed out the week links in the process, which were then optimized. The results indicated that the problems of shrinkage porosity defects have been resolved by increasing the pouring temperature and casting speed. It was also found that, by adding the insulation materials around the gate and riser, the system could gain more stability.

3 Key Observations and Findings of the Study

Various researchers have applied different techniques for optimization of casting process parameters. They have mainly focused on the design and simulation for optimization of the casting process parameters, using softwares like AUTO CAST X, Z-cast, ESI Pro Cast, MAGMASOFT, etc. Different statistical techniques, such as Taguchi method, ANOVA, DOE, RSM, etc., have also been used for casting process parameter optimization. The extant literature also reveals that the application of reliability optimization methods to casting process design provides for more than just an optimal solution. It provides for an overview of all possible solutions, some of which might be novel and innovative.

It can be found that the reliability-based design optimization and casting simulation can be integrated to go a step forward in the development of optimization methods, by including uncertainties in the process and model variables and determining an optimal solution with known probability of success. Use of reliability in different application areas could prove that it works more efficiently for the process optimization by modelling the system errors. It is also observed that:

- Very few researchers have worked on the reliability in casting areas for casting process optimization.
- Reliability theory has evolved as a discipline with the time.
- Literature suggests that reliability technique is multidisciplinary and is not bound by the specific field.

4 Conclusion

A brief overview of the background of the casting process and its optimization has been done in this study and it was found that the optimization of casting process parameters is a prime need of the industries, suffering from various casting defects. Various conventional techniques are found having used for reducing the defects in the casting process. Various optimization techniques used in the casting process provide multiple possible solutions, some of which may not be countered in conventional techniques. A foundry engineer could check the sensitivity and stability in the process models as well as the actual process against variables and parameters. An overview of reliability was undertaken, wherein the design for reliability, steps in design for reliability, ways to improve reliability by design, etc., were studied.

From the literature, it was found that reliability is a multidisciplinary technique, which can be used as optimization technique to get a reliable solution. It can be easily seen throughout the literature that the optimum casting designs will be unreliable without consideration of the statistical and physical uncertainties in the casting process. Studies on optimization of casting process lack in consideration of uncertainties in the casting process. Use of reliability theory for handling uncertainties in the casting process can provide a reliable solution, instead of the optimal solution.

After reviewing the extant literature, it is concluded and recommended that the future studies could develop the comparative analysis of reliability with conventional techniques used in casting process optimization. The studies may cover implementation of reliability for casting process parameters optimization. The developed methodology can be aimed to use reliability as a multidisciplinary method for use in various application areas. It can also be expected to demonstrate how classical reliability-based concepts can be used in single and multi-objective evolutionary algorithms to enhance their scope in handling uncertainties, a matter which is common in most real-world problem solving tasks.

References

1. Sutaria M, Joshi D, Jagdishwar M, Ravi B (2011) Automatic optimization of casting feeders using feed-paths generated by VEM. In: ASME 2011 international mechanical engineering congress and exposition, Volume 3: design and manufacturing, pp 137–146
2. Ransing RS, Sood MP, Pao WK (2005) Computer implementation of Heuvers' Circle method for thermal optimisation in castings. Int J Cast Metals Res 18:119–128
3. Verma AK, Ajit S, Karanki DR (2010) Reliability and safety engineering, 1st edn. Springer, London. ISBN: 978-1-84996-231-5
4. Gupta PP, Sharma MK (1993) Reliability and MTTF evaluation of a two duplex-unit standby system with two types of repair. Microelectron Reliab 33(3):291–295
5. Ram M (2010) Reliability measures of a three-state complex system: a copula approach. Appl Appl Math Int J 5(10):1483–1492
6. Park YK, Yang JM (2011) Maximizing average efficiency of process time for pressure die casting in real foundries. Int J Adv Manuf Technol 53(9–12):889–897
7. Kumar A, Ram M (2013) Reliability measures improvement and sensitivity analysis of a coal handling unit for thermal power plant. Int J Eng Trans C Aspects 26(9):1059
8. Yourui T, Shuyong D, Xujing Y (2014) Reliability modeling and optimization of die-casting existing epistemic uncertainty. Int J Interact Des Manuf (IJIDeM), pp 1–7. https://doi.org/10.1007/s12008-014-0239-y
9. Kumar A, Varshney A, Ram M (2015) Sensitivity analysis for casting process under stochastic modeling. Int J Ind Eng Comput 6(3):419–432

10. Hardin R, Choi KK, Bechermann C (2015) Reliability-based casting process design optimization. Int J Cast Metals Res 28(3):181–192
11. Tai CC, Lin JC (1998) A runner-optimization design study of a die-casting die. J Mater Process Technol 84:1–12
12. Tai Ching-Chih (2000) The optimization accuracy control of a die-casting product part. J Mater Process Technol 103:173–188
13. Tavakoli R, Davami P (2008) Automatic optimal feeder design in steel casting process. Comput Methods Appl Mech Eng 197:921–932
14. Feng H, Chen L, Xie Z, Ding Z, Sun F (2014) Generalized constructal optimization for solidification heat transfer process of slab continuous casting based on heat loss rate. Energy 66:991–998
15. Dabade Uday A, Bhedasgaonkar Rahul C (2013) Casting defect analysis using Design of Experiments (DoE) and computer aided casting simulation technique. Procedia CIRP 7:616–621
16. Choudhari CM, Narkhede BE, Mahajan SK (2014) Casting design and simulation of cover plate using AutoCAST-X software for defect minimization with experimental validation. In: 3rd International conference on materials processing and characterisation (ICMPC 2014), Procedia Materials Science 6, pp 786–797
17. Jie Z, Dongqi Z, Pengwei W, Gang W, Feng L, Penglong D (2014) numerical simulation research of investment casting for TiB2/A356 aluminum base composite. Rare Metal Mater Eng 43(1):0047–0051