New Approach to Casting Defects Classification and Analysis Supported by Simulation

V.V.Mane[1], Amit Sata[2] and M. Y. Khire[3]

[1]Senior Lecturer, Mechanical Engineering Department, College of Engineering, Osmanabad,
E-mail: vvm_osmanabad@yahoo.co.in
[2]Lecturer, Mechanical Engineering Department, V.V.P. Engineering College, Rajkot,
E-Mail: ameet_sata2000@yahoo.com
[3]Principal, Padmashri Dr. Vitthalrao Vikhe Patil, College of Engineering, Ahmednagar,
E-mail: mykhire@gmail.com

Abstract

Foundry industry suffers from poor quality and productivity due to the large number of process parameters, combined with lower penetration of manufacturing automation and shortage of skilled workers compared to other industries. Global buyers demand defect-free castings and strict delivery schedule, which foundries are finding it very difficult to meet.

Casting defects result in increased unit cost and lower morale of shop floor personnel. The defects need to be diagnosed correctly for appropriate remedial measures, otherwise new defects may be introduced. Unfortunately, this is not an easy task, since casting process involves complex interactions among various parameters and operations related to metal composition, methods design, molding, melting, pouring, shake-out, fettling and machining. For example, if shrinkage porosity is identified as gas porosity, and the pouring temperature is lowered to reduce the same, it may lead to another defect, namely cold shut.

So far, casting defect analysis has been carried out using techniques like cause-effect diagrams, design of experiments, if-then rules (expert systems), and artificial neural networks. Most of the previous work is focused on finding process-related causes for individual defects, and optimizing the parameter values to reduce the defects. This is not sufficient for completely eliminating the defects, since parameters

related to part, tooling and methods design also affect casting quality, and these are not considered in conventional defect analysis approaches.

In this work, we present a 3-step approach to casting defect identification, analysis and rectification. The defects are classified in terms of their appearance, size, location, consistency, discovery stage and inspection method. This helps in correct identification of the defects. For defect analysis, the possible causes are grouped into design, material and process parameters. The effect of suspected cause parameters on casting quality is ascertained through simulation. Based on the results and their interpretation, the optimal values of the parameters are determined to eliminate the defects.

The proposed approach overcomes the difficulty of controlling process parameters in foundries with manual processes and unskilled labor, by making the design more robust (less sensitive) with respect to process parameters. This will especially help SME foundries to significantly improve their quality levels.

1. Introduction

Metal casting is one of the direct methods of manufacturing the desired geometry of component. The method is also called as *near net shape process*. It is one of the primary processes for several years and one of important process even today in the 21st century. Early applications of casting are in making jewellery items and golden idols. Today, casting applications include automotive components, spacecraft components and many industrial & domestic components, apart from the art and jewellery items.

The principle of manufacturing a casting involves creating a cavity inside a sand mould and then pouring the molten metal directly into the mould. Casting is a very versatile process and capable of being used in mass production. The size of components is varied from very large to small, with intricate designs. Out of the several steps involved in the casting process, moulding and melting processes are the most important stages. Improper control at these stages results in defective castings, which reduces the productivity of a foundry industry. Generally, foundry industry suffers from poor quality and productivity due to the large number of process parameters, combined with lower penetration of manufacturing automation and shortage of skilled workers compared to other industries. Also, Global buyers demand defect-free castings and strict delivery schedule, which foundries are finding it very difficult to meet.

Casting process is also known as process of uncertainty. Even in a completely controlled process, defects in casting are found out which challenges explanation about the cause of casting defects. The complexity of the process is due to the involvement of the various disciplines of science and engineering with casting. The cause of defects is often a combination of several factors rather than a single one. When these various factors are combined, the root cause of a casting defect can actually become a mystery. It is important to correctly identify the defect symptoms prior to assigning the cause to the problem. False remedies not only fail to solve the problem, they can confuse the issues and make it more difficult to cure the defect. The defects need to be diagnosed correctly for appropriate remedial measures, otherwise new defects may be introduced. Unfortunately, this is not an easy task, since casting process involves complex interactions among various parameters and operations related to metal composition, methods design, molding, melting, pouring, shake-out, fettling and machining. The proper classification and identification of a particular defect is the basic need to correct and control the quality of casting.

2. Present Approaches for Analysis of Casting Defects

At present, casting defect analysis is carried out using techniques like historical data analysis, cause-effect diagrams, design of experiments, if-then rules (expert systems), and artificial neural networks (ANN). They are briefly explained in this section.

2.1 Historical Data Analysis

To understand this concept, data for occurrence of defects are collected from one of leading casting manufacturer in Maharashtra for one year. From this data, occurrence chart has been prepared which further helps to identify occurrence major defects in castings. These data further help to prepare the chart for occurrence of defect. The details are shown in table 1 and fig. 1.

Table1.Historical Data of casting defects

Defects	**Rejected Quantity**	**Job Rejection %**	**Defects**	**Rejected Quantity**	**Job Rejection %**
Cold Shut	205	2.30	Cores Broken	16	0.17
Crush	188	2.11	Mismatch	13	0.14
Knock Crack	165	1.85	Sub. Contract Fettling Fault	10	0.11
Blowhole	123	1.38	Runout	7	0.07
Contractor's Houling Cracks	55	0.62	Hard	7	0.07
Bad Mold	42	0.47	Slurry Penetration	4	0.04
Scab	40	0.45	Low Hardness	3	0.03
Fet. Crack	32	0.36	Core Scab	1	0.01
Shrinkage	31	0.34	Swell	1	0.01
Slag	23	0.25	Sink	1	0.01
Bad Core	19	0.21	Others	3	0.003
Total	**989**			**11.1012 %**	

Figure 1: Pareto Analysis of Casting Defects

2.2 Cause- Effect diagram

Cause- effect diagram is one of the approaches to enumerate the possible causes. When all possible causes are known to us, the operating conditions are verified and applied to determine the potential cause item by item. As the primary factors are identified, they are further examined to find the specific problems that cause the defects. After the particular cause has been identified, remedies are suggested to eliminate the defects. Examples (data collected for various defects occurred during sand casting for one year at one of leading casting manufacture in Maharashtra) for checking the individual cause-effect for some of the defects are listed below.

Material: FC 200 (Gray cast iron) & Production: 18000 casting /month (Approximate)

2.2.1 Crush

The cause-effect diagram is as shown in fig. 2.Based on experience in foundry, following remedies are suggested:

Remedies:

- Change the hardness of mould.
- Proper clamping of mould boxes.
- Use of appropriate sand with adequate green compressive strength,
- Use proper pins.
- Properly clean the pattern and mould before moulding.

2.2.2 Shrinkage

The cause-effect diagram for shrinkage is shown in fig. 2. Suggested remedies are as follows:

Remedies:

- Use the suitable composition that is adjusted silicon and (1.80 to 2.10) or carbon equivalent (3.9 to 4.1) .Carry out proper ramming and maintain optimum pouring temperature and time.

2.2.3 Cold Shut

The cause-effect diagram for cold shut is shown in fig.4. Based on experience in foundry, following remedies are suggested:

Remedies:

- Smooth pouring with the help of monorail.

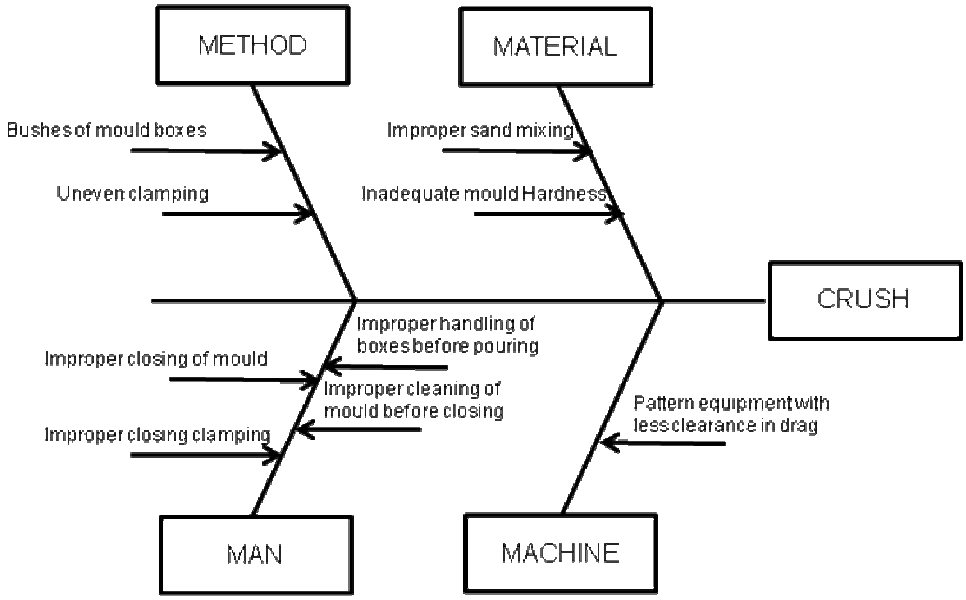


Figure 2: The cause Effect diagrams for crush

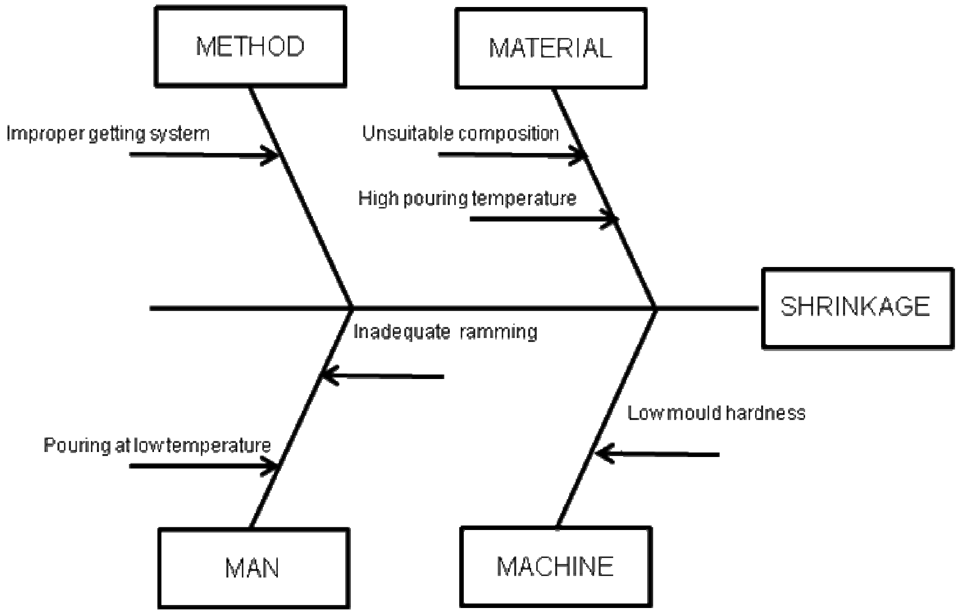


Figure 3: The cause Effect diagrams for crush

- Properly transport mould during pouring.
- Arrange proper clamping arrangement

2.2.4 Mismatch

The cause-effect diagram for mismatch is shown in fig.5. Based on experience in foundry, following remedies are suggested:

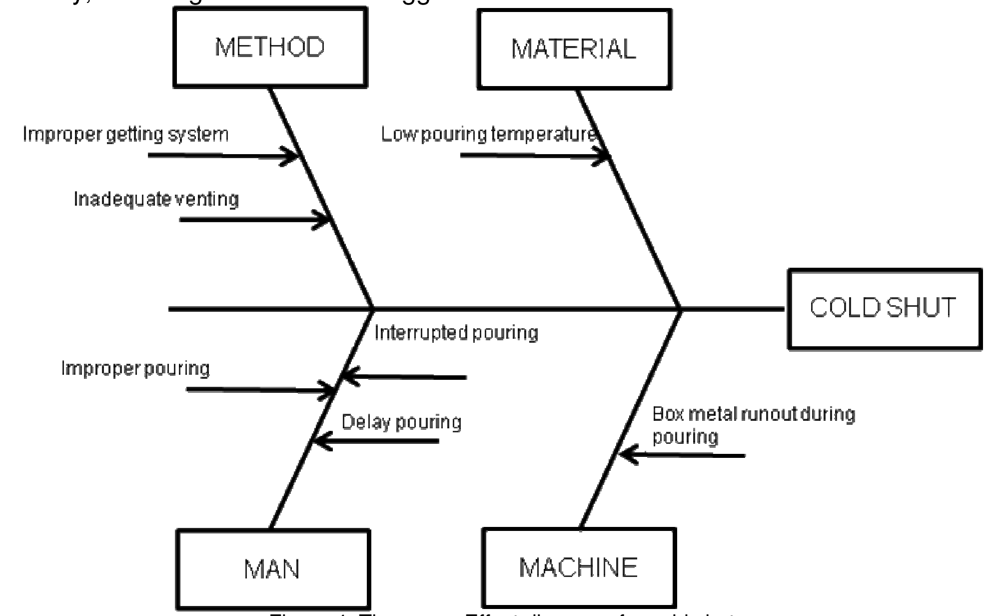


Figure 4: The cause Effect diagrams for cold shut

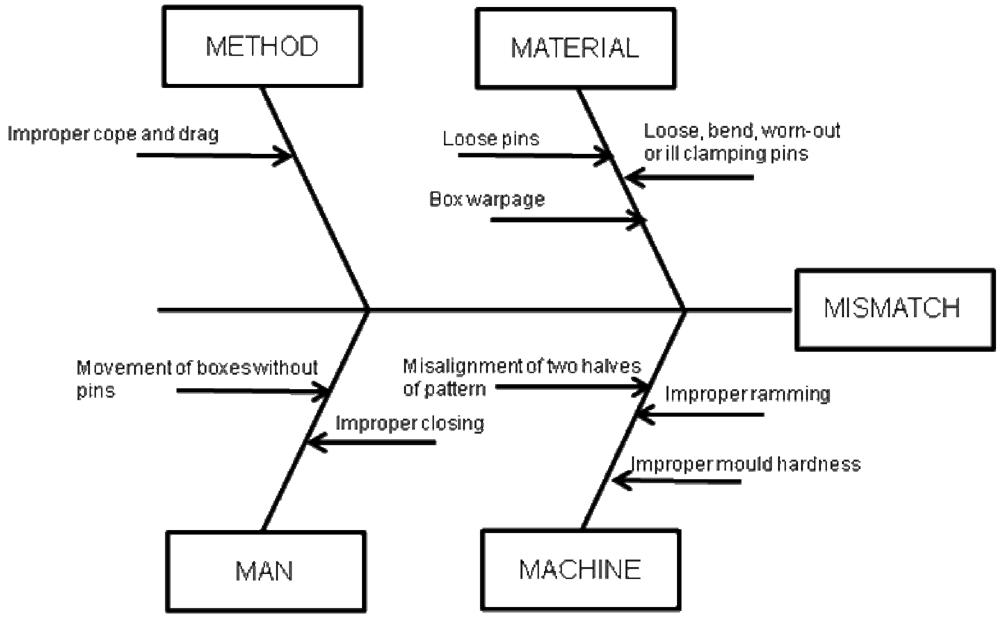


Figure 5: The cause Effect diagrams for Mismatch

Remedies:

- Properly arrange box warpage.
- Properly move boxes with pins.
- Properly clamp the boxes.

The cause-effect diagram can easily determine causes of defects and suggest their remedies to eliminate the problems. The main limitation of the cause effect diagram is that it largely depends on the experience and traditionally, it is prepared by experience or intuitively. Also, cause effect diagrams are not easily found out in literature except few casting defects.

2.3 Design of Experiments (DoE)

In casting processes, there are various parameters with different adjustment levels may influence the defects in casting. For each type of defect, several causes have been listed under differing categories such as design, moulding and pouring/melting related parameters. The focus of the design of experiment is on the robustness of the casting parameters. The methodology to achieve optimized process parameters are as given below:

- Any defect is selected which is needed to be analyzed. For example, many internal defects (shifts, warpage, blow holes, drop etc.) largely depends on the moulding.
- The target of process is to achieve “lower casting defects” by adjusting the process parameters.
- Select the most significant parameters that cause the defects in casting. These parameters can be identified by the cause effect diagram.
- Plan the experiments as per either design of experiments or orthogonal array (OA) and parameter levels. Based on the experimental conditions, collect the data.

- Analyze the data. An analysis of variance (ANOVA) table can be generated to determine the statistical significance of the parameters. Response graphs can be plotted to determine the preferred levels for each parameter of the process.
- Decide optimum settings of the control parameters. Verify the optimum settings result in the predicted reduction in the casting defects.

The pouring temperature and pouring time are very important parameters among the parameters affecting the casting quality. Experiments are, therefore, carried out to optimize the pouring temperature and pouring time by experiments for different types of casting. The data collected for one year from one of leading casting manufacture in Maharashtra. These data are related to the casting of crankcase. The Optimized pouring temperature for crankcase is used for reduction of rejection level is as shown in fig. 6. Rejection level is minimum for range of 1420 ^{0}C – 1440 ^{0}C.

The pouring time can also be adjusted in same manner by DoE. The pouring time is optimized for the Cast iron (FG 200) plate stiffener. The data collected from one of leading casting foundry at Maharashtra (fig. 7). The rejection level for plate stiffener is minimum for pouring time of 5-6 sec.

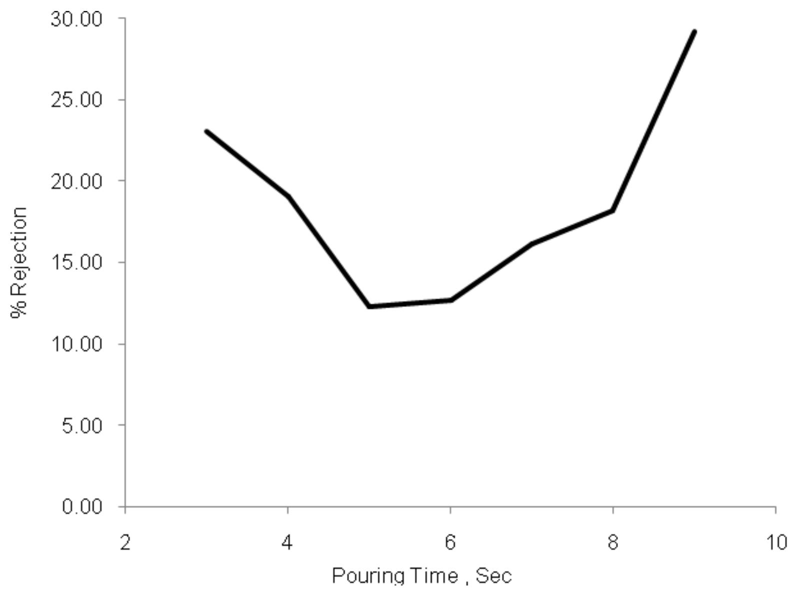


Figure 6: Pouring temperature v/s % Rejection for Crankcase

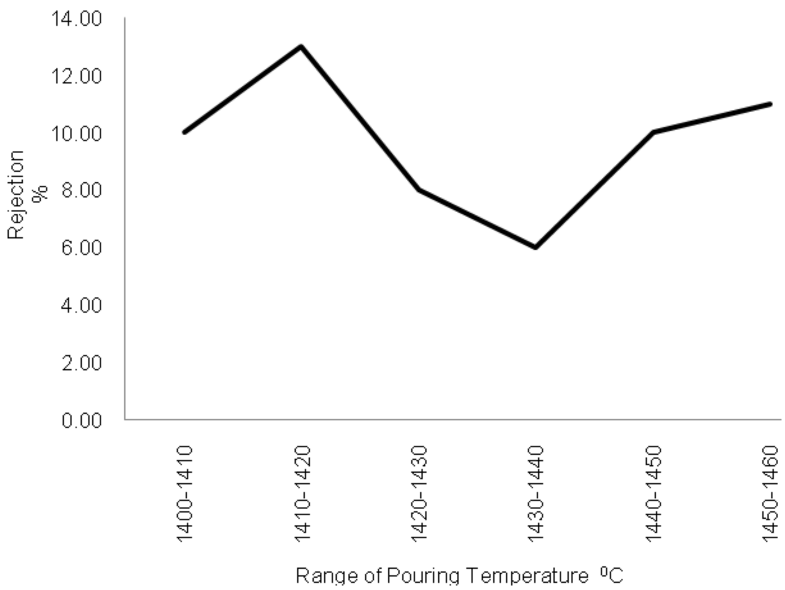


Figure 7: Pouring time v/s % Rejection for Plate stiffener

DoE appears to be an important tool to satisfy the condition. In the majority of foundry plants, the data available on the number of castings poured, along with the number of castings being considered as accepted or rejected as defectives before and after machining, is usually recorded. This data is set under various types of defects for each day, week and the month of a manufacturing casting product. This information can be obtained for each type of component. The statistical data for a selected period for any casting can be used as input to the design of experiments (DoE) for defect analysis. It can be considered as full factorial design of experiments. Further, this data will be used to analyze casting defects.

2.4 ANN

An artificial neural network is computational model of the human brain, where information processing is distributed over some interconnected processing elements, called nodes (also called neurons). They are structured in some layers. These layers are called as input, output and hidden layers and they have been operated parallel to each other. The outputs of the node in one layer are transmitted to nodes of other layer through connections. While transmitting outputs from one layer to another via some connections, they may be amplified (if necessary) through weight factors. The net input to each node (other than input node) is net sum of the weighted output of the nodes feeding that node.

Several researchers have attempted to use neural networks in analysis of casting process. Kulkarni et al. (1992) developed an expert system that could analyze casting defects in steel castings. This defect analysis expert system was user friendly and asks a sequence of questions that require a “yes” or “no” answer. Eventually, the expert system would draw a conclusion stating the nature of defect. It then lists all possible causes and remedies for the defect. During the interrogation process, if the program reaches a dead-end and no conclusion can be made, it may then be presumed that the nature and complexity of the defect is beyond the knowledge of the expert system. After the human expert determines the cause of this new defect, this new knowledge can be added to the knowledge base of the expert system. However, the knowledge domain of this expert system includes only the area of green sand moulding for steel castings.

A review of the literature clearly indicates that most of the investigators had aimed at finding out the causes of the defects, factors influencing defects, and optimum process parameters to avoid occurrence of defects in casting. They have developed expert systems based on ANN and these expert systems can be considered as a good method to capture expert logic on casting defect diagnosis and prevention of defects.

3. Proposed Approaches for Analysis of Casting Defects

Foundries are still using trial and error methods to solve defect related problems. It is very common to have different names for the same defects, it makes very difficult to solve the problems related to casting defects. It is always preferable to use more disciplined approach to define, identify and find out the root cause of a defect.

3.1 Proposed Classification

It is important to correctly identify the defect symptoms prior to assigning the cause to the problem. False remedies not only fail to solve the problem, they can confuse the issues and make it more difficult to cure the defect. So, the proper classification and identification of a particular defect is the basic need to correct and control the quality of castings. The nature of casting defects can be determined by correctly categorizing the shape, appearance, location and size of defects. Once casting defects are properly classified, the possible causes can be identified and the corrective action can be taken. Then a controlled and complete defect analysis can be done.

Defect classification of cast components proposed in literature or currently adopted by foundries are either on the basis of their geometry/location or on the basis of their metallurgical origin or specific causes. The International Atlas of Casting Defects (AFS, 1974) has described 30 defect types which are generally applicable to gray iron casting in sand mould. Classification of defects in certain broad categories which is based on origin of defects is also an accepted practice.

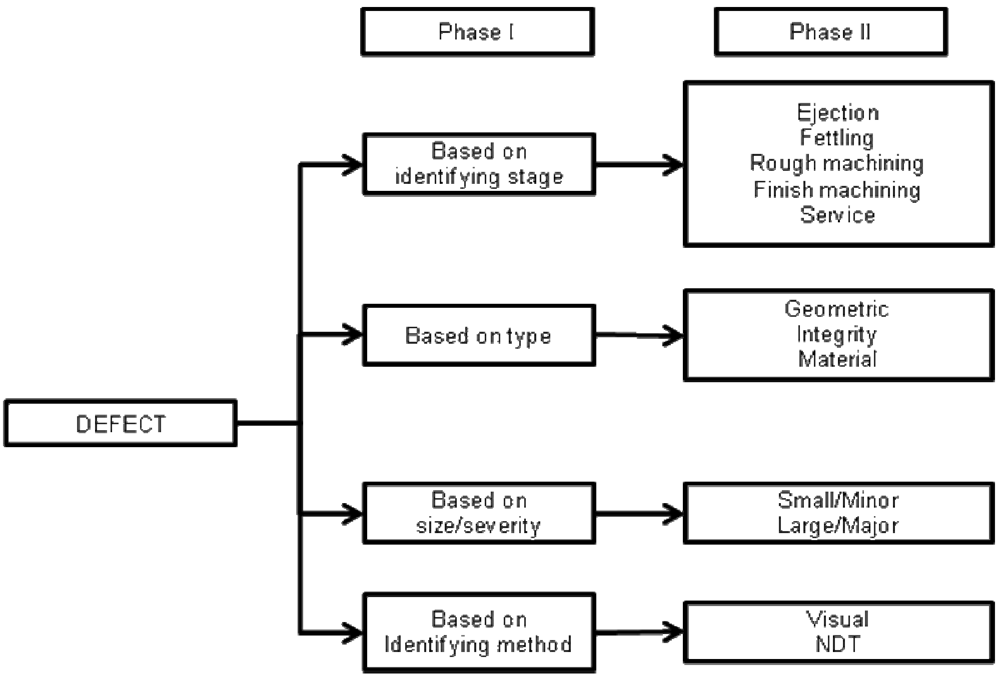


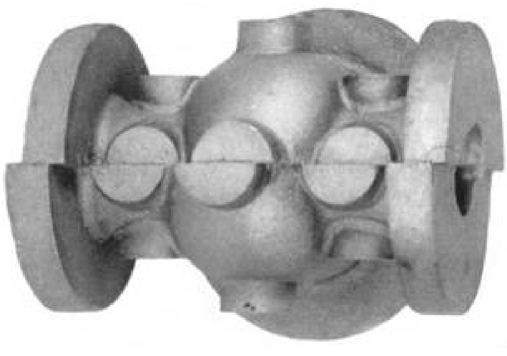
Figure 8: Proposed classification for casting defects

The proposed classification classifies casting defects in terms of their appearance, size, location, consistency, discovery stage and identifying method. This helps in correct identification of the defects.

The proposed classification of defects is of mixed type and multi-phase, as schematically shown in Fig. 8. In the first phase (phase I) the defect identifying stage, type, size/severity and identifying method is followed, taking into account the different types of controls performed on cast parts to reveal defects. Phase II is based on the sub category of the defects of phase I. Actual defect types are covered in the phase III (not shown in fig.). The final document on the classification, now in progress, a short description for each defect with illustrations and reference macro/micrographs to help readers and foundries in identifying the defects found in cast parts. One of the most common casting defects, mismatch, is illustrated in table 2. Mismatch can be easily categorized by proposed classification and it is illustrated as following.

- Mismatch is categorized as geometric defect as it affects the size, dimensions and geometry of the component. It can be further elaborated by following manner. For example: shrinkage porosity is integrity type of defect because it changes integrity of cast part, Chilled zone is property related defect in casting because it change the properties of the cast part, Mould shift is geometric type of defect as it alters geometry of cast part.

Table2.Classification of casting defect - Mismatch

<table>
<tr><td rowspan="7"></td><td>Type</td><td>Geometry</td></tr>
<tr><td>Appearance</td><td>Shearing parallel to parting line</td></tr>
<tr><td>Defect Size</td><td>Medium to large</td></tr>
<tr><td>Location</td><td>External</td></tr>
<tr><td>Consistency</td><td>Parting line</td></tr>
<tr><td>Discovery at</td><td>Cleaning</td></tr>
<tr><td>Inspection</td><td>Visual</td></tr>
</table>

- It can be categorized as medium to large size defect as size of defect is medium to large.
- It is generally discovered during cleaning operation of casting process and it can be easily identified visually so it can also be categorized under category of visual.

3.2 Proposed Approach for Analysis

For analyzing casting defects, two approaches are found in literature, one is knowledge based and other is simulation based. Being rich in experience and expertise, casting process is suitable for knowledge based analysis as casting conditions mainly relies on the experience and expertise of individuals working in production industries. But it is not safe to presume that rules of thumb which are widely used on the shop floor are accurate. Systematic knowledge accumulation regarding the manufacturing process is essential in order to study casting defects. Simulation based defect analysis also feasible but they may be limited to predict few filling related defects (blow holes) and solidification related defects (shrinkage porosity, gas porosity and hot tear). Also, simulation software is often inefficient, especially in cases where a large number of parameters are to be examined. To accomplish defect analysis taking benefits of both approaches, new hybrid approach for defect analysis is proposed. It is illustrated in fig. 9. The basic steps to analyze the casting defect are as follows:

- Choose the defect for analysis. It may be chosen on the basis of historical data.
- Identify the parameters that affect the quality of the casting. These parameters are grouped into three categories. For defect analysis, these parameters are grouped into design, material and process parameters.
- Identify the levels of these parameters as there are various parameters with different adjustment levels may influence the defects in casting. Also, for robust casting design establishment, extensive experimental work including all the parameters and adjustment levels are must.

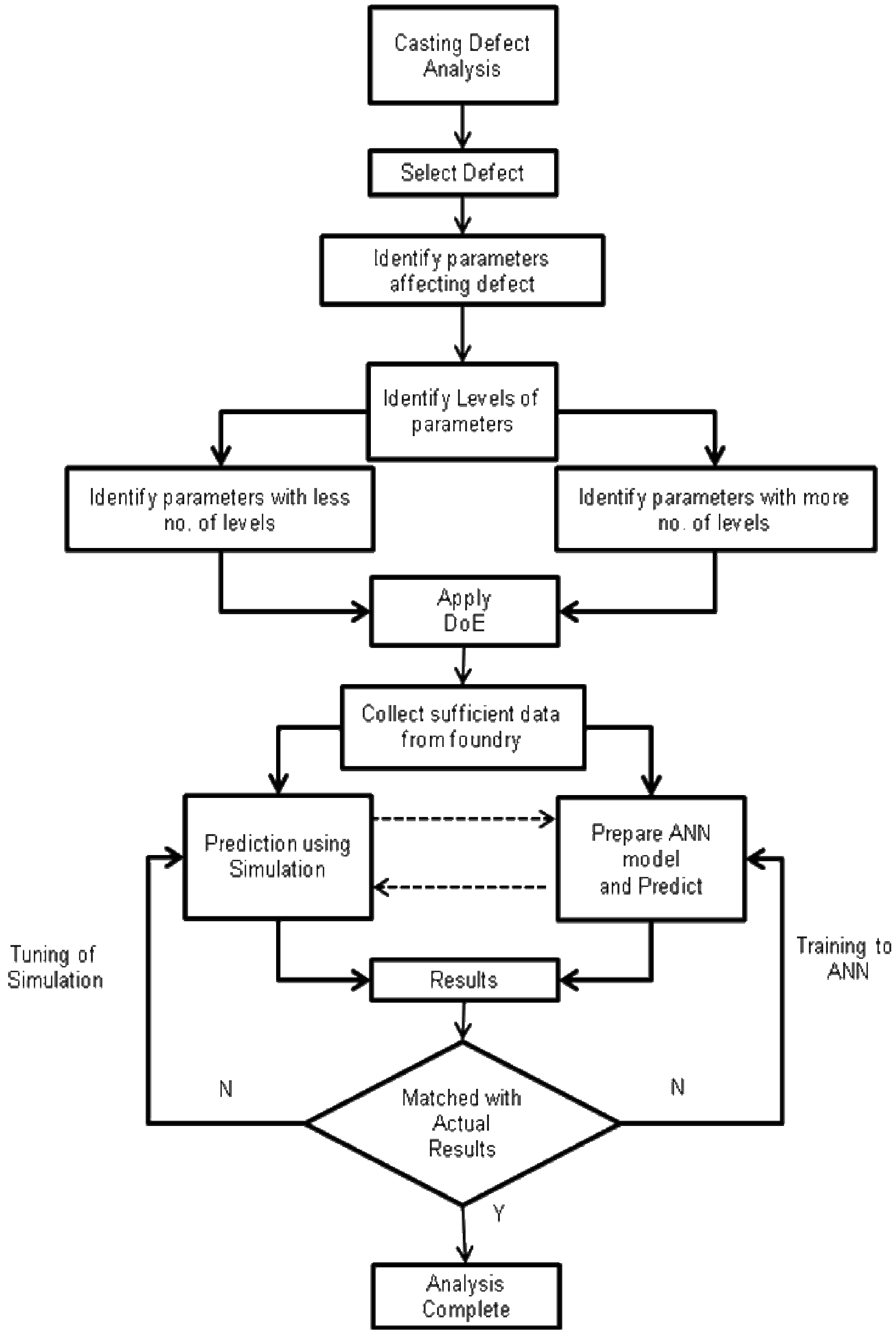


Figure 9 : Proposed approach of Defect Analysis

- Apply DoE as it is very difficult to perform experiments, in the foundry by varying so many parameters to different levels and collect the sufficient data from foundry. In the majority of foundry plants, the data available on the number of castings poured, along with the number of castings being considered as accepted or rejected as defectives before and after machining, is usually recorded. The statistical data for a selected period for any casting can be used as input to the ANN or simulation for defect analysis. It can be considered as full factorial design of experiments.

- Further, the results of defect analysis are compared with actual results. If the results are varied from actual results then these results are used to either train ANN algorithm or tune the simulation program.

The proposed approach overcomes the difficulty of controlling process parameters in foundries with manual processes and unskilled labor, by making the design more robust (less sensitive) with respect to process parameters. This will especially help SME foundries to significantly improve their quality levels.

4. Conclusions

Presently, casting defect analysis has been carried out using techniques like cause-effect diagrams, design of experiments, if-then rules (expert systems), and artificial neural networks. Most of the previous work is focused on finding process-related causes for individual defects, and optimizing the parameter values to reduce the defects. This is not sufficient for completely eliminating the defects, since parameters related to part, tooling and methods design also affect casting quality, and these are not considered in conventional defect analysis approaches. Also, defect classification of cast components proposed in literature or currently adopted by foundries are either on the basis of their geometry/location or on the basis of their metallurgical origin or specific causes. The one of the limitation of the present approach for defect analysis is that it considers only the effect of material and process parameters on occurrence of defects. It is also required to consider effect of design parameters on occurrence of defects as they play a very important role in DFM.

In a new classification methodology, classification is made based on effect of defects on casting. Accordingly, the types of defects are geometry, integrity and property related defects. In this work, we presented a 3-step approach to classify the casting defects. The defects have been classified in terms of their appearance, size, location, consistency, discovery stage and inspection method. This helps in correct identification of the defects. For defect analysis, the possible causes are grouped into design, material and process parameters. Also, to accomplish defect analysis taking benefits of both approaches, new hybrid approach for defect analysis is proposed. It helps SME foundries to significantly improve their quality levels.

5. References

1. B. Chokkalingam & S.S. Mohamed Nazirudeen,"Analysis of Casting Defect Through Defect Diagnostic Study Approach", Journal of Engineering Annals of Faculty of Engineering Hunedoara, Vol. 2, pg no. 209-212, 2009
2. B.Ravi, "Casting Simulation and Optimization:Benefits,Bottlenacks and Best Pratices", Indian foundry journal, Spcial Issue,January 2008.
3. B.Ravi,"Computer-aided Casting Design and Simulation", STTP,Nagpur,July21,2009.
4. Ben V. Takach, "The zero Defect Syndrome", Foundry, A Journal for progressive metal casters, vol. –xi, No.-1, p.p. 11-13. January/ February 1999
5. B.S. Pendse, "Foundry men-Prepare for the future", Foundry, An Indian Journal for progressive metal caters, Vol. Xi, no.-3, p.p. 45-48,May/June, 1999
6. Dr. Sumit Roy, "Total Quality Management means of survival for Indian industry, a special focus on foundries", Foundry, An Indian journal for progressive metal caters, p.p. 11-23.July / August 2003,
7. D.N. Prasad and P.K. Panda, "Production of quality castings in handfield Mn Steel", Indian foundry journal, vol. 46, no.1, p.p. 30-38January 2000.

8. Dr. P.N. Rao (2000), “Manufacturing Technology” Tata Mc-Graw-Hill publishing Company Ltd., New Delhi
9. D. Paranthaman (2000) “Quality Control” Technical Teachers Training Institute, Madras.
10. E. Gariboldi et al.," Proposal of a Classification of Defects of High Pressure Die Cast Products", la metallurgia italiana, pg. no. 39-46, 2007
11. Jiadi Wang et al.," Expert Network for Die Casting Defect Analysis", Journal of Material Science And Technology, Vol. 19 (4), pg. no. 320-323 ,2003
12. John H. Mortimer,”Foundry Technology and Market Trends into the 21 st Century”, A Journal for progressive metal casters, vol. –xi, No.-2, pp27-29 January/ Februar 1999
13. K.sieansk,S Borkowsk, “Analysis of foundry defects and preventive activities for qulity improvements of castings.”
14. K.Siekanski,S.Borkowski,”Analysis of foundry defects and preventive activities for quality improment of casting”,Metalurgija 42,57-59,2003
15. Kulkarni et al., "Casting Defect Analysis Expert System", AFS Transaction, 92-21, pg. no. 881-886.
16. M. Mahajan (1986), “Statistical Quality Control”, Dhanpat Rai & Co. (P) Ltd.
17. M.V. Kavade (1999), “Quality Management”, ISTD.
18. R.Zalewski, A.Graczyk, G.Kruszynski: “Analysis in defect in metal industry with pareto method”, problmy jakosci pp, 23-28, 1996.
19. S.N.Lyengar,“Gating and Risiring System part-2: Design of Gating System”, Foundry , An Indian Journal for progeressive Metal –caster, Vol-xi,no-1, pp-21-24, Jan/Feb. 1999.
20. Sohrab, “Quality management in foundry industry”, Indian foundry journal, vol. 41, no.-4, 11-14,April 1995