Quality casting of motor body using design of experiment and casting simulation

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Abstract: Solidification of metals stands as marvel of ultimate significance for metallurgists, casting engineers and physicist which hampers the quality of castings, material yield and cycle time. Method of solidifying in casting is intricate in natural surroundings hence the process replication is mandatory in business before it is actually enforced. Volumetric contraction allied with solidifying of liquefied metal causes defects viz: shrinkage porosity, sink and cavity. Casting defects are decreased through casting simulation software and an intellectual feeding technique. Generally, gating system controls the velocity of molten metal that affects turbulence and flowability of casting. In this research, a challenge is taken to remodel a gating system by design of experiments (DoE) and casting solidification simulation framework ('e-foundry' – a web resource with casting simulation facility) and validation of results based on experiments performed in Krislur Castomech Pvt. Ltd, Bhavnagar, Gujarat, India for minimum shrinkage porosity defect in casting.

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1 Introduction

Casting foundries in developing nations have been undergoing with adverse output or productivity and casting quality owing to connection of different influencing factors in process of casting (Campbell and Harding, 2010). It is being analysed that many practical theoretical surveys related to feeding system with casting defects have been conceded by foundry engineers and scientists in the last few decades. Just as in an exceedingly absolutely controlled method, the casting defects are witnessed and therefore casting method is additionally called method of uncertainty, encounters elucidation regarding the supply of casting defects. Exploration of casting defect en-routes the method of discovery in the foundation explanation for prevalence of defects within the rejection of casting and captivating indispensable footsteps to cut back the defects and to extend the casting profit. Since liquid metal is essentially filled up the casting cavity has to be familiarised from through gating system, it is long recognised that gating system acting is very important in casting quality.

Runyoro et al. (1992) found that collective design tools for casting and experimental calculations designed for the feeding quantitative relation, gating system size and pouring time, the different factors in casting selected by completely altered investigators have connection toward vital differences in experimental strategies. This additionally powers the foundries for holding out variety of trials and build tips supported their own expertise. Filling related defects are majorly classified into three categories: incomplete fusion, gaseous entrapment, and sand and slag inclusion. Filling related defects in casting mainly due to uncontrolled velocity of molten metal. If velocity of molten metal is in control, filling related defects can be reduced in utmost of the cast parts. Velocity of molten metal can be controlled by suitable designing of gating system. The objective of this work is to determine the relative influence of main gating system parameters such as:

1 number of ingates

2 pouring temperature

3 pouring height on velocity.

In previous few years, computer-aided design (CAD) and casting simulation tools are wide used for up casting quality and yield. It takes minor time compare to buy floor trials. Several software system packages are on the market for casting analysis like: Pro-cast, MAGMA soft, Solid cast, softCAST, etc., these software system packages simulate filling and solidification phenomena. Casting simulation experiments are computationally intensive. Investments within the range of simulations would be reduced within the length of your time spent in fitting and post-processing simulation results would permit the labour resources to be used with additional efficiency. In this paper, a replacement approach for reduction of casting defects using combination of design of experiments (Taguchi method) and computer aided casting solidification simulation technique is mentioned within the subsequent portions.

2 Literature review

From the literature survey, it is found that numerical simulations of solidification have received major attention from researchers in the past. Design of casting is de-escalated into variety of easy parts. Consequently the unsteady-state heat conductivity equation is applied to them over variety of time steps to the temperatures at totally different nodes using either finite difference method (FDM), finite element method (FEM) or, recently, vector element (VEM) approaches. In general, FEM and FDM are the most preferred methods as organisations permit a wider selection of component shapes and higher accuracy; whereas VEM is primarily based simulation programs that expect prompts for feaver. Heat-flows through the sand mould which was studied by several researchers and their accomplishment and limitations are measured here. Reis et al. (2008) successfully model the shrinkage defects throughout solidification of long and short phase freezing materials. Shrinkage defects in short phase freezing materials tends to be shrinkage porosity, whereas in long phase freezing materials defects tend to be outside of surface dejections. Seetharamu et al. (2001) deliberate the solidification incidents in sand mould for thermal stress using FEA and it is mentioned in context of the result of solidification on stress formation in casting. Sulaiman and Hamouda (2001) studied the thermal history of the sand casting method for mould filling time by FORTRAN. They have shown that finally phase freezing area is close to the casting junction. Kermanpur et al. (2008) studied the melt flow and solidification within the multi-cavity mould for automotive elements product of cast grey iron with a flywheel and brake disc. This model was developed to examine the correctness of the gating and feeding systems. They completed it to ascertain an identical heat transfer and solidification conditions for all forged elements in every multi-cavity mould, it is needed to consider symmetrical configuration. Masoumi et al. (2005) studied the results of gating system on mould filling for casting progressions. Experimental results showed that the geometry and size of gate shows the relation of the gating system and its influence on the pattern of mould filling. Hsu et al. (2009) investigated the multiple-gate runner system for gravity casting in sand mould using computational technique. Rao et al. (2009) dispensed the simulation of filling of mould. It will increase yield of the casting, improve the gating system design and mould filling pattern. Ravi and Joshi (2007) worked on computer assisted casting design and simulation. In this research work a far higher and quicker insight for optimising the feeder and gating design of castings is showcased. Here an attempt has been made to unravel the shrinkage consistence defects occurring in an exceedingly motor casing element using online e-foundry internet resource facility.

3 Problem definition

The objectives of this study is to represent motor casing optimum gating design using DoE (Taguchi method) and casting solidification simulation using online e-foundry net resource facility. In Krislur Castomech Pvt. Ltd, motor casing casting element is made from gray cast iron material and furan no-bake sand through sand casting method. The Motor casing body dimension is 313 × 350 × 536 millimetre respectively width, length and height. Mass of motor casing is 47 kg. The current motor casing element was subjected to high quantity of shrinkage body defect that was the key cause for the rejection in foundry and it is shown in Figure 1.

The objective was to get optimum gating design and develop a defect free casting with the development within the feed ability index that represents yield of risers and quality of casting which is affected by solidification characteristics. As per Ravi et al. (2008) high feed ability index implies absence of isolated hot spots in the casting, well connected feed paths and proper cooling rates to avoid solidification related defects such as shrinkage porosity. Based on literature survey, gating design was known wherever the base of hotspot was expected by simple analysis that was at the thickest section of the casting. In addition to that the importance of known criterion for evaluating the controlled solidification of casting, so called geometrical modulus which influences the solidification should be considered. Therefore, improvement based on gating system along with feeders is resolution of drawback. Online e-foundry has intrinsic options to see hot spot intensity at casting solidification process. It additionally shows high and low intensity level for decent hotspot. Through these options, the position of the feeder at thicker section is determined. Correct feeding aids have helped in obtaining the recent hotspot fully shifted within the feeder.

Figure 1 Shrinkage porosity defect in present casting component (see online version for colours)

4 Methodology

In this proposed methodology of casting defect minimisation, the DoE (Taguchi method) is employed for optimisation of gating parameters along with addition of risers (feeders) that are associated with defects like shrinkage consistence, cavity and sink. And computer assisted simulation is employed for early prediction of hot spot zone and uncontrolled feed path at solidifying process. Work flow for propose methodology of casting defect analysis is shown in Figure 2.

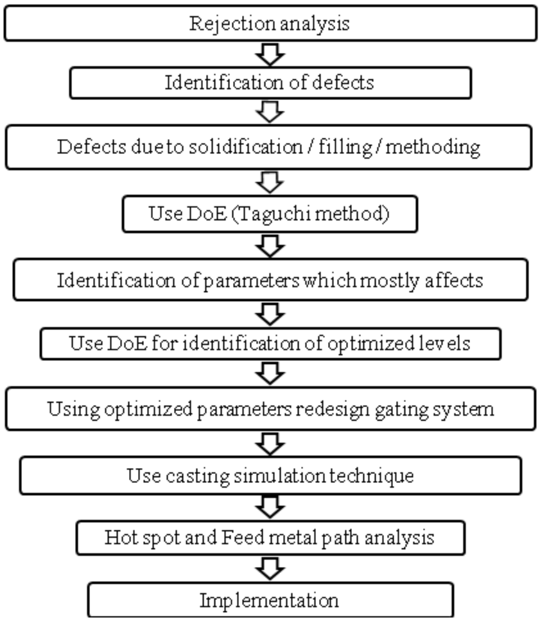
4.1 DoE (Taguchi method) for optimisation of gating design

After literature survey, it can be concluded that the Taguchi method pre-dominates possibility of designing experiments within the gating system design. Taguchi approach is acceptable in experimental design for planning and developing strong product or method dissimilar of variation in ecological conditions. This analysis is expounded with sand casting method (furan no-bake) which has numerous parameters at completely different levels and affects the casting quality. Using Taguchi method, optimum value of parameters of gating system design is employed for cut back the share of rejection ratio. The methodology used to achieve optimised gating system style parameters using DoE is as specified under:

- Selection of defects detected due to gating system design. Fixed the target 'lower casting defects' by regulating gating system design parameters.
- Selection of most significant parameters affecting defects.

- Selection of constraints and their stages. Execute the experimentations as per DoE and collect the data.
- Evaluate the results by ANOVA tool. Means and S/N ratio is planned to regulate the desired stages of constraints deliberated for testing.
- Selection of optimal levels of control parameters, accomplish validation and implement the process.

Figure 2 Work flow of casting design analysis using doe and casting simulation technique



A motor casing model was used as the check sand casting to determine the numerical optimisation. 3-D CAD model of the test casting is shown in Figure 3. This casting material is defined as grey cast iron and the weight of motor casing casting is about 48 kg.

In this experiment, top gating system of mould was used on the motor casing casting. A pour-cup and sprue were used and metal was introduced the casting cavity through two runner and five ingates that were symmetrically vertical to the casting. Two equal air-vents added to top of the motor casing for venting purpose. The gating system is controlled by three parameters namely number of ingates, pouring height and pouring temperature. With the use of assembly option various gating components are assembled with motor casing in 3-D model which is shown into Figure 3.

In this study, the sound casting consistently, the improvement criteria for motor casing casting gating system design sample were outlined as:

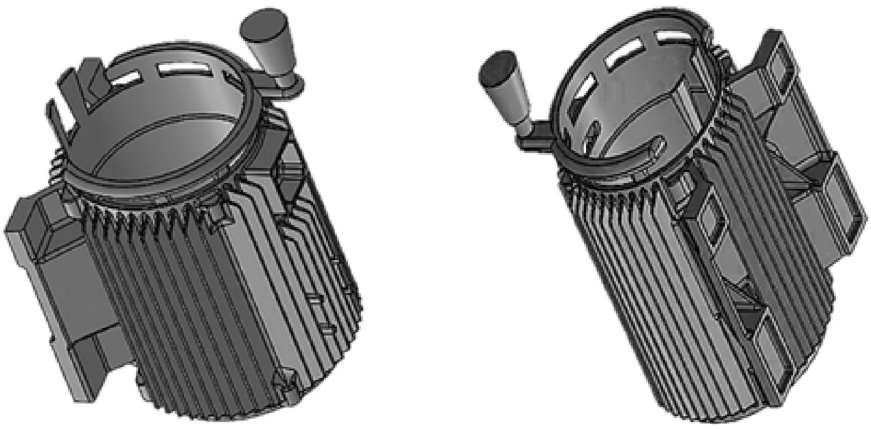
1 number of ingates

2 pouring temperature

3 pouring height.

The liquefied metal filling velocity and casting shrinkage porosity will demonstrate the casting yield and casting quality.

Figure 3 3-D model of motor casing with existing gating design



4.1.1 Experimental work

Casting gating design parameters of sand casting that influence the known defects in motor casing with their levels are shown in Table 1.

Table 1 Design parameters and their levels

Input parameter	*Level 1*	*Level 2*	*Level 3*
Number of ingates	4	5	6
Pouring temperature (°C)	1,325	1,350	1,375
Pouring height (m)	0.10	0.12	0.14

Table 2 Experimental plan using L_9 orthogonal array

Experiment number	*(A) No. of ingates*	*(B) Pouring temperature (°C)*	*(C) Pouring height (m)*
1	4	1,325	0.10
2	4	1,350	0.12
3	4	1,375	0.14
4	5	1,325	0.12
5	5	1,350	0.14
6	5	1,375	0.10
7	6	1,325	0.14
8	6	1,350	0.10
9	6	1,375	0.12

Out of three input parameters, all parameters have three levels. Therefore, L_9 orthogonal array is selected for the experimentation. Three parameters iterations like A ∗ B, B ∗ C and A ∗ C were considered. The response variable was the percentage rejection of casting due to defect that is quantitative in relation of rejection due to considered design parameters to the quantity poured. As per L_9 orthogonal array; nine experiments were performed randomly. Every experiment was performed thrice and average proportion of rejection in every experiment was considered as the response variable.

For the test, L_9 orthogonal array using three columns and nine rows was taken. The investigational arrangement for three gating system factors by orthogonal array is shown in Table 2.

4.1.2 Analysis of S/N ratio with velocity performance characteristics

The Taguchi methodology uses signal to noise (S/N) ratio relation rather than the velocity value to interpret the trial results data into a value for the evaluation characteristic within the optimum setting analysis. As a result of signal to noise ratio relation, it can replicate the velocity and variation of the standard characteristics. If the S/N ratio η is expressed in dB units, it may be outlined as equation (1) by a logarithmic function based on the mean square deviation (*MSD*) about the object:

$$\eta = -10\log(MSD) \tag{1}$$

where *MSD* is the output characteristic and to obtain optimum gating design, the better quality characteristic for product should be taken. On the other hand, the lower the better quality characteristic for filling velocity and shrinkage porosity can also be taken for getting the optimum casting quality. The *MSD* for the lower the better quality characteristic are often expressed as equation (2):

$$MSD = \frac{1}{n}\sum_{i=1}^{n} S_i^2 \tag{2}$$

where, S_i is the value of filling rate and shrinkage porosity at the i^{th} test. Filling rate is calculated by identifying time for filling of particular volume and for shrinkage porosity as per Li et al. (2007) the diameter D_{sh} of shrinkage porosity that occurs in element is evaluated by calculating the diameter of shrinkage porosity from the shrinkage porosity volume V_p and further by considering coefficients.

$$D_{sh} = \frac{E_s}{c_2 - c_1}\left(V_p - c_1\right) \tag{3}$$

where E_s denotes size of elements, c_1 denotes lower limit and c_2 denotes upper limit of fixed coefficients which depend upon size of element. The S/N ratio is calculated based on ‘smaller is better’ characteristics and it is shown below in Table 3. The lower values of S/N ratio, deviation from actual is in the range of ±3 shows better match of experiment and DoE result.

Table 3 Result of S/N ratio

Experiment no.	*Response*	*S/N ratio*
1	1.165	2.11
2	1.273	1.34
3	1.381	0.63
4	0.938	0.55
5	1.025	–0.21
6	1.125	–0.92
7	0.784	–1.32
8	0.857	–2.09
9	0.929	–2.83

4.2 Analysis of variance

The purpose of the analysis of variance is to analyse the gating system design parameters with multiple characteristics that considerably have an effect on the standard characteristic. The ANOVA was established on the sum of square (*SS*), the degree of freedom (DoF), the variance (V_p) and therefore the percentage of the contribution to the total variance (*P*). These five connective parameter symbols will be calculated as equations (4) and (5):

$$SS_T = \sum_{i=1}^{m} \eta_{ic}^2 - \frac{1}{m}\left[\sum_{i=1}^{m} \eta_{ic}\right]^2 \tag{4}$$

$$SS_P = \sum_{i=1}^{m} \frac{\left(S_{\eta jc}\right)^2}{t} - \frac{1}{m}\left[\sum_{i=1}^{m} \eta_{ic}\right]^2 \tag{5}$$

where *m* is that the variety of the experiments ($m = 9$). *p* represents one of the tested parameters, *j* is the level, number of this parameter *p*, *t* is the repetition of every level of the parameters *p*, and $S_{\eta jc}$ is total of the multi response S/N ratio involving parameter *p* and *j*. The total degree of freedom is $D_t = m - 1$, for the tested parameter $D_p = t - 1$. As the following equations (6)–(8) the variance (V_p) is outlined because the total of squares of every trial total result is concerned with the factor, divided by the degree of freedom of the factor. The corrected sum of squares (CSS_p) is outlined as sum of squares minus the error variance times the degree of freedom of each factor. The contribution (P_p) denotes the percentage of the total variance of each individual factor.

$$V_p(\%) = \frac{SS_p}{D_p} \times 100 \tag{6}$$

$$CSS_p = SS_p - D_p V_e \tag{7}$$

$$P_p(\%) = \frac{CSS_p}{SS_T} \times 100 \tag{8}$$

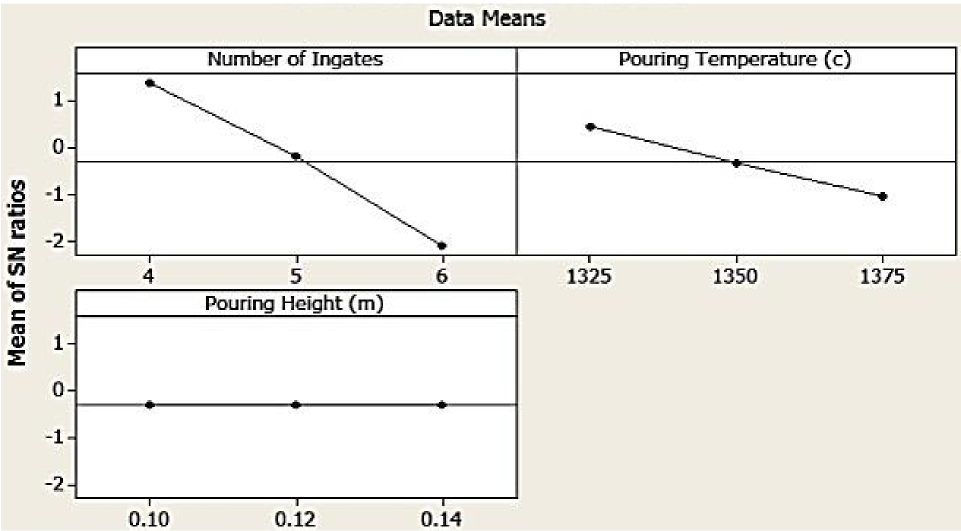
Analysis of experimental results was performed using Minitab 16 software and ANOVA and AOM plots obtained area unit are given in Table 4 and Figure 4 separately. ANOVA results in Table 4 indicate the number of ingates, pouring temperature and pouring height. Parameters for considerable contribution in percentage are shown in Table 4.

Table 4 Analysis of variance (ANOVA) results for S/N ratio

Source	*DoF*	SS_p	V_p	CSS_p	P_p, %
A	2	17.8723	8.93614	17.8723	84.41
B	2	3.2996	1.64979	3.2996	15.58
C	2	0.0001	0.00006	0.0001	0.0005
Error	2	0.0001	0.00004	0.0001	0
Total	8	21.1721			99.9905
S = 0.006654		R-sq = 100.0%		R-sq = 99.9905%	

AOM plot in Figure 4 indicates that percentage of rejection is low at third level of number of ingates, third level of pouring temperature and at every level of pouring height.

Figure 4 Main effects plot for S/N ratio (see online version for colours)



Note: Signal-to-noise: smaller is better.

4.3 Confirmation experiments

The confirmation experiment is that the final step in confirming the conclusions from the previous testing. The calculated S/N ratio relation η_{opt} exploitation the best level gating parameters are often calculated as equation (9):

$$\eta_{opt} = \eta_{tm} + \sum_{j=1}^{n} \left(\eta_{om} - \eta_{tm} \right) \quad (9)$$

where η_{tm} is total mean of the multi response S/N ratio η_{om} is mean of the multi response S/N ratio at the optimal level and n is that the number of the main design parameters that have an effect on the standard characteristics.

Three confirmation experiments were performed at the optimised settings of the method parameters, the results of that are shown in Table 5. Continuing with the application of Taguchi technique response owing to number of ingates is more compare to different parameters. Using response rank actual experiment on workplace and in casting simulation software is main confirmation of experiments and is shown in Table 5.

Table 5 Response table for confirmation experiments

Level	*Number of ingates*	*Pouring temperature (°C)*	*Pouring height (m)*
1	1.3646	0.4477	–0.3017
2	–0.1935	–0.3236	–0.3088
3	–2.0819	–1.0350	–0.3004
Delta	3.4465	1.4827	0.0084
Rank	1	2	3

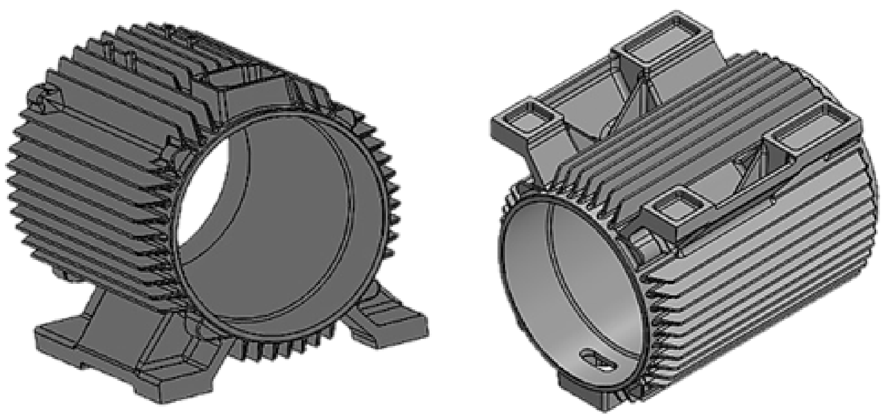
5 Computational experiments

Casting simulation technique may be efficiently used for analysis of casting defects associated with gating system like shrinkage porosity by the hotspot and casting solidification analysis. Simulation of mould filling and solidification process is for desired geometrical info for the casting, the gating system and the sand mould.

5.1 Data collection

In this phase, selected casting data concerning the present defects, process parameters, materials and gating system design is collected and analysed. Existing design of motor casing with defects is shown in problem definition phase. Solid CAD model was created using the Solidworks^{TM} 2014 software of Dassault system and it is shown into Figure 5.

Figure 5 Solid 3-D model of as-cast motor casing

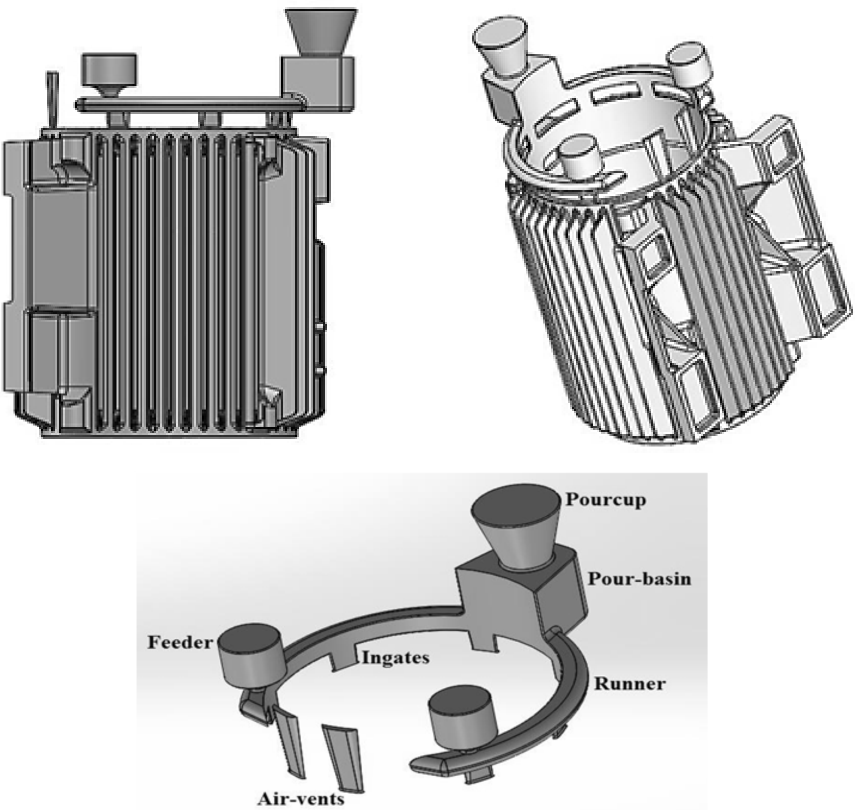


5.2 Methods design for proposed gating system

In existing method, five ingates and other gating design parts could not control the molten metal velocity and feed the casting during solidification of motor casing cavity. This gating system design was not feeding the motor casing casting correctly which resulted in shrinkage porosity in motor casing, refer Figure 1.

A proposed gating system was designed using results of DoE and hypothetical formulations for feeding and gating design. Feeder was designed by Caine method and Modulus method. Two feeders were placed at the bottom of motor casing because heavy section is easily feed with defects free area. Proposed gating system is shown in Figure 6.

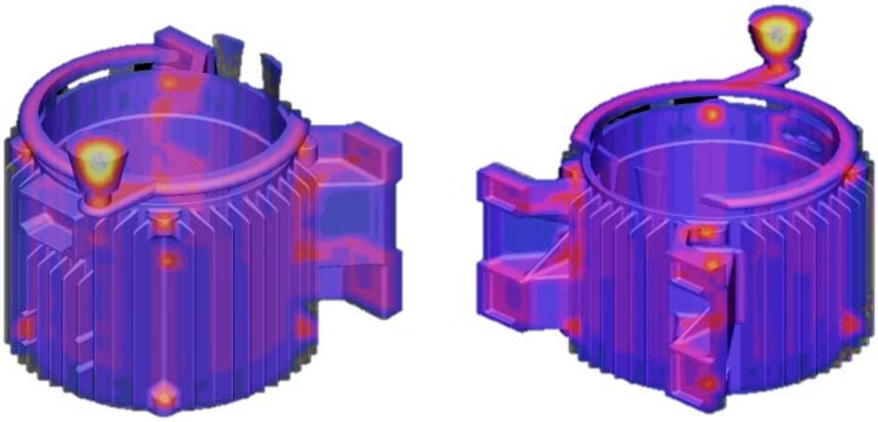
Figure 6 Proposed design of gating system of motor casing



5.3 Simulation of design of motor casing

For the solidification simulation purpose, online e-foundry web resource facility is employed for solidification analysis. In existing gating system, one pour-cup, small sprue and runner are provided to fill the mould cavity and it is shown in Figure 3. Simulations for solidification analysis with this gating system reveal that the untested shrinkage porosities of non-acceptable kind exist within the motor casing casting (refer to Figure 7). This leads to prevalence of shrinkage porosities within the casting and thus causes rejection. Therefore, it is necessary to create appropriate changes in gating system to get rid of or scale back the amount of shrinkage porosities. In proposed gating system, pour cup is directly attached with pouring basin and by results of DoE, taking number of ingates is six and two feeders are placed at heavy section of motor casing for good quality design of proposed gating system and it is shown in Figure 6.

Figure 7 Simulation results of existing design of motor casing (see online version for colours)



Notes: ▢ – hot-spots, ■ – early freezing area.

Therefore, to minimise the shrinkage porosities design of experiments (Taguchi method) is used for optimum method or gating system.

Simulation results of proposed motor casing design for shrinkage porosities or hot-spots (refer to Figure 8); show that with optimum gating system design the shrinkage porosities or hot-spots is significantly reduced up to acceptable level as compared to simulation results of existing design of motor casing. When referring Figure 8, it can be concluded that feeders placed at thick section in motor casing design work satisfactorily and lead to adequate feeding of casting throughout solidification and therefore there is reduction in level of shrinkage porosities within the casting. Also there is little shrinkage porousness within the direction of feeder and pouring basin and at thick crosswise of the casting that is of acceptable level.

Figure 8 Simulation results of proposed motor casing design (see online version for colours)

6 Result and discussion

This analysis has validated that the shrinkage body defects are reduced by Taguchi technique and casting simulation during casting software. The casting simulation-based approach helps the hot-spot location by carrying a fast casting solidification simulation. The hot-spot reduction is driven by casting quality because the proportion of casting volume is free from shrinkage body. During this analysis, it was absolutely determined that casting solidification simulation allows visualisation of the progress of freezing and changes within a casting and identification of the last freezing change regions or hot-spots. Placement of additional range of ingates and feeder at the last solidification regions shifted the hot-spot fully into feeder and managed the liquid metal velocity in mould. This approach has helped in minimising the solidification connected defects, thereby providing a defect free casting. This analysis shows that Taguchi technique and casting simulation can be of good use in optimising the gating design parameters, increasing feeding potency and minimising shrinkage related defects.

7 Conclusions

The present research has applied Taguchi method to investigate the gating system design parameters, which have been proposed to affect the velocity of molten metal in motor casing sand cast. The conclusion of study can be summarised as follows:

- An innovative technique of casting defects analysis is planned and thought of, that is arrangement of design of experiments method (Taguchi method) and computer assisted casting simulation technique for defects associated with method, filling and solidification in furan no-bake sand casting.
- Table 3 shows the best combinations of gating system which is six numbers of ingates, 1,375°C pouring temperature and 0.12 m pouring height is optimised and is efficient experiment for proposed gating system design.
- The optimised levels of selected process parameters with its contribution on process obtained by Taguchi method are:
  - a number of ingates, 84.41%
  - b pouring temp., 15.58%
  - c pouring height, 0.0005%.
- The optimum constraints for the feeding arrangement is also diverse by altered method factors from different incident within which causes and considerations have independent purposes that are ought to be outlined and support the actual engineering condition.
- The gating system design along with feeder design is also modified based on the simulation result as given in computational experiment section.

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