Optimization of Sand Casting Parameters for Reducing Casting Defects Using Taguchi Method and Casting Simulation Technique

by

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Declaration

This is to certify that the thesis work entitled "*Optimization of Sand Casting Parameters for Reducing Casting Defects using Taguchi Method and Casting Simulation Technique* "has been carried out by *Mst. Nazma Sultana* in the Department of *Industrial Engineering and Management*, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

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The Author

Abstract

The aim of the present work is to reduce the rejection rate of cast products in a foundry shop due to casting defects in sand casting process using a statistical tool namely Taguchi method and a computer aided simulation technique. Conventional techniques require a larger number of trials for checking outputs when the variety of input conditions increase and this problem can be reduced using this two techniques. In this investigation, the various casting process parameters such as moisture content (%), green compression strength (g/cm^2) and permeability number are considered and organized according to Taguchi L18 orthogonal array. Taguchi approach is utilized to find out the most significant control factors which will reduce casting defects. Besides, the percentage contribution of process parameter has been determined using statistical Analysis of variance (ANOVA). Finally, the general regression equation is formulated and better cast product is obtained with less defects and it is validated by means of confirmation test. It is observed from experimental trials in foundry shop that average value of minimum casting defect is 3.1% for aluminum flywheel. Not only that in this thesis an attempt has been taken to redesign gating and feeding system for producing a casting free from defects. Defects such as shrinkage porosity, improper solidification, air entrapment, mold erosion are directly related with gating and feeding system design. Number of iterations using casting simulation software are performed for mold filling and solidification analysis to reduce the rejection level in cast component. With new gating and feeding system design improvement in casting yield (about 15%) is observed.

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Nomenclature

A_t	Area of sprue(top)
A_c	Area of choke
h_t	Height of sprue(top)
h_c	Height of choke
t	Pouring time
d	Mass density molten metal
g	Acceleration due to gravity
H	Effective sprue height
C	Efficiency factor,0.90
Q	Metal flow rate
M_c	Modulus of casting
D	Diameter of casting
w	Mass of metal poured into the mold

CHAPTER I

Introduction

1.1 General

Sand casting is one of the versatile methods of metal shaping because it is used most frequently for intricate shape casting practically both of ferrous or nonferrous material. Further, the necessary tools required for sand casting are very simple and inexpensive. For this reason it is an ideal method for trial production or production of a small lot. It consists of pouring molten metal into a sand mold cavity, allowing the metal to solidify and then breaking away the mold for getting the cast product. However the surface finish and dimensional accuracy achieved by normal sand casting process are not adequate for final output in many cases, therefore many improvements can be done through quite modifications of casting process. Green sand casting process parameters perform a vital role for enhancing the quality of cast products. Many researchers performed their research on optimizing the value of casting process parameters to improve the quality of cast products using various techniques over the past few years. Up to now following methods are used for process design: Design of Experiments (DoE) techniques such as Taguchi approach, Response Surface Methodology (RSM), integrated approach of Taguchi approach and Response Surface Methodology (RSM), Finite Element Analysis (FEA), casting simulation techniques such as Magma 5, Quick CAST, Auto CAST X, Solid CAST simulation software's, Artificial Neural Network (ANN), Gradient Search method [1-2].

CHAPTER II

Literature Review

2.1 Literature Review

This section describes the previous works and achieved results of various researchers on casting process using different techniques. Taguchi model is suitable for robust design such as designing processes or products for minimizing variation of components or environmental conditions or variation around a target value [3, 4]. Taguchi's method was used to determine the optimal process parameters for the green sand casting process in an automobile foundry industry, India. The authors observed that process parameters (i.e., moisture content, green strength, pouring temperature, mold hardness vertical and mold hardness horizontal) significantly affect the casting defects [5]. A process window approach was applied for minimizing the error of casting cast iron flywheel [6]. The researcher showed that casting quality involves with a large number of process variables in his gear blank casting process [7].

Taguchi’s method was also used for optimizing the mechanical properties of the Vacuum V-casting process [8]. The effect of transient heat transfer, foam degradation and liquid metal flow in casting process was studied through a simple mathematical model [9]. The author determined the optimal process parameters using the Taguchi's method for the green sand casting process. The selected process factors are moisture content, green compression strength, permeability, and mold hardness which significantly affect the casting defects of spheroidal graphite cast iron rigid coupling castings [10]. Control factors are the independent variables of any experiment that have various effects on the response or output variables at different levels of input variables. They can be subdivided into qualitative control factors and quantitative control factors. Noise factors are the uncontrollable variables that influence the output variables. This factors may or may not be known. For preventing the noise factors from interfering in the experimental results special attention should be given [11]. Recently researchers applied Taguchi approach for optimizing green casting process parameters for enhancing the quality of mild steel [12]. In Aluminum re-melting process a robust design technique was applied for finding out the optimal settings of design parameters for increasing performance, reducing quality and cost [13]. Taguchi approach is applied in other casting processes. In die casting for Aluminum alloy the authors analyzed different process parameters and achieved optimal levels of die casting parameters for improving casting yield [14]. Some other techniques such as artificial neural network was applied for identifying the complex relationship in hot-deformation process. Through this network, it reduced the number of experiments required to characterize a material's behavior and also the problems associated with empirical, semi-empirical models which involve with the evaluation of a great number of constants [15].

In modern manufacturing defect free casting production is a great challenge for reducing the percentage of scrap. The formation of various casting defects is not only related with sand casting process parameters but also highly related to nature of fluid flow during the mold filling stage and type of solidification. Any improper designing of gating and feeding system results in mold erosion, air entrapment, nonuniform solidification, shrinkage porosities, lower casting yield (%) etc. Therefore it is necessary to take special care in designing gating and feeding system to obtain defect free casting. The main function of gating system is to carry clean molten metal from ladle to the casting cavity ensuring complete filling.

For a given casting geometry an optimized gating design satisfying the entire requirement is obtained by experimentation through trial and error methods. But this technique takes a long time to get the desired dimensions of the gating channels and also increases cost to the company. This problem can be solved easily by using simulation that represents the actual mold filling and solidification process, so that we can predict the results in advance before producing actual casting. Research work published on optimization of gating system recommends maximizing the casting yield, minimizing the in-gate velocity of molten metal, ensuring directional solidification, optimizing the in-gate and riser location.

In this research the contributions of various researchers on casting simulation techniques for various gating and feeding system in reducing casting defects in variety of cast parts are also studied. Gating design has a great impact on mold filling for light metal casting processes and the author provided validation of this statement through experimentation [16]. The suggestion of this authors is that optimization method assists in reducing casting related defects. The proper location, size and design of gating and feeder system improved the shrinkage porosity and cracks in cast products [17].

The authors described that proper dimension and positioning of riser and in-gates is very important in casting processes and they performed simulation for casting gear box of automobile components with the help of Auto-CAST software. They concluded that simulation of filling and gating system reduced the casting defects of cast iron in foundries

[18]. One of the critical elements that has to be considered for producing a high quality sand casting product is the gating and risering system design [19-20]. Improper design of gating and risering system results in cold shut and shrinkage porosities. These defects negatively affect mechanical properties. Therefore adequate care is necessary in designing gating and risering systems for improved yield of defect free castings [21].

It has been shown that good gating system design could reduce the turbulence in the melt flow, air entrapment, sand inclusion, oxide film and dross [22–27]. Melt flow influences solidification time, which is an important parameter that could alter the microstructure and mechanical properties of the cast part. This parameter is influenced by design and dimension of gating components and also impart on the cooling rate of the casting. Metal head height/pressure head/metal head is a vital gating component; it is the vertical distance between the metal pouring height and the top surface of the casting or simply the height of the metal in the sprue [28]. Hot spot from casting can be removed through optimum positioning and designing of riser and author has designed riser with higher value of modulus for increasing the solidification time compared to casting [29]. Computer-aided casting design and simulation is a faster tool for optimizing the feeder design of castings [30]. ABAQUS is applied for detection of casting defects during solidification of Aluminum alloy and author has concluded that most of the defects are formed where the metal solidified last [31]. Thermal analysis during mold filling time using FORTRAN has been done and the findings of this research is that the lastly solidifying area is near the junction [32]. The application of computer aided methoding, and casting simulation in foundries can minimize the bottlenecks and non-value added time in casting development, as it reduces the number of trial casting required on the shop floor [33].

Design of experiments and computer simulation technique are used combinely for analyzing sand related and method related defects of sand casting process. From this experiment they observed that newly designed gating and feeding system reduced shrinkage porosity about 15% and improvement of yield was approximately 5% [34]. In recent years simulation techniques are applied highly for increasing casting yield through reducing casting defects for different types of products. The authors applied AutoCAST-X1 simulation software for analyzing this defects for wear plate mass production. They described that vertical gating and feeding system is not suitable for thick cast metal. They proposed horizontal gating and feeding system in this case and in their experiments 30% defects are reduced [35]. For reducing the shrinkage at the joint between the axle head and the main body of the impellor of 200ZJA slurry pump was reduced only reducing the distance from risers to axle head without changing the number or the design of gating system using ProCAST software [36]. The authors observed that solidification simulation using Vector Gradient Method (VGM) enables visualization of the progress of freezing inside a casting and identification of the last freezing regions or hot spots. Placement of the feeder at the last solidifying regions did not shift the hot spot completely into the feeder. Hence, an exothermic sleeve was attached to the feeder, which has completely shifted the hot spot in the feeder and there by eliminated shrinkage defect problem. This facilitated the optimized placement and design of feeders with improvement in yield by 20 % while ensuring casting soundness without expensive and time-consuming trial runs [37].

From the above literature review it can be concluded that Taguchi method is used successfully for reducing casting defects through process parameters optimization and simulation technique helps to reduce filling and solidification related casting defects. The entire study has been carried out in two ways of optimization techniques. One is process parameter optimization that consists of following stages: preparing an orthogonal array using selected process parameters, performing experimental trials according to this array, collecting data from trial castings, finding out the influential factors using mean effect, S/N ratio plot and ANOVA analysis, forming regression equation and finally confirmation test in the selected level through castings in foundry shop. Lastly simulation technique consists of following stages, viz. analyzing the various design of multi-cavity mold with feeder and gating system, comparative analysis of the conventional and newly designed gating systems based on simulation results using Click2Cast simulation software, finding out the optimum gating and feeding system from simulation results, experimental validation with simulation results through job shop trials.

2.2 Objectives

1. To establish the optimum settings of molding sand related parameters for achieving minimum defects of selected cast component using Taguchi Method.
2. To analyze filling and solidification related defects using casting simulation technique (Click2Cast).
3. To measure the effectiveness of the proposed techniques through confirmation test.

CHAPTER III

Materials and methods

3.1 Materials

The materials used in this research are green sand as molding material and wooden pattern of flywheels. The equipment used included molding box, rammer, runner, riser, shovel, furnace, and crucible, draw screw and vent wire. For casting, aluminum alloy is collected from local market. But in simulation AlSi7Mg aluminum alloy is considered and its chemical composition is shown in the Table 1.

Table 1: Chemical composition of Aluminum Alloy (AlSi7Mg) matrix

Si %	Fe %	Cu %	Mn %	Mg %	Zn %	Ni %	Ti %	Sn%	Pb%	Others%	Al%
6.5-7.5	0.55	0.2	0.35	0.2-0.65	0.15	0.15	0.25	0.05	0.15	<0.15	92

3.2 Fabrication procedure

This section explains the casting procedure of making aluminum flywheel. Fabrication process consists of pattern making, mold box preparation, pouring metal, solidification, shake out and cleaning.

A standard size mold box of dimension 14inch × 12inch × 6inch was used. The mold cavity was to be prepared in two parts, cope, the upper part and drag, the lower part. To prevent entrapment of hot gases during pouring, vent holes were made by using a vent wire. Cope and drag were joined and mold box was prepared. Figure 1 represents the necessary tools for mold making with casting process. Standard procedures and equipment were used to evaluate the moisture content, permeability number and green compression strength of the molding sand sample. All experimental tests were carried out at Khulna University of Engineering and Technology (KUET), Khulna, Bangladesh. The moisture content test was performed using oven heat treatment. Molten aluminum at a temperature of 713^0C from the furnace was poured into the pouring basin of the mold box until the mold was filled completely. After pouring the molten metal into cavity the casting was allowed to solidify for 1 hour. After solidification, metal component was removed from its mold by shaking using a draw screw. Next cleaning process was performed for the removal of sand, scale and excess metal from the casting.

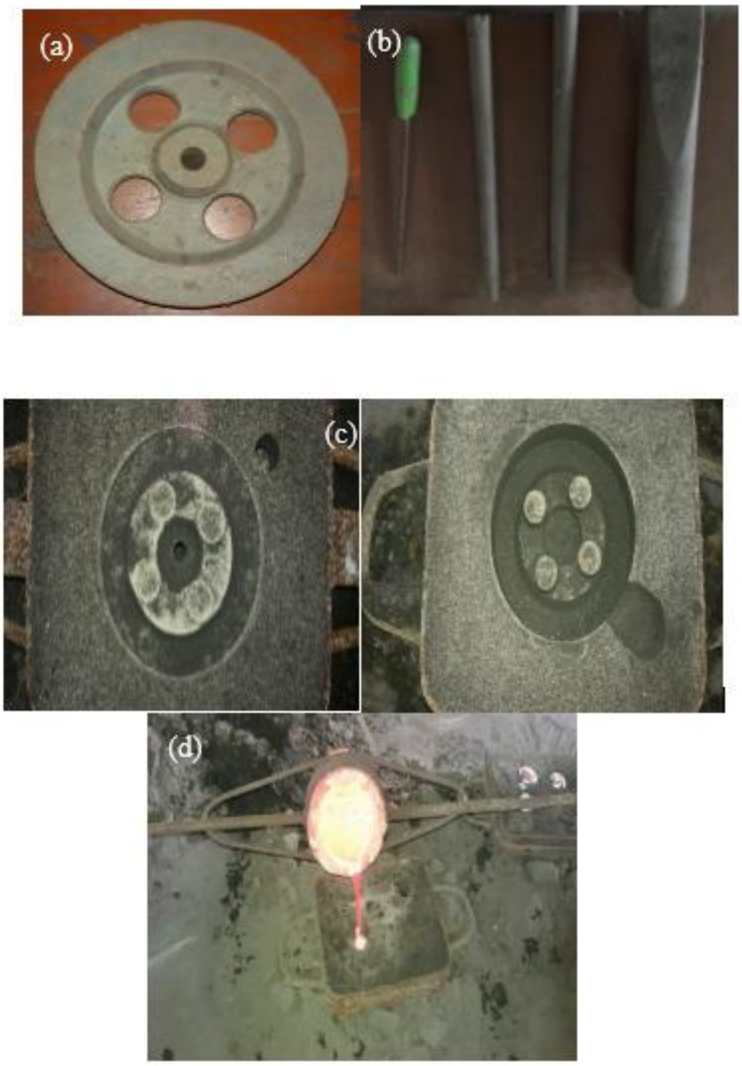


Figure 1: (a) wooden pattern; (b) casting tools; (c) mold box (cope and drag) preparation with cavity and (d) pouring molten aluminum into mold cavity

3.3 Methodology for optimization

In this proposed method of rejection rate due to casting defect analysis, the DoE (Taguchi method) is used for analysis of sand and mold related defects such as sand drop, bad mold, blow holes, cuts and washes, etc. Whereas computer aided casting simulation technique is used for filling and solidification related defects such as shrinkage porosity, air entrapment, mold erosion etc. Flow chart of proposed method of rejection rate due to casting defects analysis is shown in Figure 2.

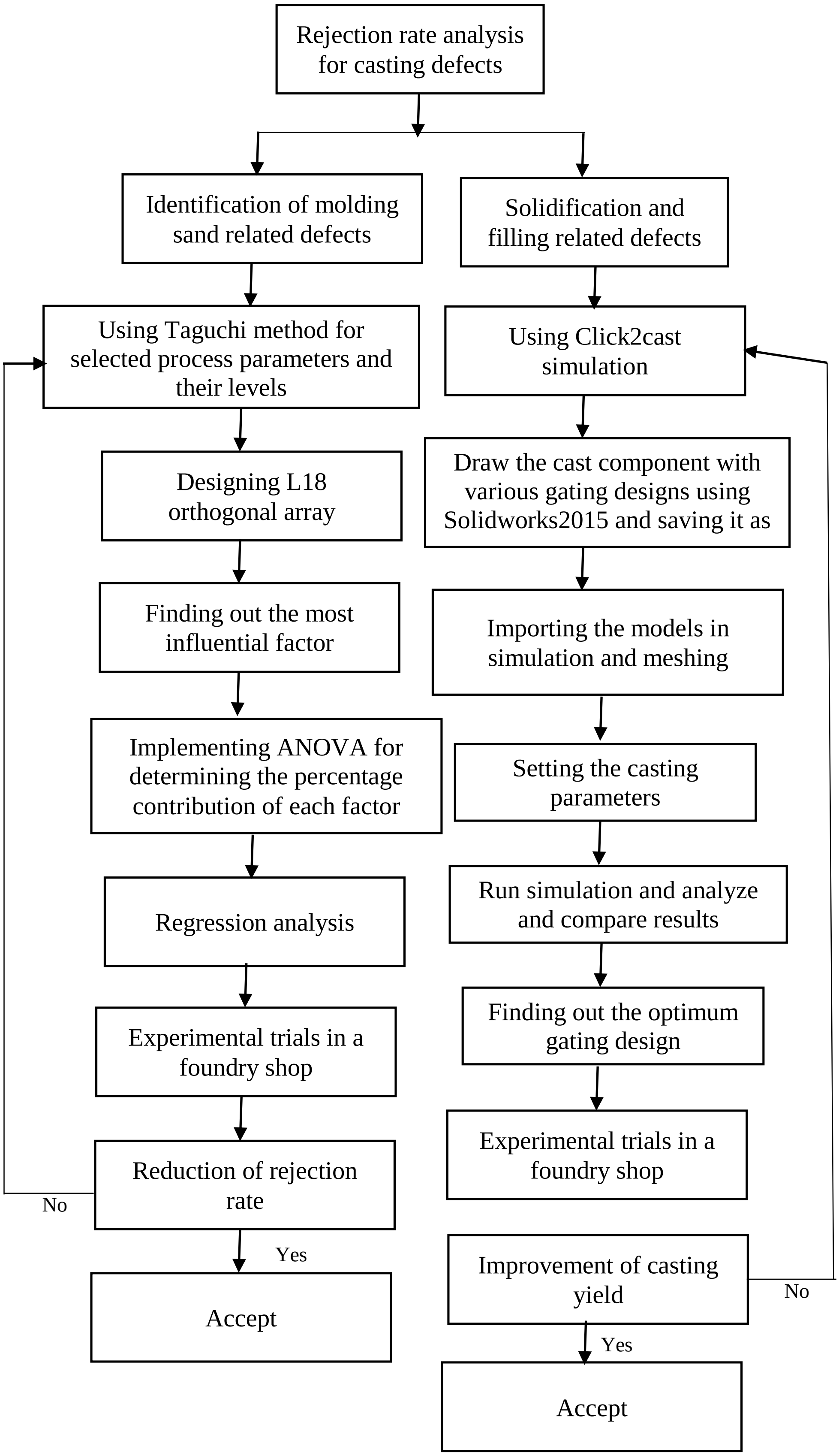


Figure 2: Optimization (proposed) techniques for casting defects analysis

3.3.1 Taguchi method

Taguchi method is an efficient problem solving tool for design of experiments when number of process parameters are involved in the process. This technique reduces significantly experimental time and cost and also improves the performance of the process, system, design and product. Taguchi approach is suitable in experimental design for designing and developing robust products or processes irrespective of variation in process parameter (within set limits) or variation in environmental conditions. For analysis the entire process parameters Taguchi method generally employs special designed orthogonal arrays with small number of experiments. This method uses the signal to noise ratio for measuring the deviation of the quality characteristic from the desired value because ‘signal’ represents the desirable value namely mean for the output characteristics and ‘noise’ represents the undesirable value or standard deviation for the output characteristics. The L18 orthogonal array has been used for this study. The three important input parameters have been considered for this process, moisture percentage, green compression strength and permeability which are shown in table 2. The present research as associated with sand casting process which involves various parameters at different levels and affects the casting quality. Considering these features of Taguchi method, it is used to reduce the percentage of rejection due to sand and molding related defects by setting the optimum values of the process parameters of the green sand casting. The methodology used to achieve optimized process parameters using Taguchi is as given below:

1. To select the influencing process parameters with their levels and perform the trial casting as per Taguchi method, then collect data.

2. To analyze the data using statistical tools. An Analysis of variance (ANOVA) can be obtained to determine the statistical significance of the parameters. Means plots can be plotted to determine the preferred levels of parameters considered for experimentation. Regression analysis is performed to determine the relationship between dependent and independent variables.

3. Select optimum levels of control parameters, perform confirmation experiments and implement the process.

3.3.2 ANOVA (Analysis of variance)

ANOVA is one of the most common statistical techniques for determining the percentage contribution of each input parameter on the results of experiments. Formally, ANOVA helps in testing the significance of all input factors and their interactions through comparing the mean square against the estimation of experimental errors at specific confidence levels. The main reason of using ANOVA in this analysis is to measure the significance of each process parameters on casting defects.

Table 2: Experimental layout of L18 orthogonal array

Input parameters	Trial No.																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Corresponding value for levels
Moisture percentage	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	1=4% 2=5%
Green compression strength	1	1	1	2	2	2	3	3	3	1	1	1	2	2	2	3	3	3	1=1200g/cm^2 2=1300 g/cm^2 3=1400 g/cm^2
Permeability number	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1=90 2=120 3=140

3.3.3 Simulation technique for casting defects analysis

Simulation is the process of imitating a real phenomenon using a set of mathematical equations implemented in a computer program. The following steps of Figure 3 are followed in this thesis for simulation analysis.

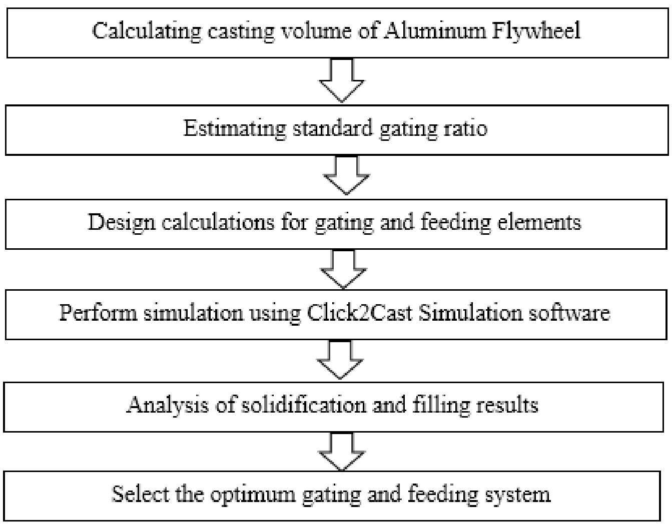


Figure 3: Casting simulation-optimization methodology

The simulation programs are based on finite element analysis of 3D models of castings and involve sophisticated functions for user interface, computation and display. The casting model (with feeders and gates) has to be created using a solid modelling system and imported into the simulation program [38]. In casting simulation the mold filling and solidification analysis is done by using an algorithm or program based on finite volume method, to identify the hot spots and hence defects like shrinkage porosities, air entrapment, etc**.**

CHAPTER IV

Experimental results & Discussions

4.1 Process parameter optimization results

4.1.1 Taguchi method analysis results

At first sand casting is performed according to L18 orthogonal array of Taguchi approach. Table 3 represents the experimental mean values of casting defects which are visually inspected. Rejection rate is determined from the ratio rejected metal due to casting defects to the amount of metal poured.

Table 3: Experimental layout of L18 orthogonal array Input process parameters and output characteristics of L18 orthogonal array

Trial No.	Input process parameters			Output characteristics	
	Moisture content (%)	Green compression strength (g/cm^2)	Permeability number	Average rejection rate due to Casting defects (%)	S/N ratios
1	4	1200	90	3.33	-10.4489
2	4	1200	120	3.00	-9.5424
3	4	1200	140	3.67	-11.2933
4	4	1300	90	5.00	-13.9794
5	4	1300	120	4.00	-12.0412
6	4	1300	140	4.00	-12.0412
7	4	1400	90	4.33	-12.7298
8	4	1400	120	5.00	-13.9794
9	4	1400	140	4.67	-13.3863
10	5	1200	90	4.67	-13.3863
11	5	1200	120	5.00	-13.9794
12	5	1200	140	3.33	-10.4489
13	5	1300	90	4.00	-12.0412
14	5	1300	120	3.67	-11.2933
15	5	1300	140	5.00	-13.9794
16	5	1400	90	4.00	-13.9794
17	5	1400	120	5.00	-13.5339
18	5	1400	140	5.33	-14.5345

In this research one time recycled sand is used and three important properties (Moisture content, Green compression strength, Permeability) are considered where the first property has two levels and other twos have three levels. All the combinations are used for two times castings. Figure 4 clearly represents the percentage of rejection for casting defects in different trials. It is observed from the above analysis that the minimum value of rejection for casting defects is approximately 3.00% which is achieved at 4% moisture content with 120 permeability number and1200 g/cm^2 green compression strength.

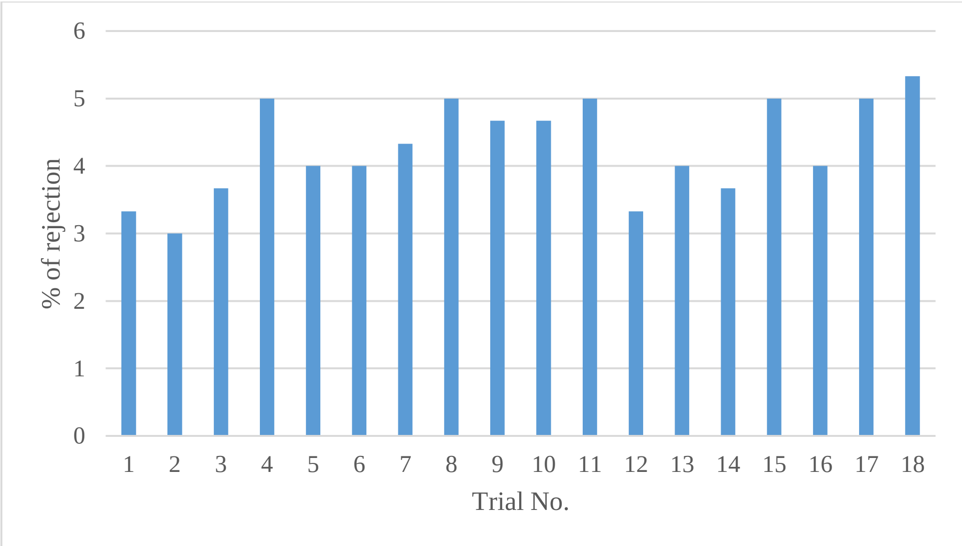


Figure 4: Percentage of rejection for casting defects at different levels

4.1.2 Signal-to-noise [S/N] ratio results

In this study, rejection rate due to casting defect is considered as the main characteristic. The MINITAB®17 software is used to calculate the influence of process parameters on rejection rate due to casting defects response. In order to assess the influence of factors on the response, the mean and the Signal-to-noise ratio for each control factor are calculated and represented in table 4. The decisive factor - 'smaller is better' is used for choosing the S/N ratio. The response table for means and S/N ratio are shown in the tables 4 and 5.

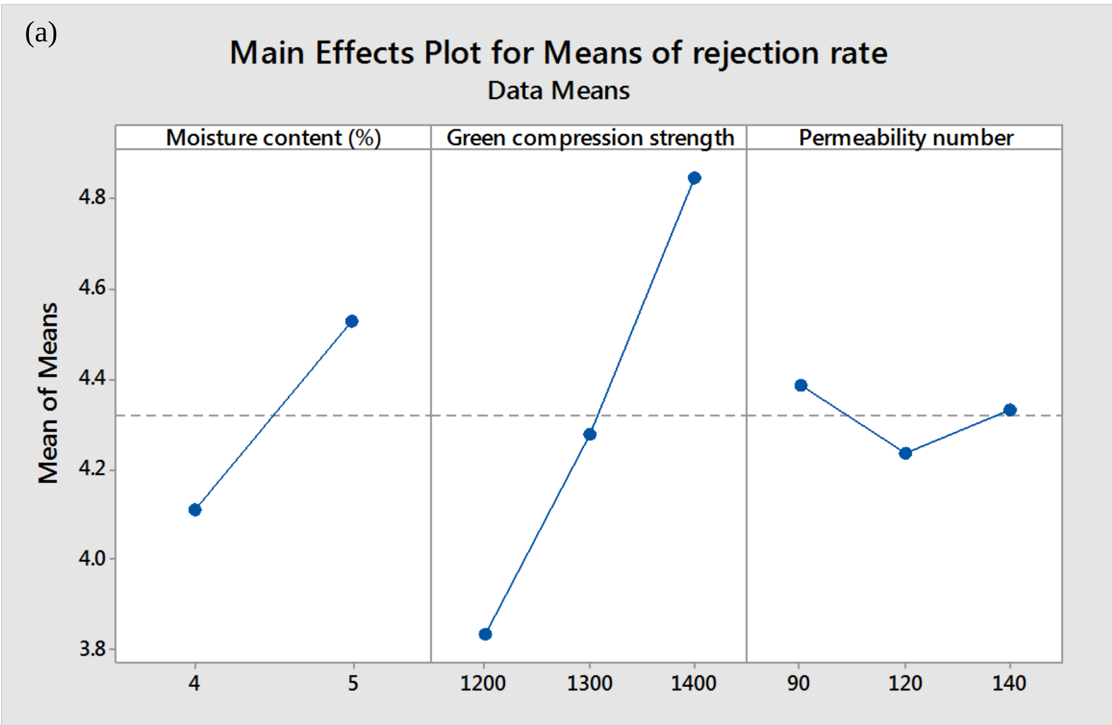
Table 4: Response table for means of rejection rate for casting defects at various levels of input parameters

Level	Means of rejection rate for casting defects		
	Moisture content (%)	Green compression strength (g/cm^2)	Permeability number
1	4.111	3.833	4.388
2	4.444	4.278	4.112
3	-	4.722	4.333
Delta	0.333	0.888	0.277
Rank	2	1	3

Table 5: Response table for S/N ratios of rejection rate for casting defects at various levels of input parameters

Level	S/N ratios of rejection rate for casting defects		
	Moisture content (%)	Green compression strength (g/cm^2)	Permeability number
1	-12.16	-11.52	-12.76
2	-12.85	-12.56	-12.15
3	-	-13.44	-12.61
Delta	0.86	2.17	0.37
Rank	2	1	3

The figures 5(a) and 5(b) represents the main effect plots for means and S/N ratio of casting defects, respectively. From this tables and figures, it can be concluded that green compression strength of green sand mold is the most influential factor for changing the percentage of casting defects and permeability has less effect. This results agree with previous research studies [34]. Rejection rate is minimum in first level of moisture content (4%) and green compression strength (1200 g/cm^2) and second level of permeability (120) from main effects plot of both mean values and S/N ratios respectively.



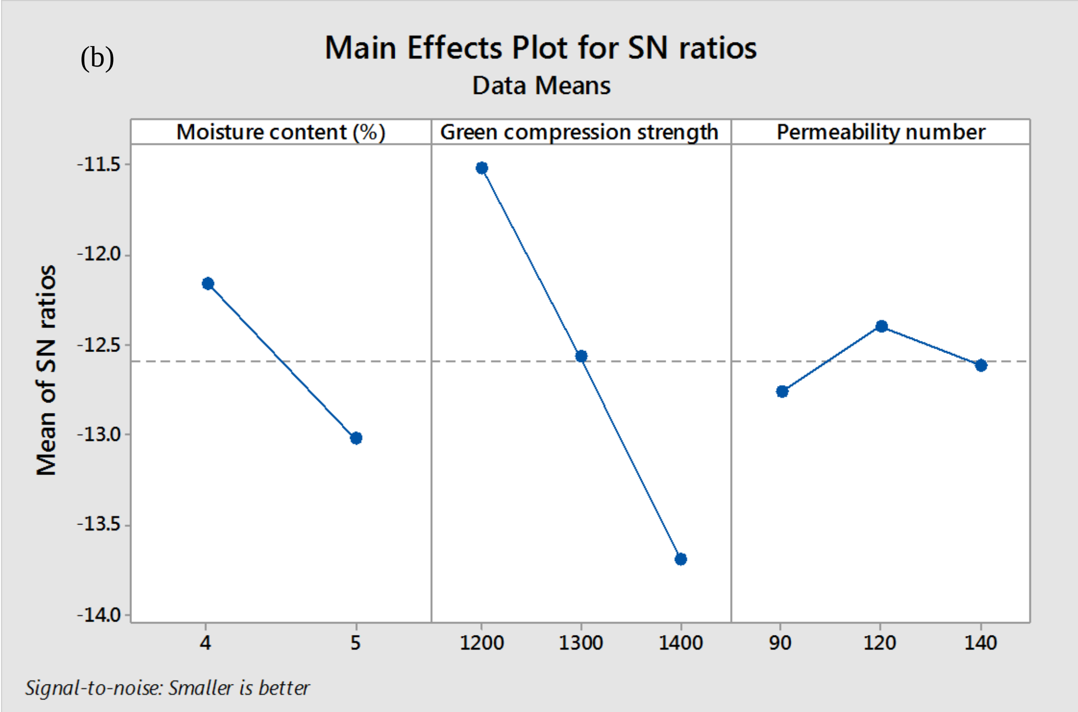


Figure 5: Main effect plots for (a) mean values and (b) S/N ratios of rejection rate due to casting defects

4.1.3 Analysis of variance (ANOVA) test results

ANOVA is one of the most commonly used statistical tools for determining the percentage contribution of each parameter in any process analysis. In this study green sand casting is performed for making aluminum flywheel and the factors which are responsible for casting defects are found by using this ANOVA method. The software MINITAB®17 is used to calculate the percentage contribution of each process parameter to the overall casting defects. The tables 6 and 7 show the results obtained using ANOVA for both mean rejection rate and S/N ratios of rejection rate for casting defects. In this investigation, the results acquired from the ANOVA process implies that the green compression strength has majority of percentage contribution for the casting defects of about 36% and 37% in mean values and S/N ratios sequentially. Figure 6 represents the percentage of contribution by each factor through bar charts. It is found that moisture content is the second largest influential factor for increasing casting defects.

Table 6: ANOVA analysis for average rejection rate for casting defects at 95% confidence level with percentage contribution of each parameters

Source	Sum of squares (SS)	Degrees of Freedom (DF)	Mean of squares (MS)	F ratio	P value	R^2 (%)	S	Percent contribution (%)
Moisture content	0.78125	1	0.78125	1.68	0.231	56.8	0.682149	9.02
Green compression strength	3.095	2	1.54787	3.33	0.089			36
Permeability	0.07	2	0.03537	0.08	0.927			0.81
Moisture content×Green compression strength	0.93	2	0.46565	1.0	0.409			10.8
Moisture content×Permeability	0.015	2	0.0076	0.02	0.984			0.17
Error	3.72	8	0.465					
Total	8.61125	17						

Table 7: ANOVA analysis for S/N ratios of rejection rate for casting defects at 95% confidence level with percentage contribution of each parameters

Source	Sum of squares (SS)	Degrees of Freedom (DF)	Mean of squares (MS)	F ratio	P value	R^2 (%)	S	Percent contribution (%)
Moisture content	3.3234	1	3.3234	1.68	0.231	58.79	1.41	8.7
Green compression strength	14.1857	2	7.09283	3.59	0.07			37
Permeability	0.4068	2	0.20342	0.1	0.903			1.1
Moisture content×Green compression strength	4.5119	2	2.25593	1.14	0.366			11.8
Moisture content×Permeability	0.1107	2	0.05535	0.03	0.972			0.2
Error	15.7964	8	1.97455					
Total	38.3394	17						

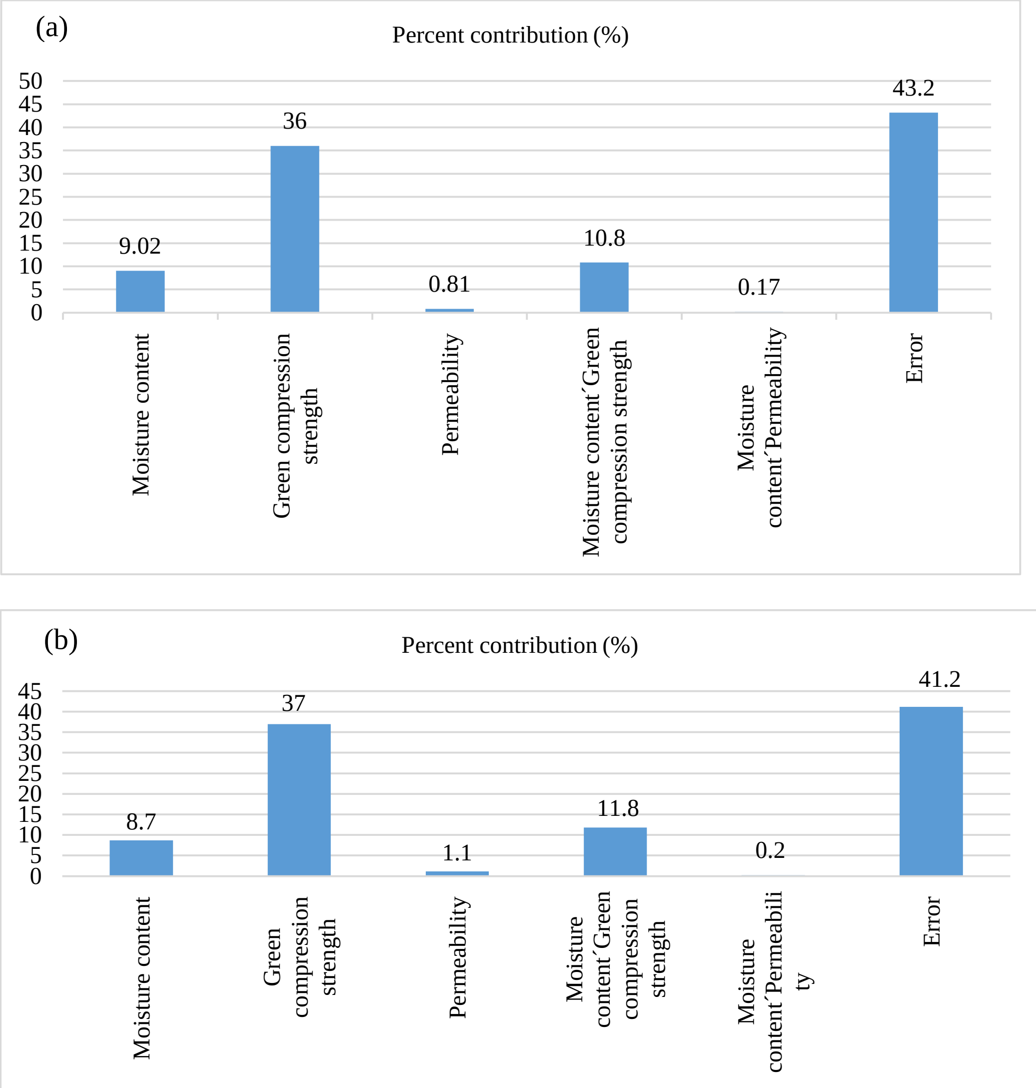


Figure 6: (a) Percentage contribution of process parameters in mean values of rejection rate for casting defects and (b) Percentage contribution of process parameters in S/N ratios of rejection rate for casting defects

4.1.4 Regression analysis results

The regression analysis is a numerical means for the examination of interaction between various parameters. In this study, the optimal rejection rate for casting defect is obtained by means of regression analysis using MINITAB® 17. The feature of the regression equation is formed by providing input and output parameters in the Taguchi L18 orthogonal array. This helps to determine the cause result of one variable upon another. The equation is formed based on the value of three factors and two interactions. In this study, the regression equations of rejection rate for casting defects are obtained by the input parameters such as moisture content (%), green compression strength (g/cm^2) and permeability number. The regression equation for rejection rate is shown below:

$$Rejection\ rate\ (\%) = -21.5 + 4.31\ Moisture\ content + 0.0195\ Green\ compression\ strength - 0.0116\ Permeability\ number - 0.00320\ Moisture\ content * Green\ compression\ strength + 0.0023\ Moisture\ content * Permeability\ number \quad \ldots\ldots (1)$$

Table 8 represents the experimental values, predicted values (from regression equation) and residuals of casting defects for 18 trials.

Table 8: Residuals of average rejection rate for casting defects in various trials

Trial No.	Experimental values of rejection rate for casting defects (%)	Optimum values of rejection rate for casting defects (%)	Residuals
1	3.33	3.51228	-0.182281
2	3.00	3.43596	-0.435965
3	3.67	3.38509	0.284912
4	5.00	4.17895	0.821053
5	4.00	4.10263	-0.102632
6	4.00	4.05175	-0.051754
7	4.33	4.84561	-0.515614
8	5.00	4.76930	0.230702
9	4.67	4.71842	-0.048421
10	4.67	4.18860	0.481404
11	5.00	4.18018	0.819825
12	3.33	4.17456	-0.844561
13	4.00	4.53526	-0.535263
14	3.67	4.52684	-0.856842
15	5.00	4.52123	0.478772
16	5.00	4.88193	0.118070
17	4.75	4.87351	-0.123509
18	5.33	4.86789	0.462105

The corresponding value of input factors are considered for calculating the minimum casting defects of work piece by using regression equation. The rejection rate for casting defect is 3.43% obtained from above equation, corresponding values for each factor moisture content (%), green compression strength and permeability number are 4%, 1200 g/cm^2 and 120 respectively. The values are substituted in the provided equation. Experimental values and predicted values (from regression equation) of rejection rate for casting defects for means are also clearly described in figure 7.

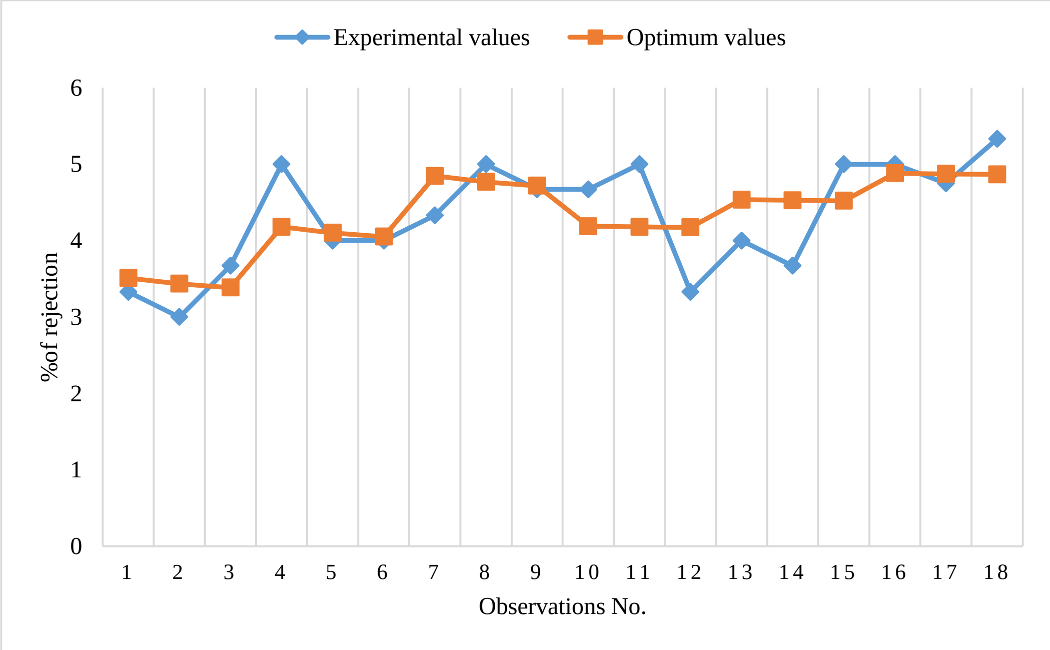


Figure 7: Experimental and optimal values of average rejection rate for casting defects in 18 trials

4.1.5 Confirmation test results

The main objective of confirmation run is to determine that the selected control parameter values produce better results than those produced in the conventional experiment. Total ten confirmation experiments are conducted in foundry shop at the optimal settings of the process parameters which is shown in table 9. The average of the rejection rate for casting defect value is 3.103%. But in conventional method the percentage of rejection rate for casting defects was 5.7%. So it can be declared that the selected parameters with their levels are significant enough to obtain the desired result.

Table 9: Results of the confirmation experimental runs in selected levels of parameters

	Experimental runs at optimal settings of parameters										Average rate of rejection%
	1	2	3	4	5	6	7	8	9	10	
Percentage rejection in experiment (%)	3.11	2.8	2.69	3.45	3.3	3.07	3	3.5	2.98	3.13	3.103

4.2 Solidification and filling related defects analysis using casting simulation technique

As per the foundry requirement, Aluminum (AlSi7Mg) has been used as a casting material. Green sand is selected as mold material. The specifications of the cast parts are 165 mm diameter, 32 mm height with a center hole of 13 mm diameter, and four holes. Wooden pattern is used for getting good quality of mold cavity and casting and it is easily available at a cheap rate.

4.2.1 Conventional gating and feeding system

Studying the conventional design of gating and feeding system of multi-cavity mold is one of the prerequisite steps of proposing a new design of gating system for minimizing casting defects. The first observation is that, in the conventional process no theoretical calculations are applied. The horizontal top gate and riser are used for filling of molten metal into the cavity with no runner extension. Riser is placed on the top center of the plate as well as the height and diameter of riser is 76.2mm and 13mm sequentially. The other dimensions of sprue, runner, and in-gate are shown in table 10 where, D=Diameter, H=Height, L=Length, W=Width.

The total volume of cast aluminum flywheel=466856mm^3

Table 10: Dimensions of conventional gating and feeding system

Type	Sprue (mm)			Sprue base well (mm)		Runner(mm)			Riser(mm)		In-gates(mm)		
Conventional gating and feeding system	D(base)	D(top)	H	D	H	W	L	H	D	H	W	L	H
	12.7	25.4	76.2	25.4	16	25.4	50.8	8	13	76.2	-	-	-

4.2.2 Designing and positioning of elements of proposed gating and feeding system

In this step a new design of gating system is proposed and comparative analysis is performed for conventional and proposed design. For attaining the goal of our research, proper dimensioning and positioning of sprue, runner, riser and in-gates are determined based on various established mathematical calculations. Total seven iterations are performed with various dimensions of gating elements that are shown in appendices. Any Casting design mainly consists of three basic designs: pattern design, gating system design and finally the feeder/riser design. Pattern allowances are provided in casting processes for compensating dimensional and structural inaccuracies. Not only that some other allowances such as machining allowance, draft allowance and shrinkage allowance etc. are also considered. The molten metal flows from the sprue to cavity through runner and in-gates. So the proper dimensions and positioning of sprue, runner and in-gates have a great influence on casting defects.

Element 1: Pouring basin

It is not a wise decision to pour molten metal directly into the mold cavity because it may cause mold erosion. The main function of pouring basin is to reduce the momentum of the liquid flowing into the mold. For preventing turbulent flow of metal through sprue the entrance into the sprue contains a smooth radius [39]. It is also desirable for Aluminum casting because of preventing formation of oxide skins. Figure 8 shows the 3D view of conventional and proposed pouring basin with dimensions for this analysis.

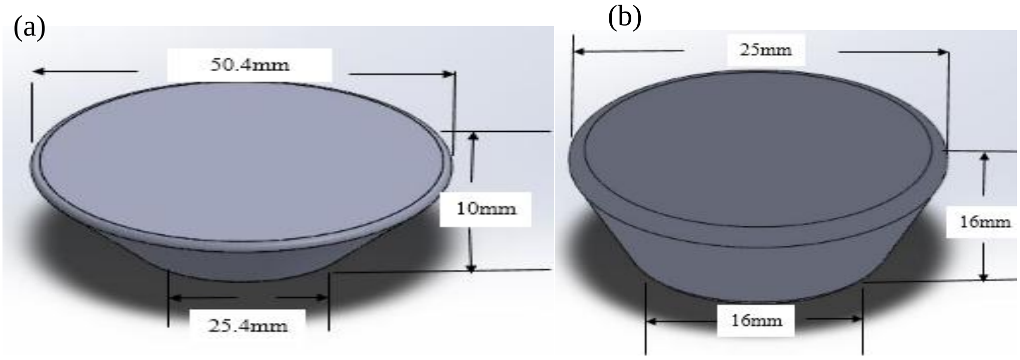


Figure 8: 3D view of (a) conventional and (b) proposed pouring basin

Element 2: Sprue and sprue base well

The passage which connects the pouring basin to the runner or in-gate is called sprue. It is generally designed taper shaped in downward to avoid aspiration of air in sand casting because straight cylindrical shape creates a low pressure area around the metal of the sprue. The exact tapering dimension and choke area are measured using equation 2 and 3 [39]. Sprue base well is a reservoir for metal at the bottom of the sprue which reduces the mold erosion through reducing the momentum of flow metal. Generally the well diameter for one runner system is twice the width of a runner. 3D view of sprue with sprue base well is represented in Figure 9.

For tapered dimensions, $\frac{A_t}{A_c} = \sqrt{\frac{h_c}{h_t}}$ ……………………………….. (2)

Choke Area, $A_c = \frac{W}{dtC\sqrt{2gH}}$ mm^2 ……………………...……… (3)

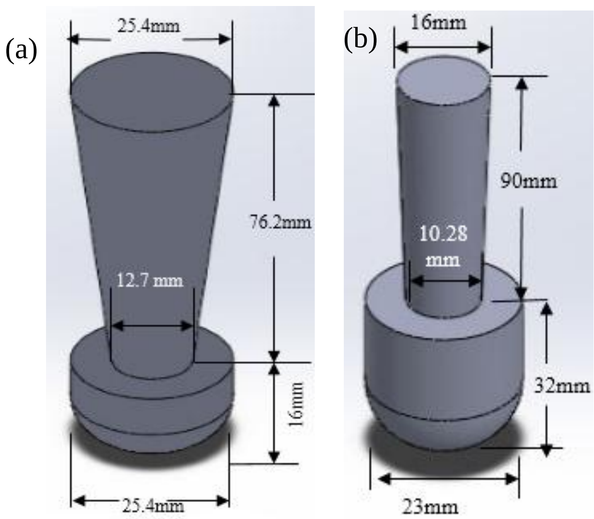


Figure 9: 3D view of (a) conventional and (b) proposed sprue with sprue base well

Element 3: Runner with its extension

It is generally located in the horizontal plane (parting plane) which connects the sprue to its in-gates. The main considerations of runner design is its dimension because if the size of in-gates is larger than runner then uniform flow will be disturbed and runner extension is provided in this design because it helps to trap the slag of molten metal.

Element 4: In-gates

The connection between runner and mold cavity is maintained through this small passage. The cross section of in-gates may be square, rectangular and trapezoidal. The in-gates are generally made wider compared to depth, up to a ratio of 4. In this study two partial in-gates with same dimensions are provided. Pressurized gating system with gating ratio 1(sprue):2(runner):1(in-gate) is used in this analysis. In non-Pressurized gating system approximate gating ratio 1(sprue):4(runner):4(in-gate) is used [39].

Element 5: Riser and its positioning

Shrinkage is a very normal nature of molten metal during solidification. The function of a riser is to feed the casting during solidification so that no shrinkage cavities are formed. For that reason it is also named feeder. In this analysis the optimum riser size is determined using Modulus method. Two center risers are used for this casting which provides directional solidification and the dimensions are calculated using following formulas.

Diameter of Riser, $D_r = 6M_c$

M_c = Modulus of casting

Modulus of casting, $M_C = \frac{DH}{2(D+2H)}$ …………………. (4) [39]

D= diameter of casting, H= height of casting

Using the above mathematical equations dimensions for different gating and feeding components are derived which are shown in table 11.

Table 11: Dimensions of proposed gating and feeding system
(D=Diameter, H=Height, L=Length, W=Width)

Type	Sprue (mm)			Sprue base well (mm)		Runner(mm)			Riser(mm)		In-gates(mm)		
optimized gating and feeding system	D(base)	D(top)	H	D	H	W	L	H	D	H	W	L	H
	10.28	16	90	23	32	18	200	16	40	100	10	40	8

Casting Yield:

The casting yield is the proportion of the actual casting mass to the mass of metal poured into the mold expressed as a percentage.

$$\text{Casting yield} = \frac{W}{w} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(5)} \qquad [39]$$

W= actual casting mass, w= mass of metal poured into the mold

4.2.3. Comparative analysis of conventional and proposed gating and feeding system

This section highlights the application of Click2cast software for analyzing casting defects during filling and solidification of molten metal.

4.2.3.1 PART Module

The prerequisite of this software is to create the part model in CAD software and save it as a standard STL format for importing in Click2Cast. The simulation is carried out for AlSi7Mg-Green sand casting process. Process parameters such as the melting point of aluminum 713^{0}C, green sand temperature 20^{0}C, and gravity flow of molten metal are selected for simulation. Figure 10 shows the 3D view of flywheel with conventional and optimized gating and feeding system. The casting is automatically meshed into cubic elements for internal computations such as thickness, solidification and mold filling. The mesh size is defined as 2 mm.

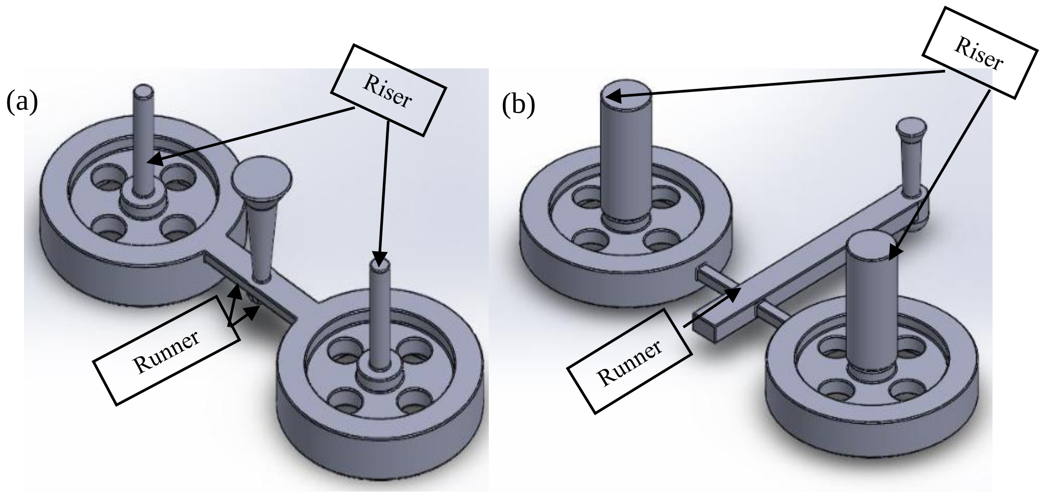


Figure 10: CAD models of (a) conventional and (b) proposed gating and feeding design of flywheel

4.2.3.2 Filling process analysis results

Filling process is simulated to view the flow of molten metal through the gating system and to predict the filling related defects such as air entrapment, mold erosion etc. This helps in verifying the optimal gating system. Air entrapment into cast element helps to produce blow holes. In this study air entrapment is shown using blue colored dots. In conventional gating system air is entrapped into the product which is completely replaced from the cast body to gating and feeding location in modified deign which is shown in figure 11.

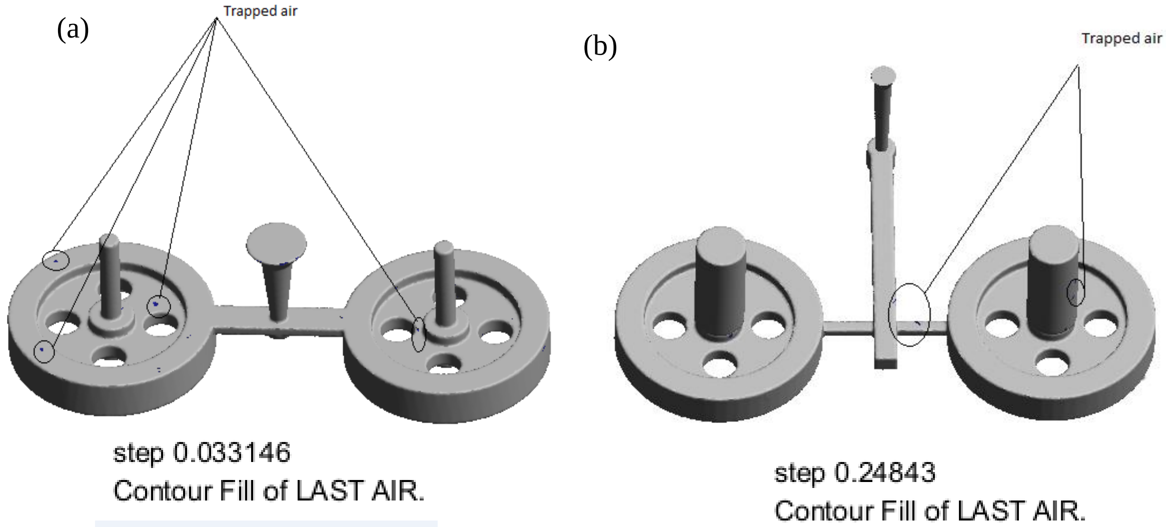


Figure 11: Air entrapment result of (a) conventional and (b) proposed gating and feeding design

Mold erosion is also analyzed in this step. The main reason of occurring mold erosion is high velocity of flowing molten metal into the cavity. From simulation results it is found that in conventional gating system the maximum velocity of liquid flow from sprue to runner is 403.74 m/s but in modified gating design provides only 152.58 m/s velocity and in this design the molten metal cannot enter the cavity directly from runner so the entering velocity is much more lower than conventional design. Mold erosion is almost disappeared in modified gating system but in conventional gating design percentage of mold erosion is appeared in most of the regions of cast product which is viewed in figure 12.

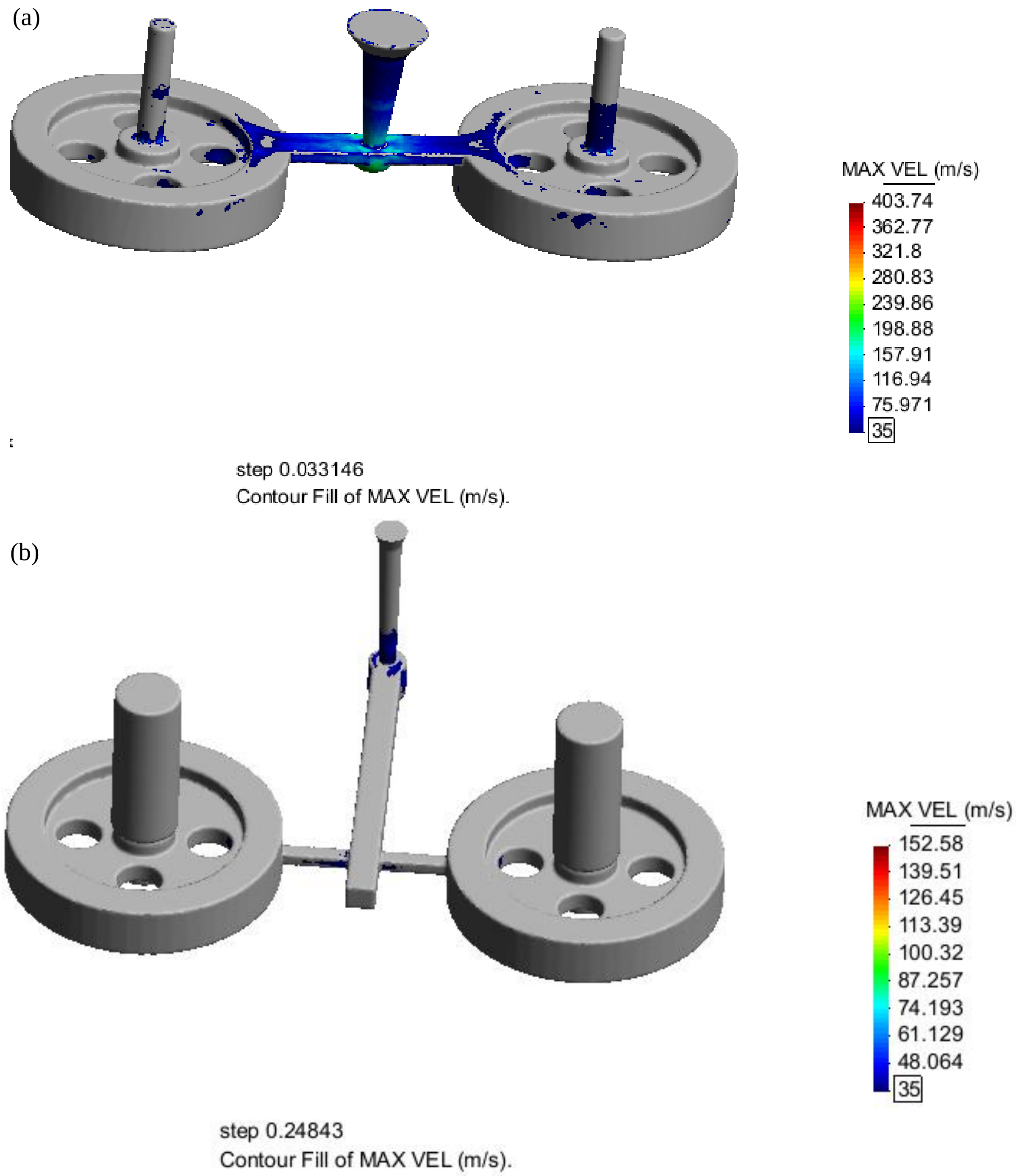


Figure 12: Mold erosion of (a) conventional and (b) proposed gating and feeding design

4.2.3.3 Solidification analysis results

Casting solidification helps to view the cooling process from exterior casting surface to interior, and to detect the location of shrinkage porosity in figure 13. This analysis helps optimize and verify the design of risers, so that the casting yield is improved with desired quality. Here, two main results are achieved: one is directional solidification (thin regions solidify faster than thick regions) and another is progressive solidification meant casting surface to interior. Equal temperature distribution throughout the cast body is an indication of progressive solidification.

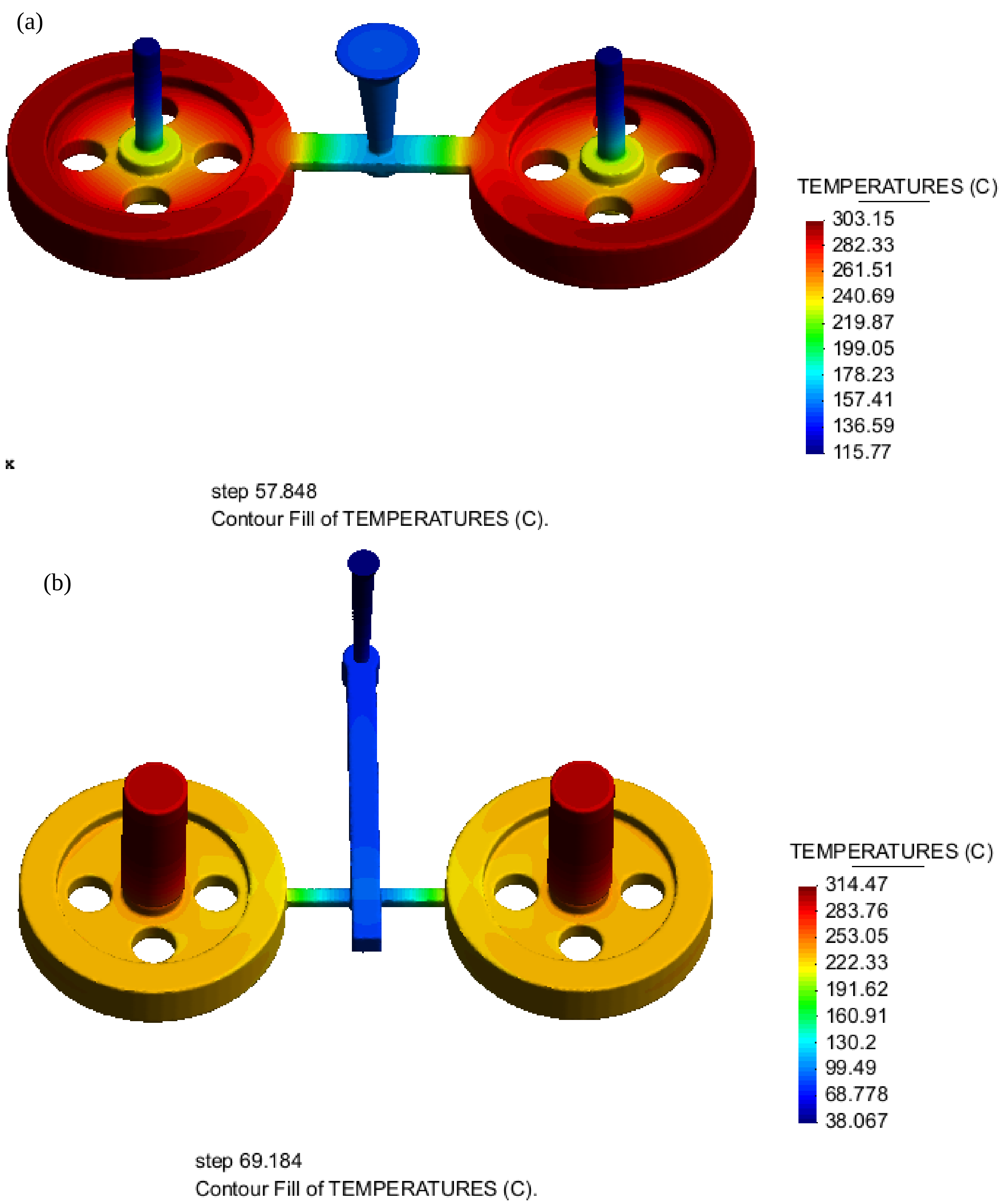
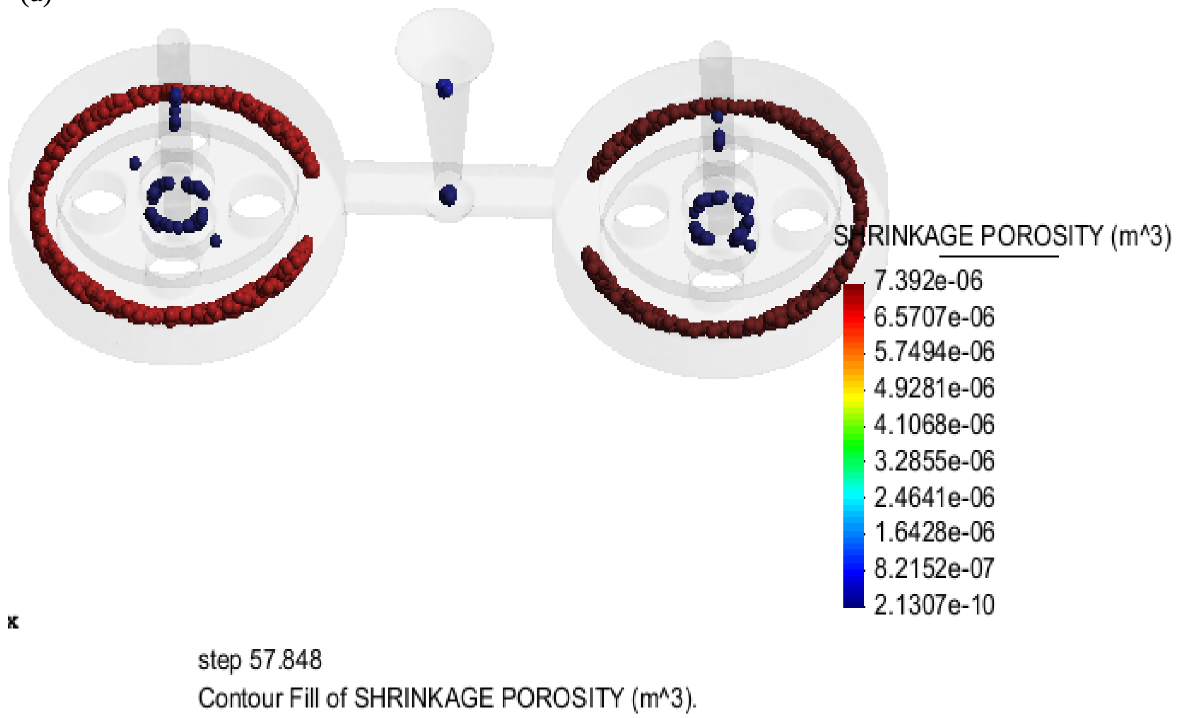


Figure 13: Solidification results of (a) conventional and (b) proposed gating and feeding design based on temperature distribution

From the figure 13 it is noticed that both progressive and directional solidification is achieved in modified gating and feeding system design. From temperature scale it is clearly shown that yellow= low temperature and red= high temperature.

(a)



(b)

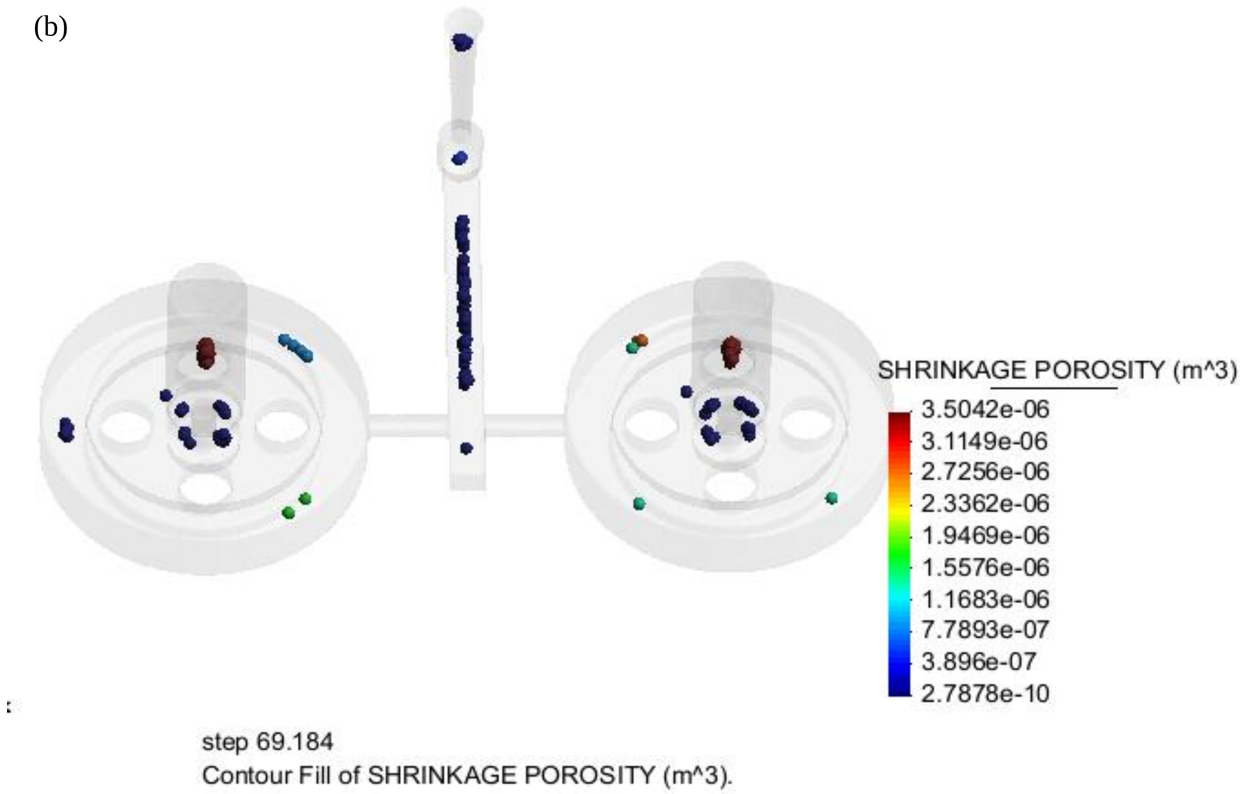


Figure 14: Shrinkage porosity of (a) conventional and (b) proposed gating and feeding design

In conventional gating and feeding system riser is solidified before the solidification of cast body so directional solidification is not achieved and it is one of the main reasons of occurring shrinkage porosity in cast product. The obtained results of shrinkage porosity (colored dots represents shrinkage porosity) in figure 14 also declares that the modified gating and feeding design is better than conventional design.

4.2.3.4 Experimental Trial casting in proposed gating system

The first step of experimental trial is to prepare a wooden pattern of flywheel, molding box, sprue and sprue base well, runner, in-gates and riser as per the design dimensions for flywheel casting. All these part are represented in figure 15. Bentonite is used as a binding material that increases the mold strength. The mold cavity consists of two parts, cope (20×12×6) inch - the upper part and drag (20×12×3) inch - the lower part.

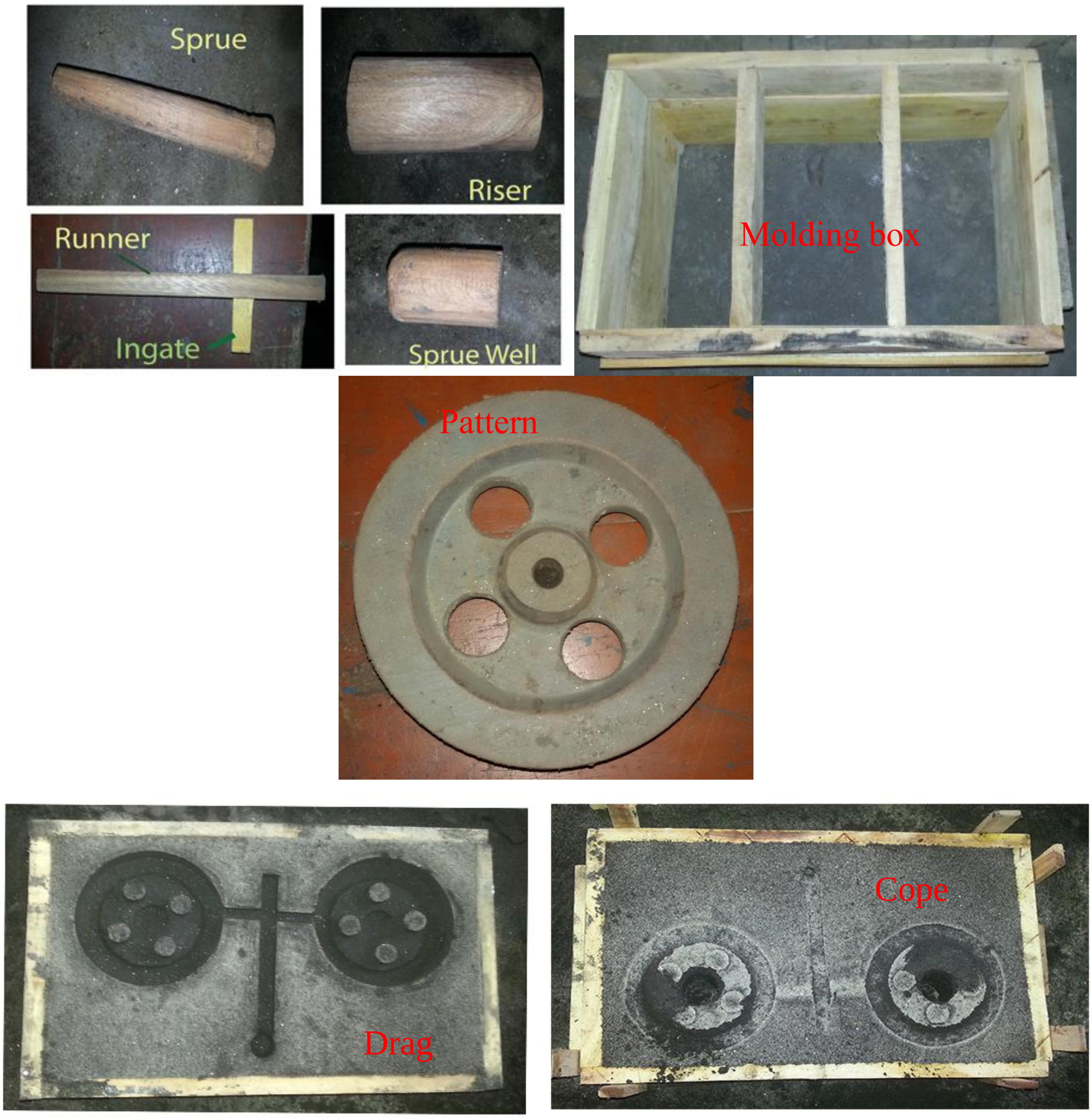


Figure 15: Components of proposed gating and feeding system with multi-cavity mold

After preparing mold box molten Aluminum is removed from furnace at 713°C and poured into mold cavity. After 1 hour passing the cast product is collected from molding box. Sand, dust are washed out using water and then excess metal, gates, runner and risers are cut off from cast product. At last the final product is found which is represented in figure 16.

(a)

(b)

(c)

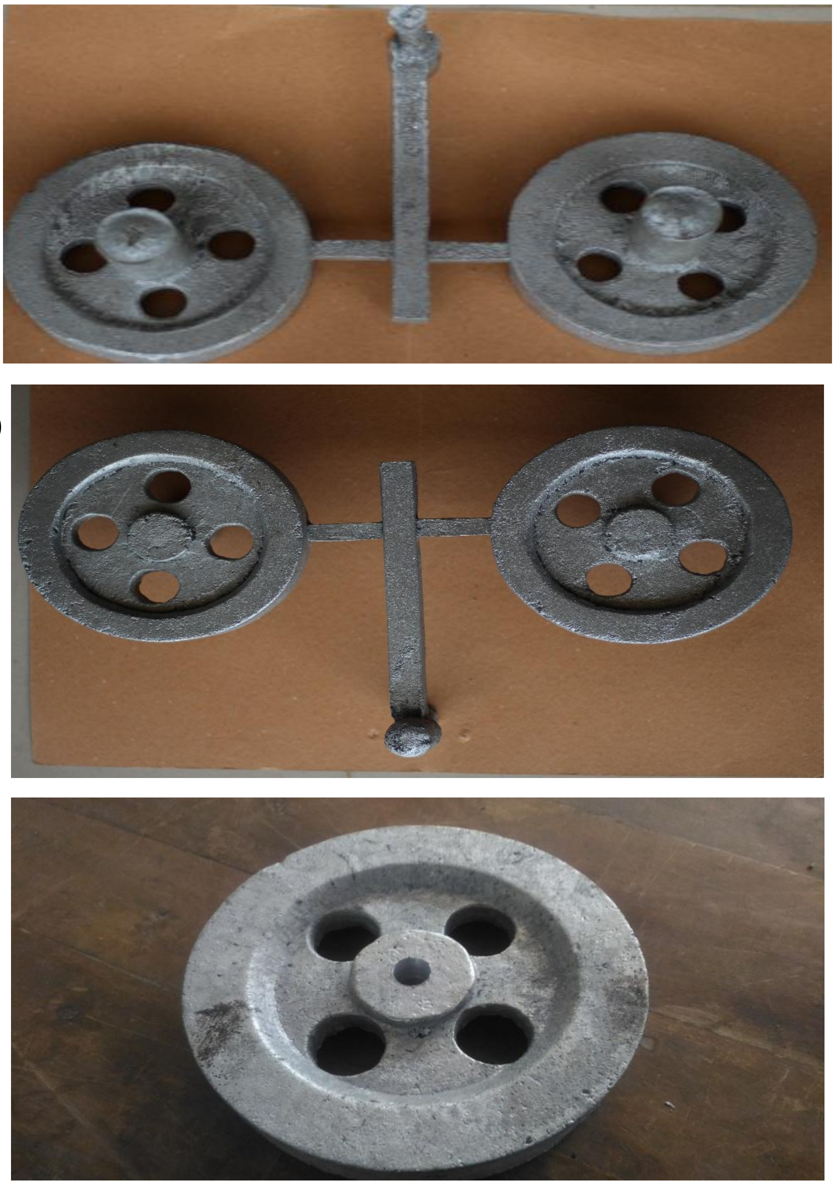


Figure 16: (a) Top view and (b) bottom view of cast product with proposed gating and feeding design; (c) cast flywheel after removing gating elements and cleaning dust

Finally casting yield is determined using equation 5 for both gating system cast product that are represented in table 12 and casting yield is increased 15% more than conventional gating design.

Table 12: Casting yield for conventional and proposed gating system design

Iteration No.	Conventional gating system	Proposed gating system
Casting yield(%)	39	45

4.3 Discussions

Taguchi technique of process parameter design is used in this study to determine the optimal settings of process parameters for minimizing the rejection level of green sand casting process. For this, L18 orthogonal array experiments at different levels of the selected process parameters are performed and the experimental analysis is carried out by using MINITAB® 17. Experimental results indicate:

1. The optimum levels of the process parameters at which rejection rate is minimum are: green compression strength at level 1 (1,200 g/cm^2), permeability at level 2 (120) and moisture content at level 1 (4%).
2. From ANOVA results it is found that green compression strength and moisture content are more significant than permeability.
3. Percentage contribution of process parameters for mean values: green compression strength (36%) has the most dominant effect on total variation, interaction effect of moisture content (%)* green compression strength (g/cm^2) is also remarkable(10.8%) and then moisture content (9.02%). For S/N ratios analysis similar results is obtained for process parameter contribution on casting defects.
4. With optimal parameters setting of 3.1% rejection rate has been found in foundry shop practically applying the selected process parameters levels which was 5.7% in traditional method. So casting quality is improved through this process.

In other way, simulation technique is used in this study to determine the optimal size and positioning of gating and feeding systems for minimizing the defects. The findings are:

1. The optimum size of the gating elements in pressurized parting gating system are: sprue (D_{base}=10.28mm, D_{top}=16mm, H=90mm),runner (W=18mm, L=200mm, H=16mm), ingate(W=10mm, L=40mm, H=8mm), riser (D=40mm, H=100mm).
2. Filling results: Modified gating system helps to reduce mold erosion. Air entrapment is replaced from cast product to riser.
3. From solidification results it is found that directional solidification is achieved through changing the size and positioning of gating elements. Shrinkage porosity of cast product is almost removed in newly designed gating system.
4. Simulation results is found to be a good agreement with experimental results and casting yield is found 45% in modified gating system. So it can be declared that system is improved.

CHAPTER V

Conclusions and Future Scope of this Thesis

5.1 Conclusions

The feasibility of using statistical techniques for reducing casting defects have been proved successfully. It can be concluded that simulation helps to visualize filling and solidification phenomena with no wastage of time, energy, labor and money. Hence casting simulation enables to provide ‘correct at the first time’ through preventing potential problems related to flow of metals or during the time of freezing compatible with both product requirements and foundry capability. This technique also reduces lead time, increases productivity and minimizes the percentage of rejections. A high percentage of casting defects in job shop has a great impact on three parameters like method design, process capabilities and low compatibility between part requirements. For achieving the desired quality at the least cost without shop-floor trials these three must be optimized in an integrated manner. “These facts can make all the small and medium foundries in Bangladesh to implement simulation activity in casting as the need of hour.”

5.2 Future Scope of thesis

In future other process parameters such as grain size of sand, dry compression strength, hardness number of molding sand may be varied for finding out the effect of this parameters on rejection rate. This gating and feeding system may be analyzed for other cast material.

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APPENDICES

Appendix A:

Dimensions for seven iterations and obtained casting yield are provided in table A-1. The first six iterations are performed in pressurized gating system only the seventh iteration is performed in non-pressurized gating system.

Table A-1: Iteration design dimensions for gating and feeding system with casting yield

No.	Sprue(mm)			Runner(mm)			In- gates(mm)			Riser(mm)		Casting Yield (%)
	D (base)	D (top)	H	W	L	H	W	L	H	D	H	
1 (Conventional)	12.7	25.4	76.2	25.4	50.8	8	-	-	-	13	76.2	**39**
2	16	22	76.2	25.4	50.8	8	-	-	-	16	76.2	36.73
3 (Optimized)	10.28	16	90	18	200	16	10	40	8	40	100	**45**
4	11	15	73	20	205	16	11	44	7.3	40	100	41.78
5	13	16	50	25	215	16	10	40	10	40	100	40.71
6	11	15	73	20	205	16	11	44	7.3	20	50	40.71
7	22	25	100	32	100	16	32	24	16	37	163	32

Here, *L=Length W=Width, H=Height, D=Diameter*

Sample calculation for iteration no.3 (All iterations are done in the similar way)

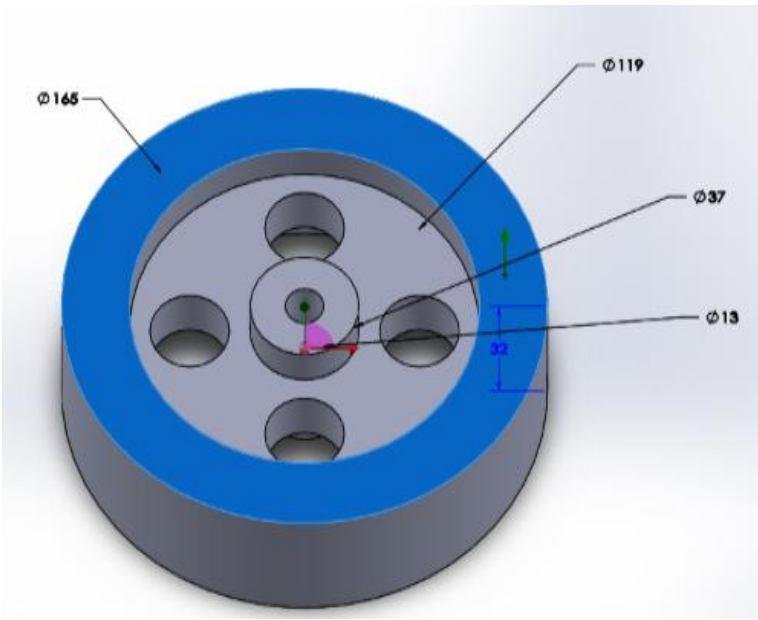


Figure A-1: CAD design of Flywheel (all dimensions are in mm)

Total volume of flywheel=$\left(\frac{3.14}{4}*165*165*32\right)-\left(4*\frac{3.14}{4}*27*27*13\right)-\left(\frac{3.14}{4}*119*119*19+\left(\frac{3.14}{4}*37*37*26\right)-\left(\frac{3.14}{4}*13*13*32\right)=466856\ mm3\right.$

Mass of multi-cavity casting=$2*466856*0.00000265=2.5\ kg$

Mass of metal poured=$\frac{2.5}{0.45}=5.6kg$, after casting the mass of flywheel=2.5kg

For Aluminum alloy maximum pouring rate=$0.3kg/s$ [39]

Pouring time=$\frac{5.6}{0.3}=18.67s$ [39]

Casting yield=$\frac{2.5}{5.6}$=45% [39]

Choke area:

Parting gate is used so effective sprue height =90mm

Assume C=0.9 because single runner tapered sprue [39]

So, $choke\ area=\frac{0.3}{0.9*0.00000265*\sqrt{2*9.81*90}}=82.97\text{mm}^2$ [39]

Choke diameter= 10.28mm

In pressurized gating system choke is in sprue so

Bottom sprue diameter= 10.28mm

Top sprue diameter= 16mm

Sprue area= $82.97*1.732=143.704\text{mm}^2$

Gating ratio for Aluminum, sprue (1): runner (2): in-gates (1) [39]

Runner area:

Runner area= $2*143.704\text{mm}^2$= 287.408 mm^2

Assume Runner height=16mm;
Runner width=18mm;
Runner extension=$18*2=36mm$;

Total Runner length=$36+165$ =201mm;

In-gates area:

Two ingate system is selected

In-gates area= 143.704mm^2

Each in-gate area=71.852mm^2

Assume, In-gate width= $10mm$
In-gate height= $7.1852mm$
In-gate length= $4*10=40mm$

Sprue base well:

Area=$82.97*5=414.85\text{mm}^2$; Diameter= 23mm; Height=32mm

Riser:

Applying Modulus method-

Mc=$165*\frac{32}{2(165+2*32)}=11.53$ [39]

Riser diameter= 69.17mm=70mm but for proper positioning of riser on flywheel diameter is considered 40mm. Riser height= 100mm and Riser neck= 35mm

Appendix B:

CAD models for various gating and feeding system except iteration no. 1 and 3.

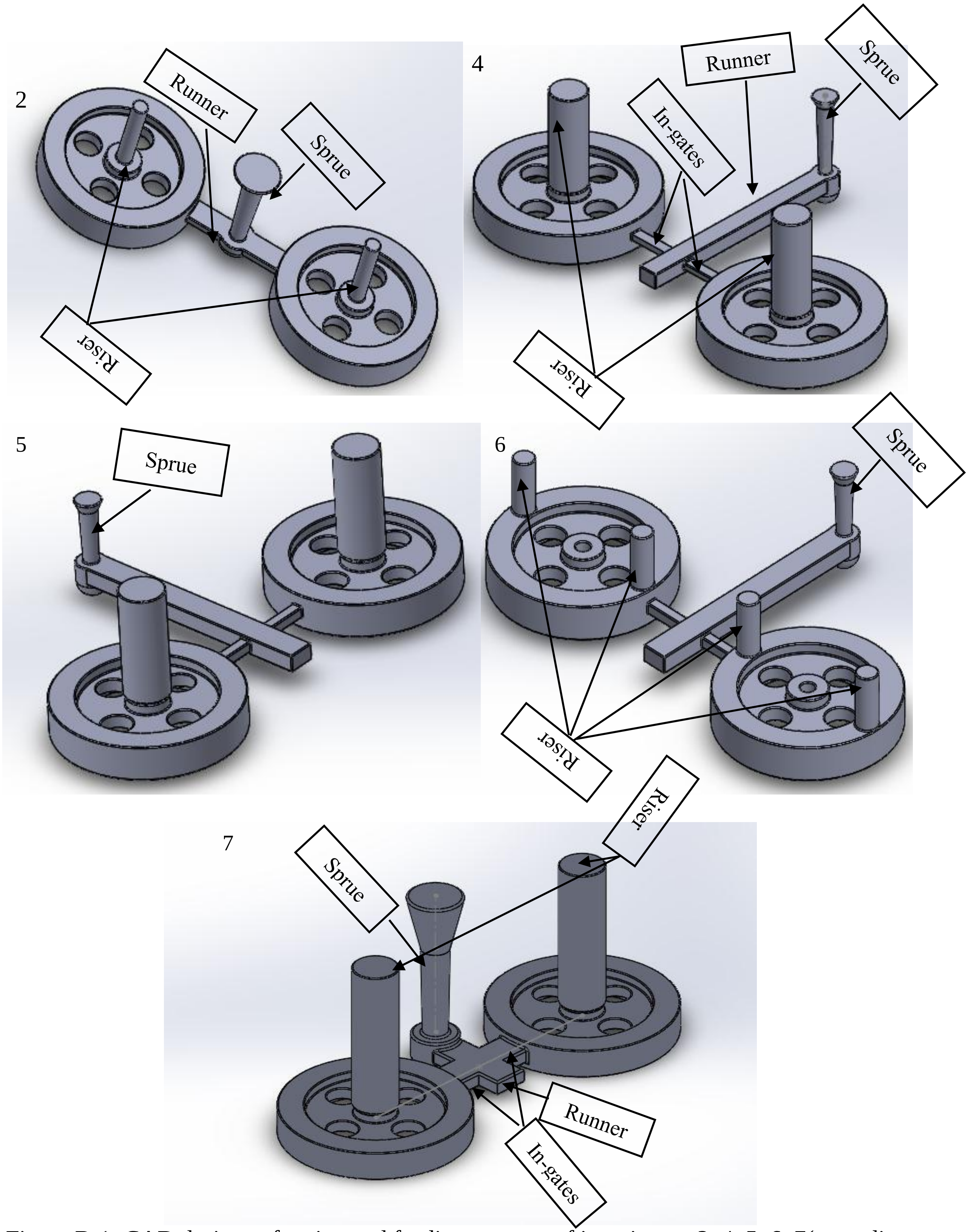
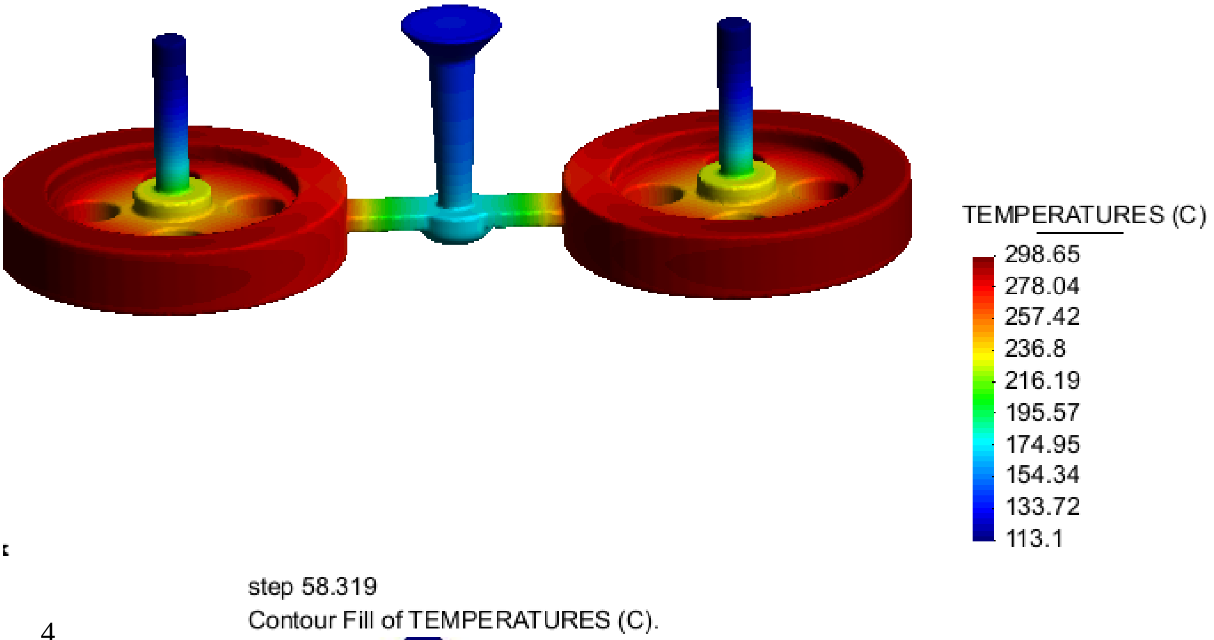


Figure B-1: CAD designs of gating and feeding systems of iteration no.2, 4, 5, 6, 7(according to the number declared in table A-1).

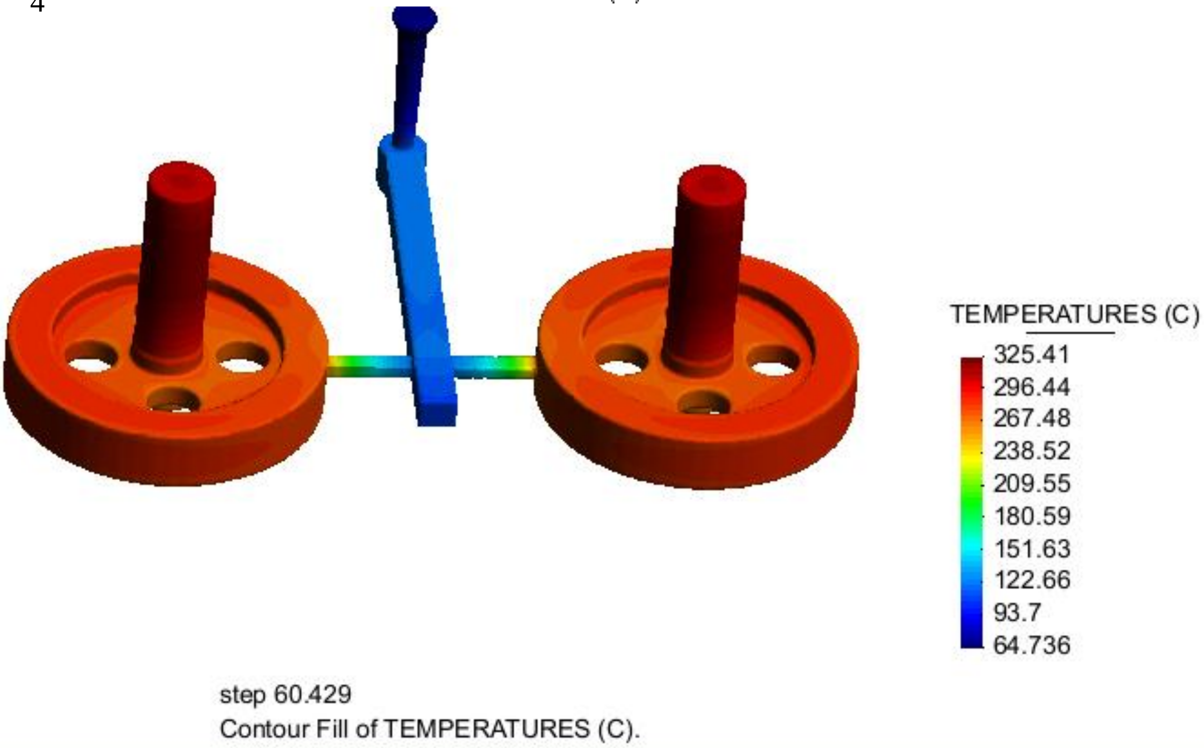
Appendix C:
Solidification results analysis for iterations using Click2Cast simulation software are shown for two things. One is directional solidification results (using temperature distribution) and another is shrinkage porosity.

Directional solidification results: Temperature distribution in cast component with various gating and feeding systems are shown in figure C-1.

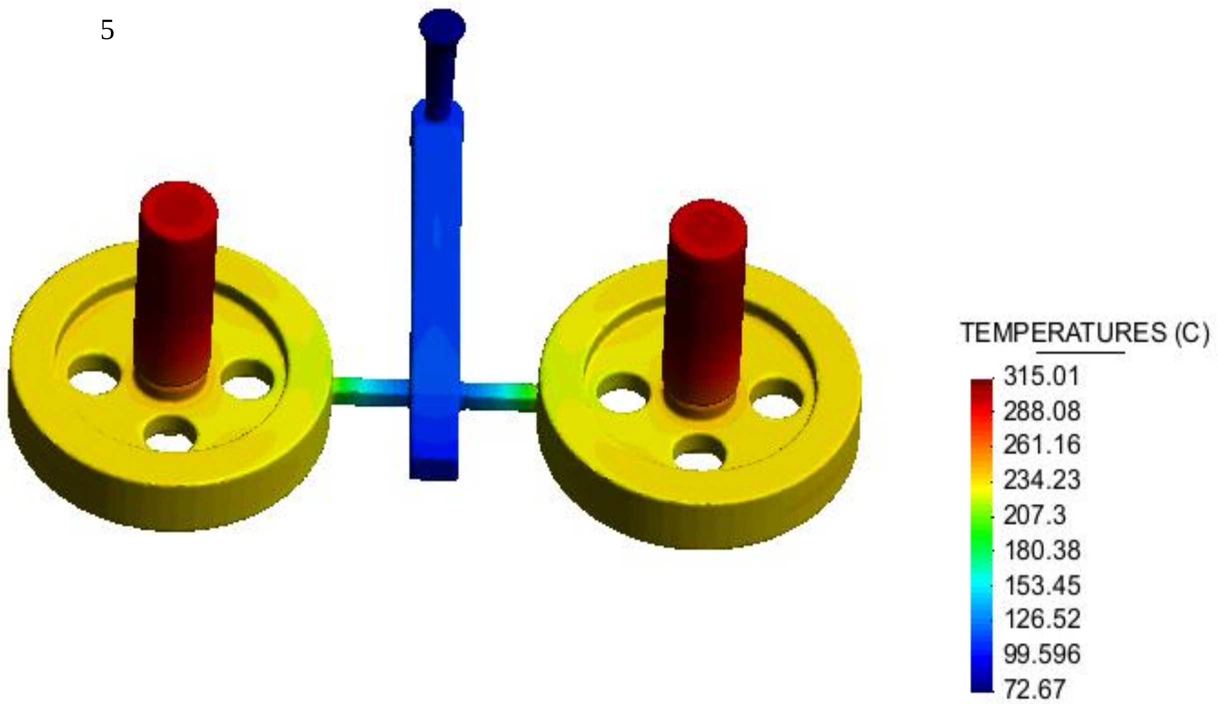
2



4

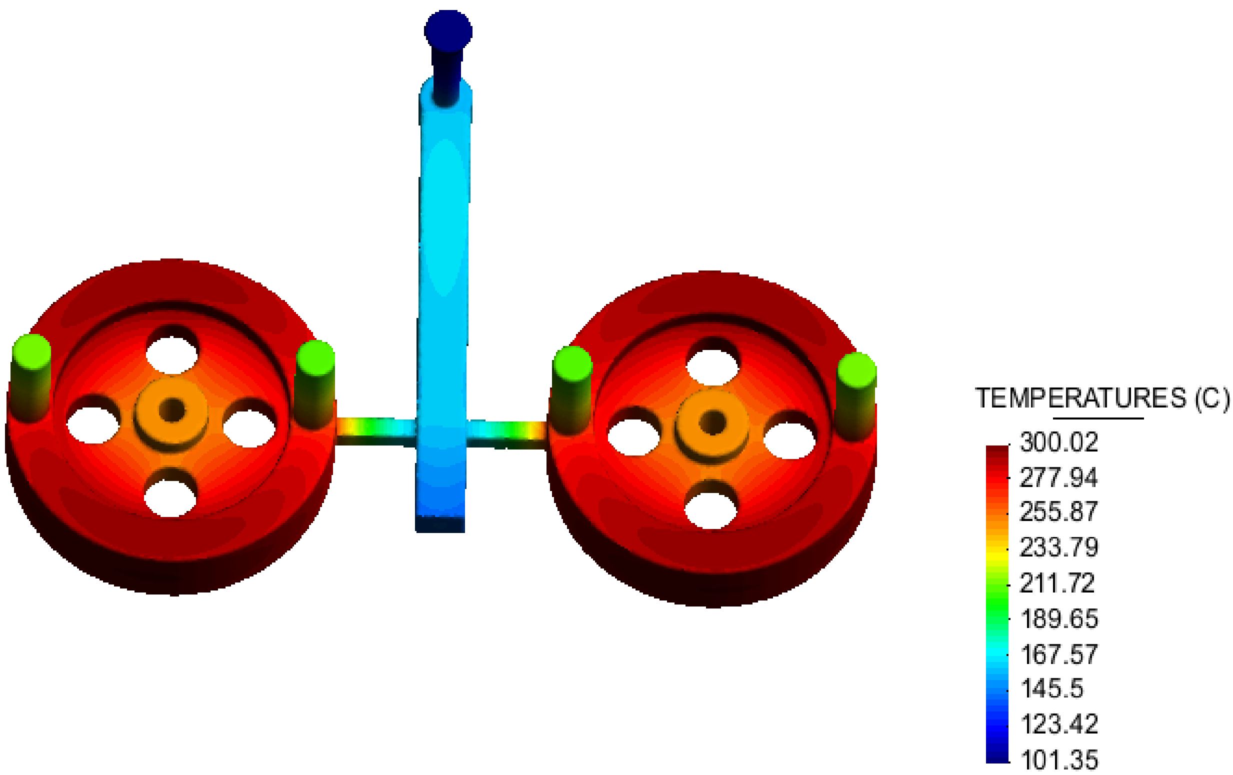


5



step 69.047
Contour Fill of TEMPERATURES (C).

6



step 58.177
Contour Fill of TEMPERATURES (C).

7

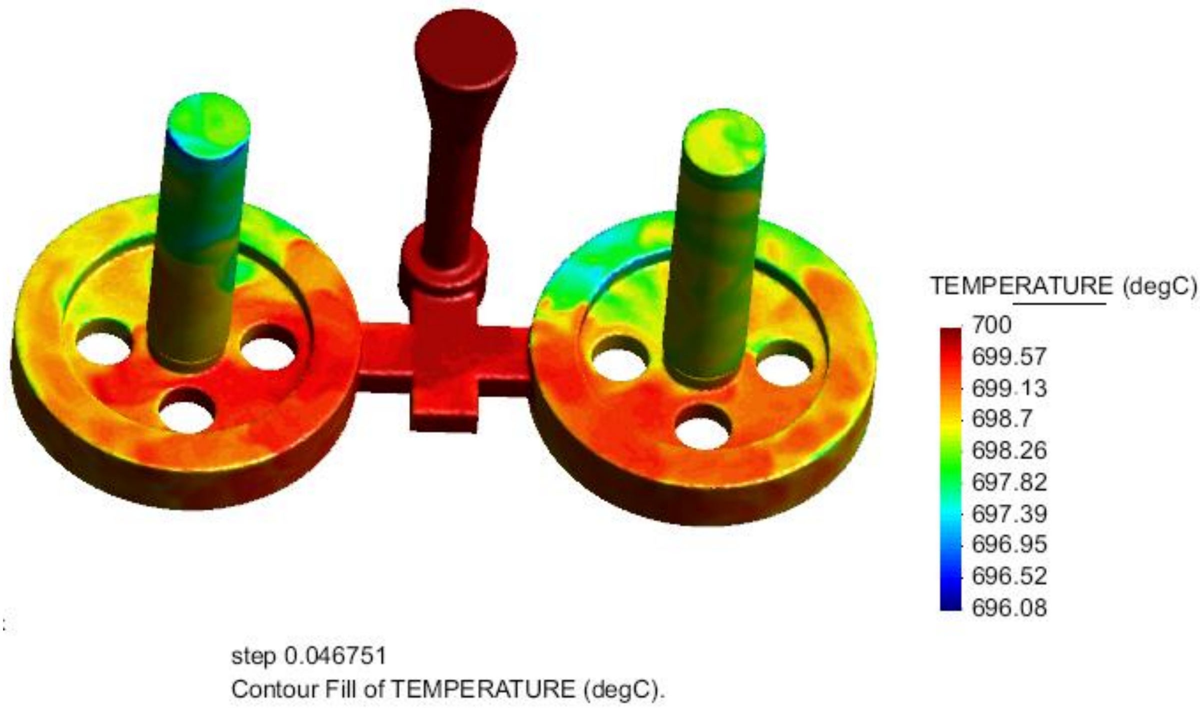
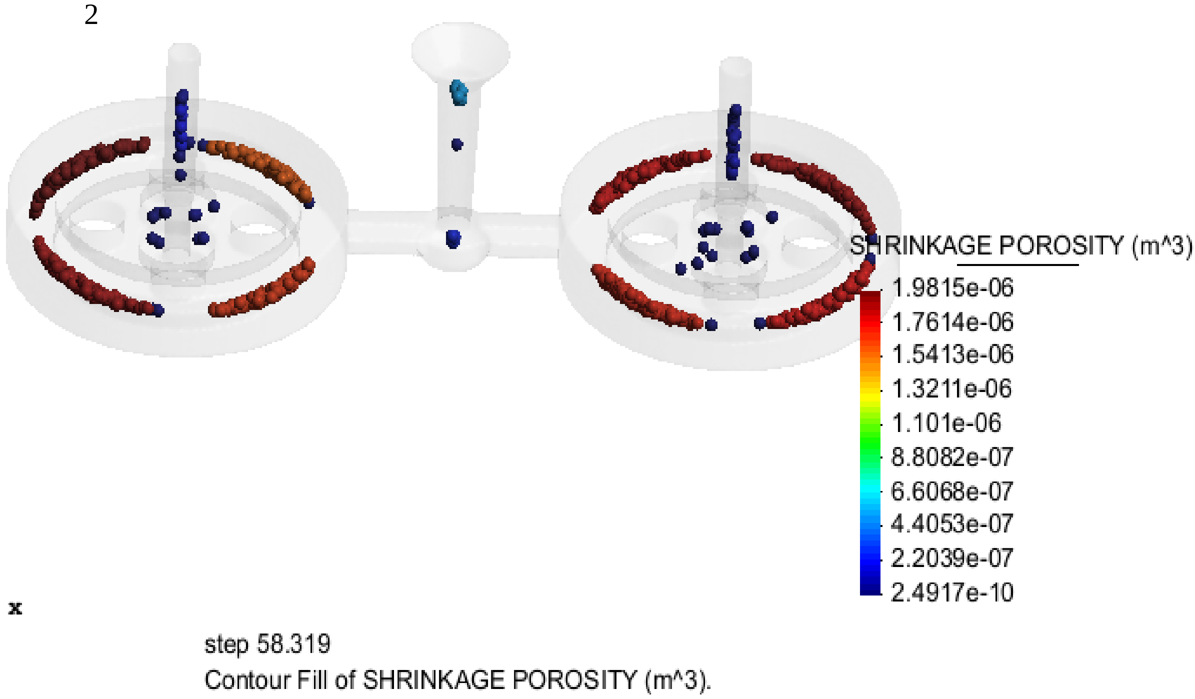


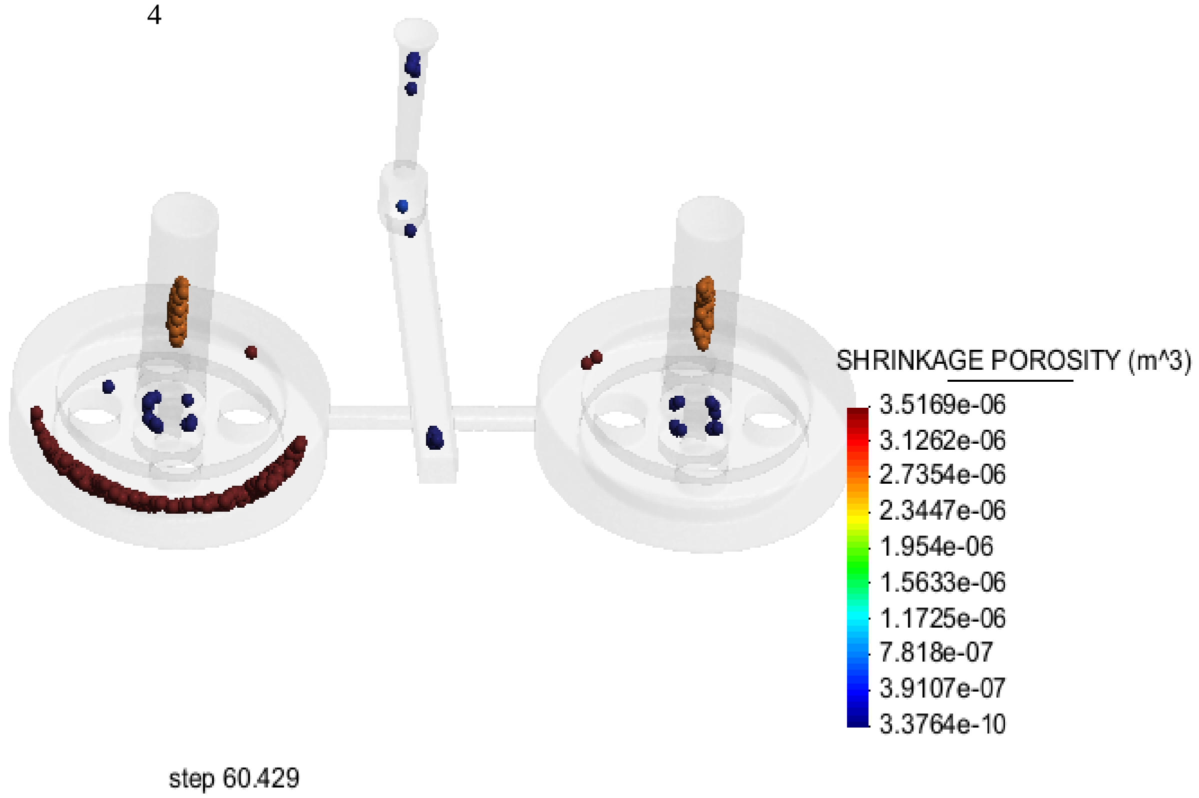
Figure C-1: Solidification process with temperature distribution of various gating and feeding systems of iteration no.2, 4, 5, 6, 7(according to the number declared in table A-1).

Shrinkage porosity results: presence of shrinkage porosity cast component with various gating and feeding systems are shown in figure C-2.

2

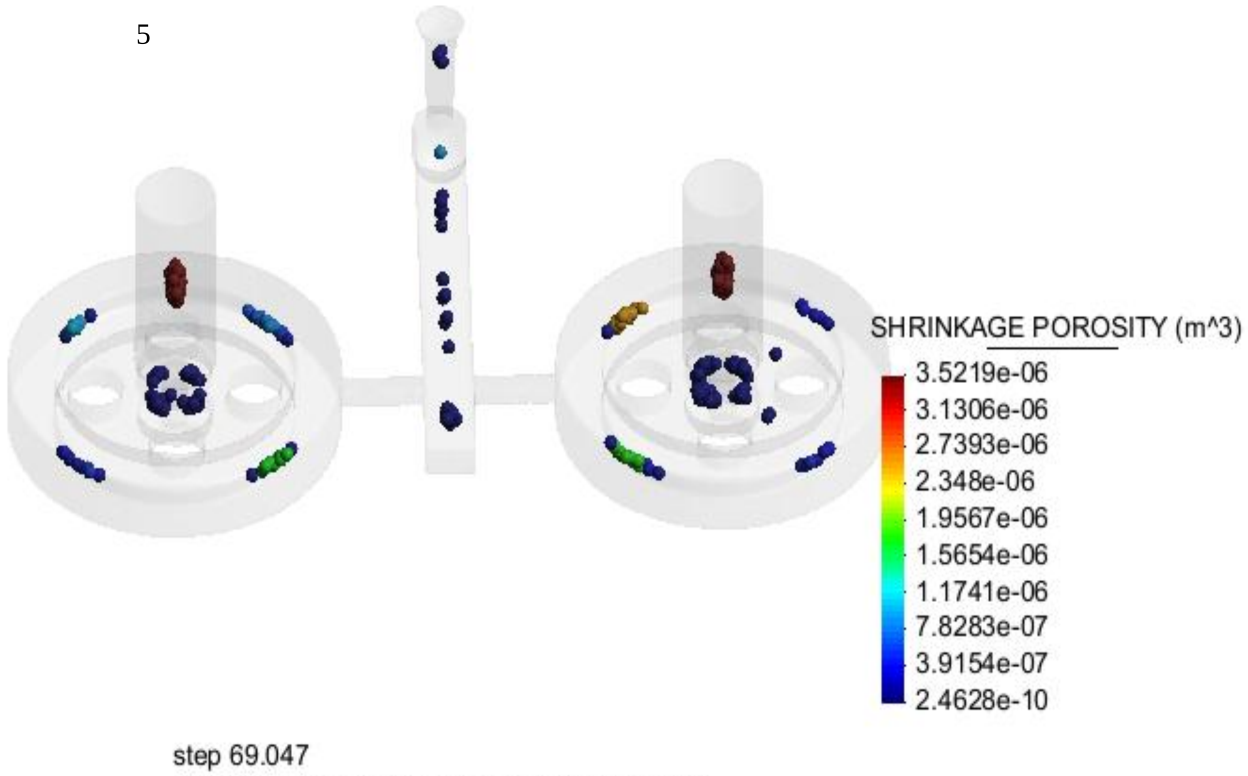


4



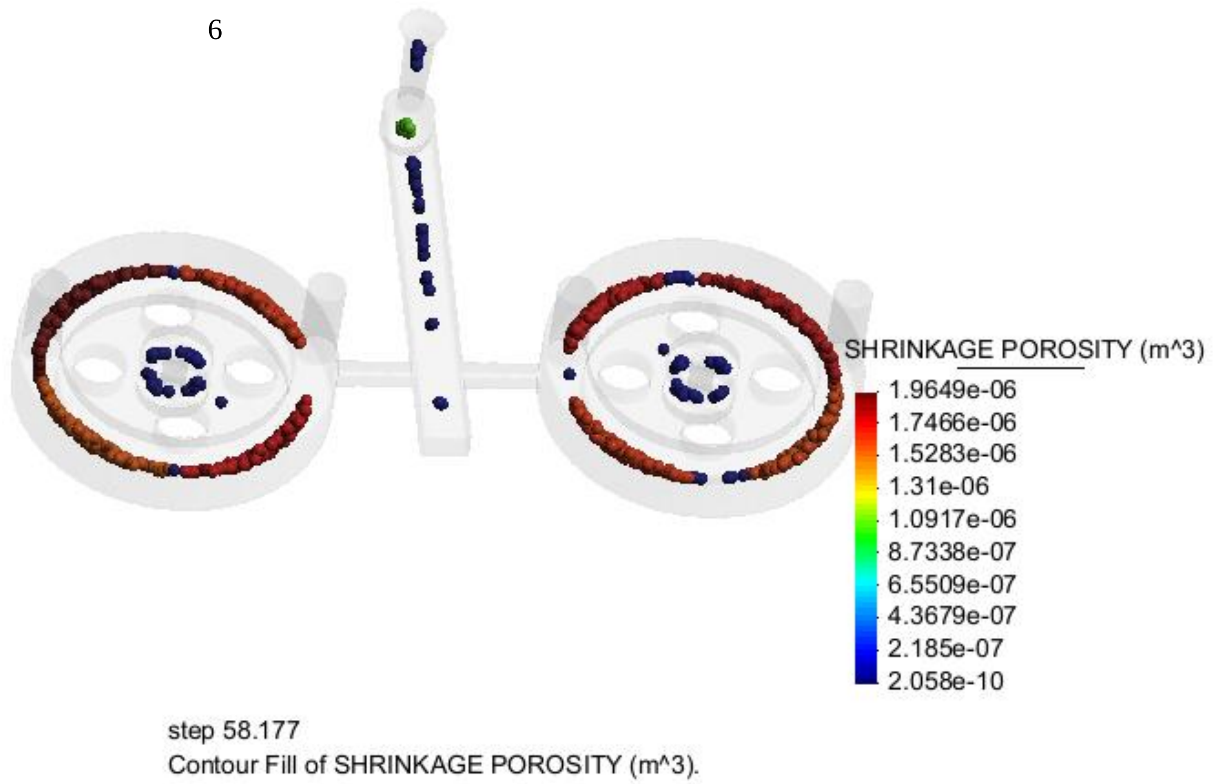
Contour Fill of SHRINKAGE POROSITY (m^3).

5



Contour Fill of SHRINKAGE POROSITY (m^3).

6



7

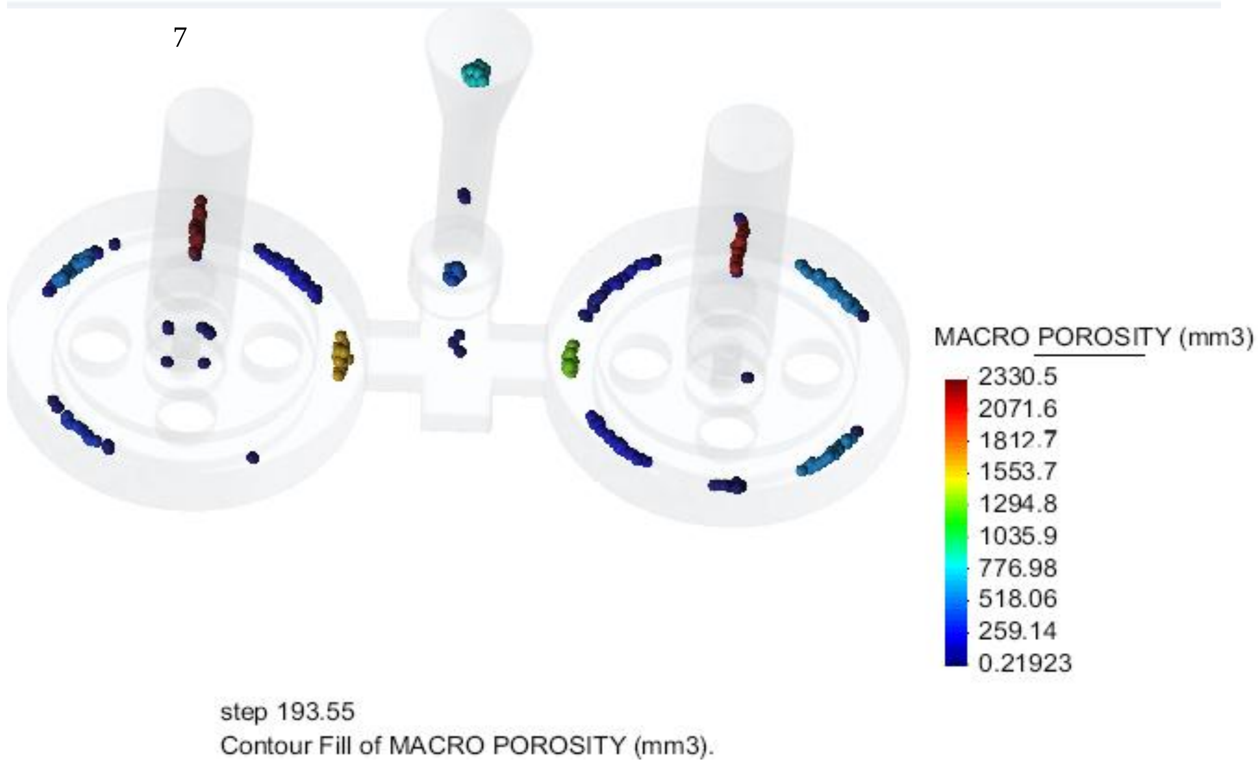
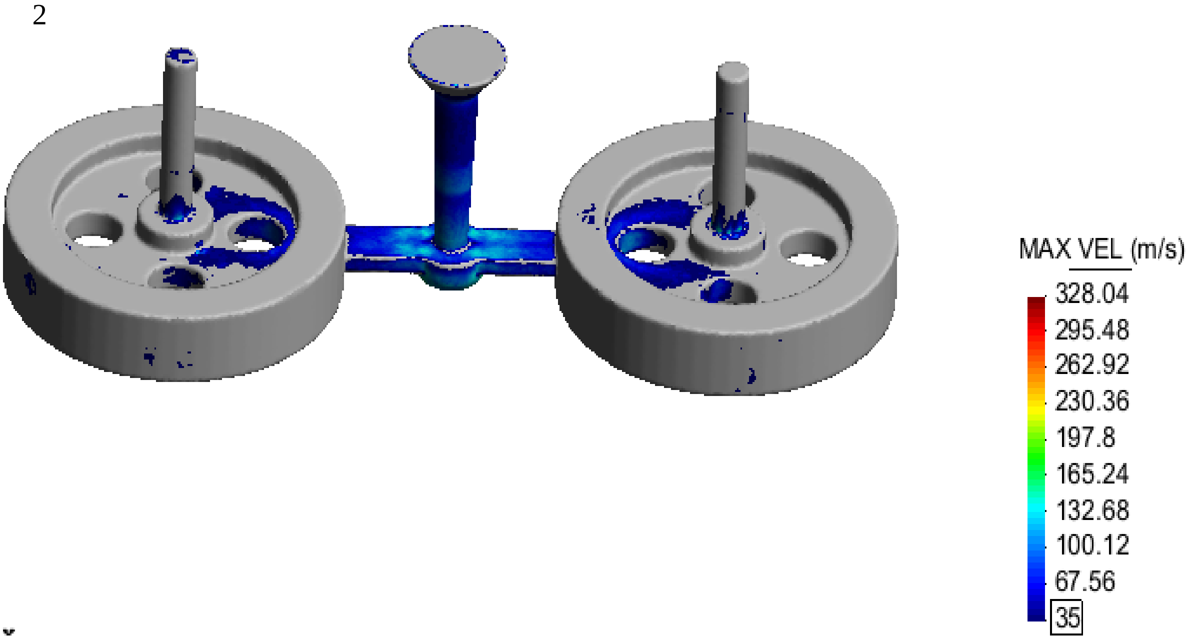


Figure C-2: Shrinkage porosity of gating and feeding systems of iteration no. 2,4,5,6, 7 (according to the number declared in table A-1).

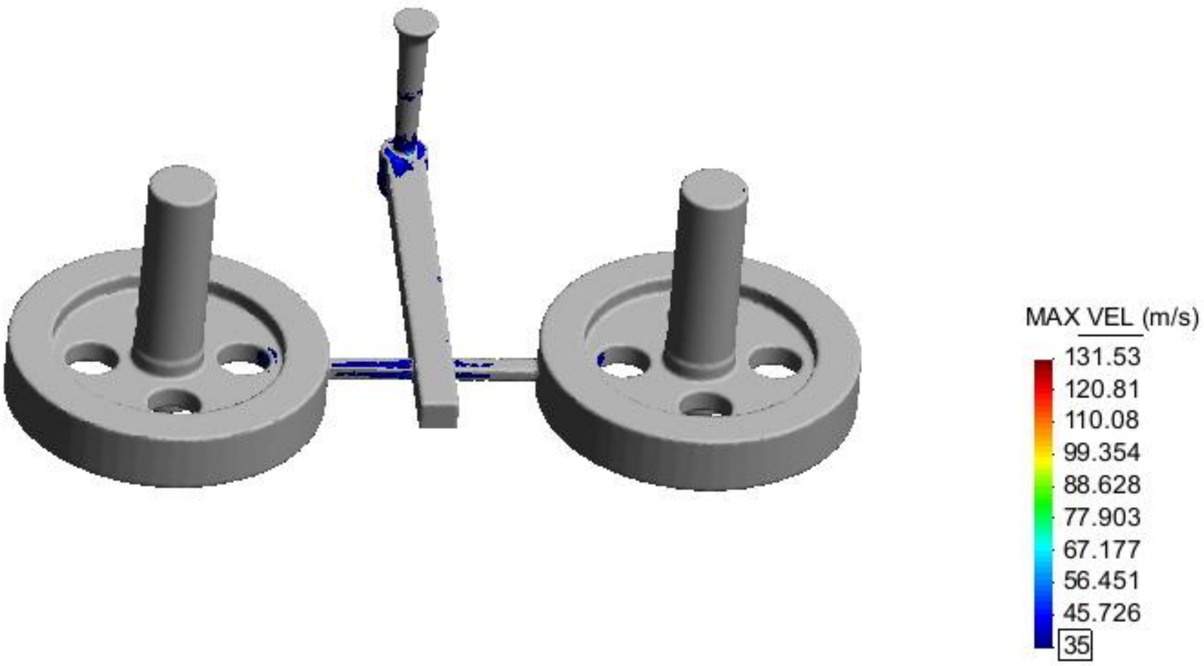
Appendix D:
Filling results analysis for iterations using Click2Cast simulation software are shown for two things. One is mold erosion (using velocity analysis) and another is air entrapment.

Mold erosion results: velocity scaling for mold erosion in cast component with various gating and feeding systems are shown in figure D-1. Blue color indicates mold erosion.

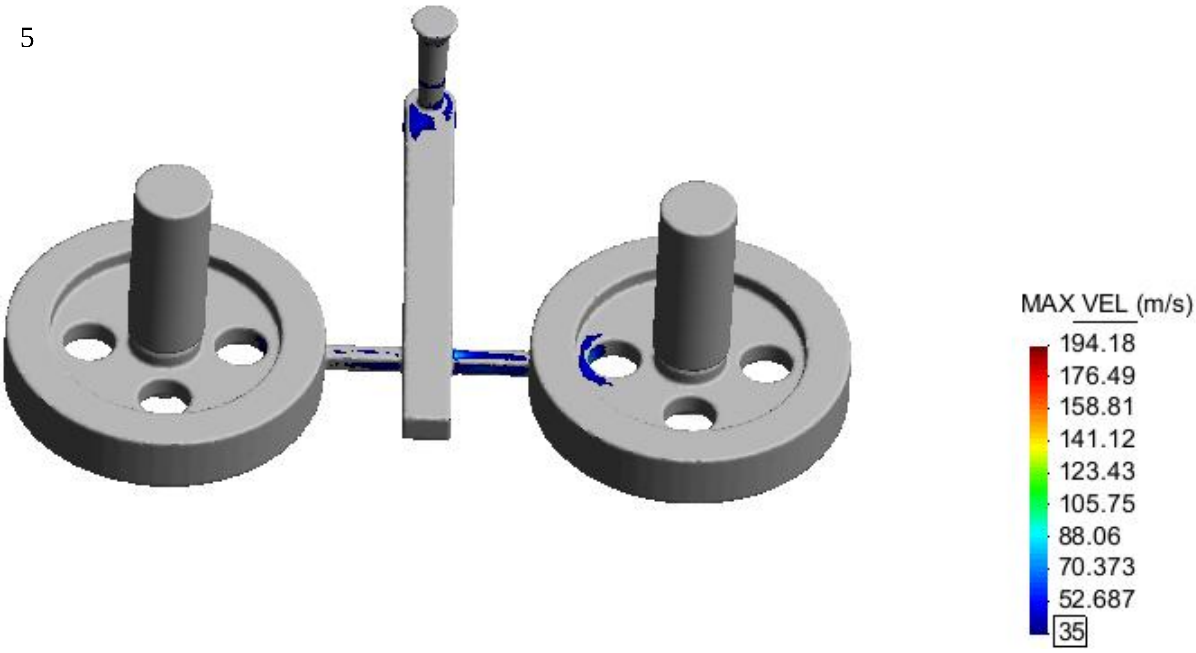
2



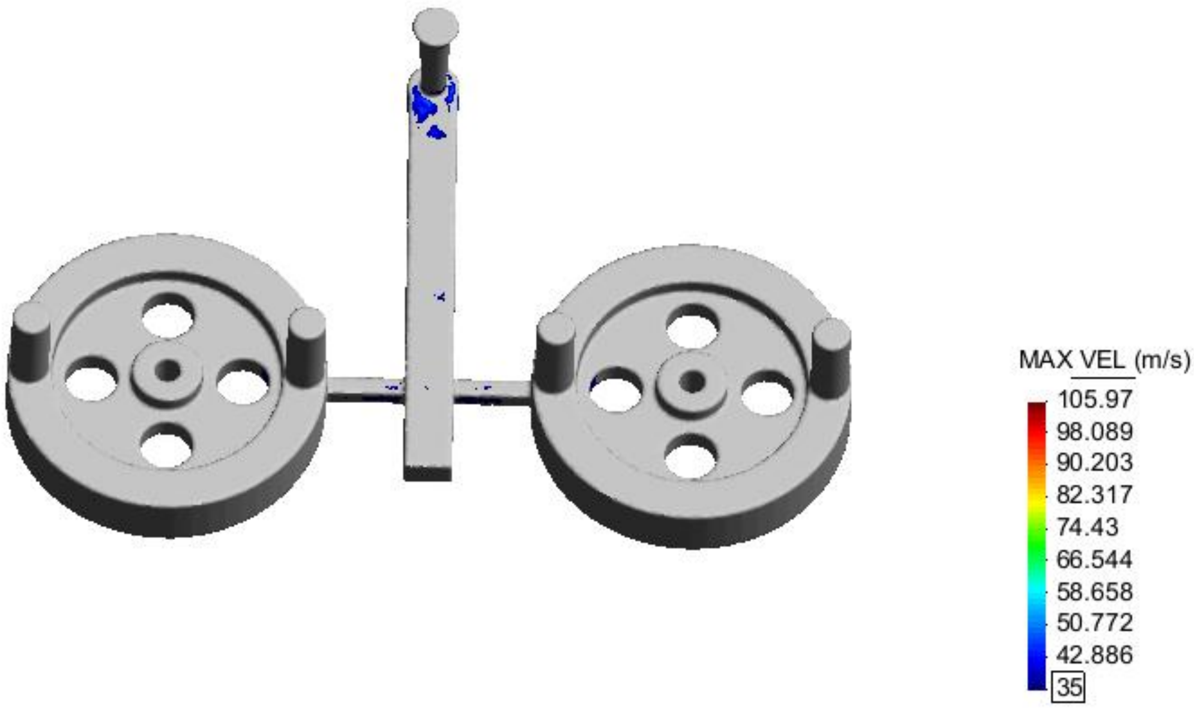
4



5


MAX VEL (m/s)
194.18
176.49
158.81
141.12
123.43
105.75
88.06
70.373
52.687
35

6


MAX VEL (m/s)
105.97
98.089
90.203
82.317
74.43
66.544
58.658
50.772
42.886
35

7

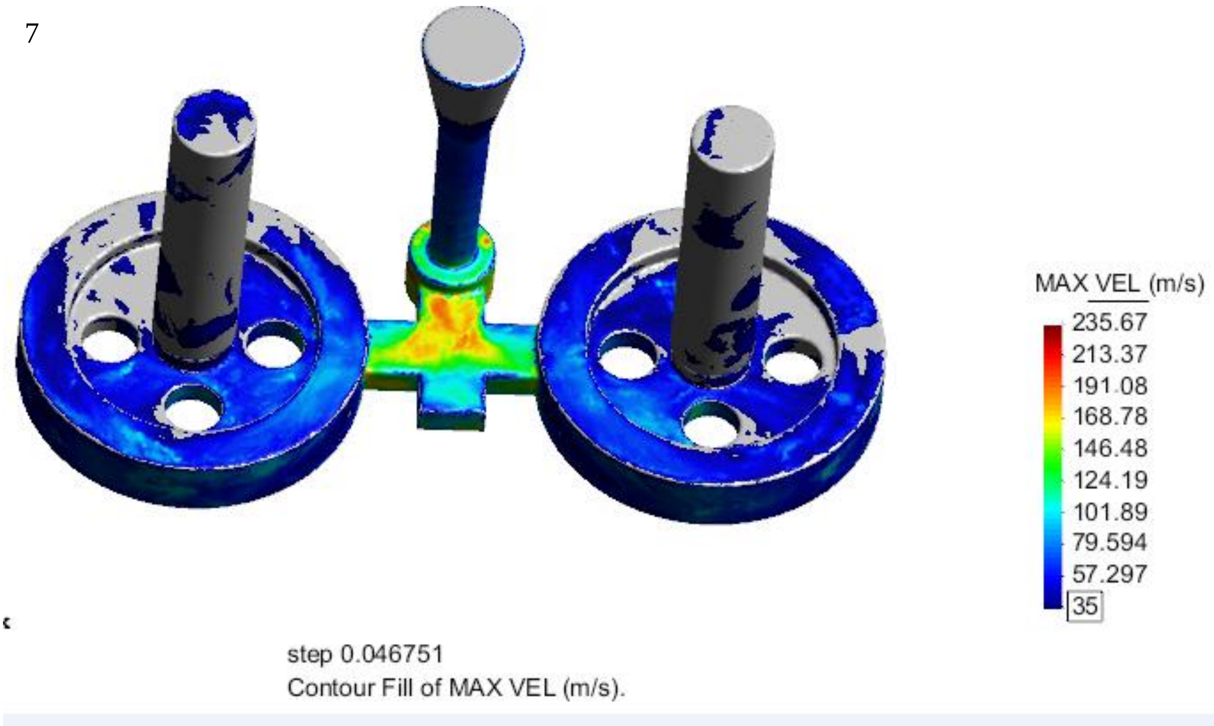
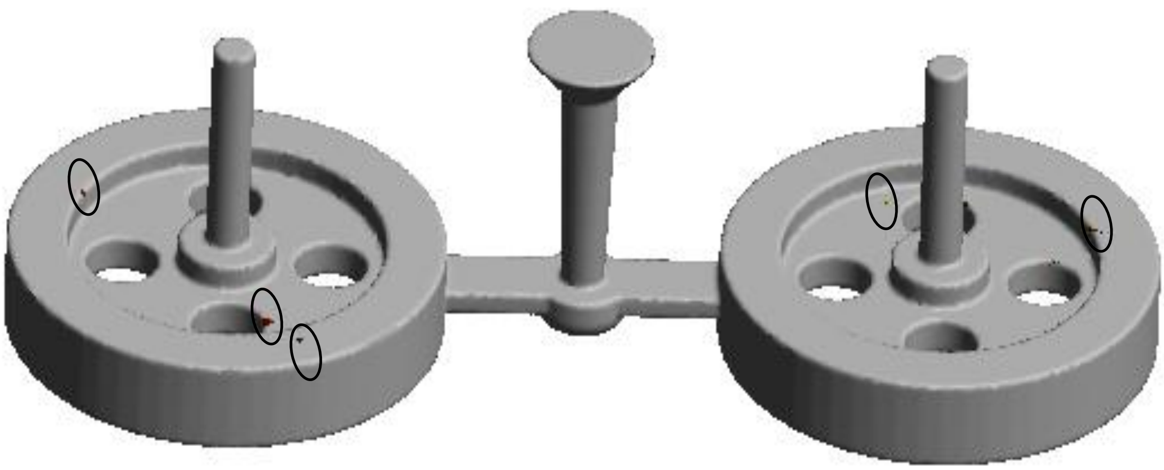


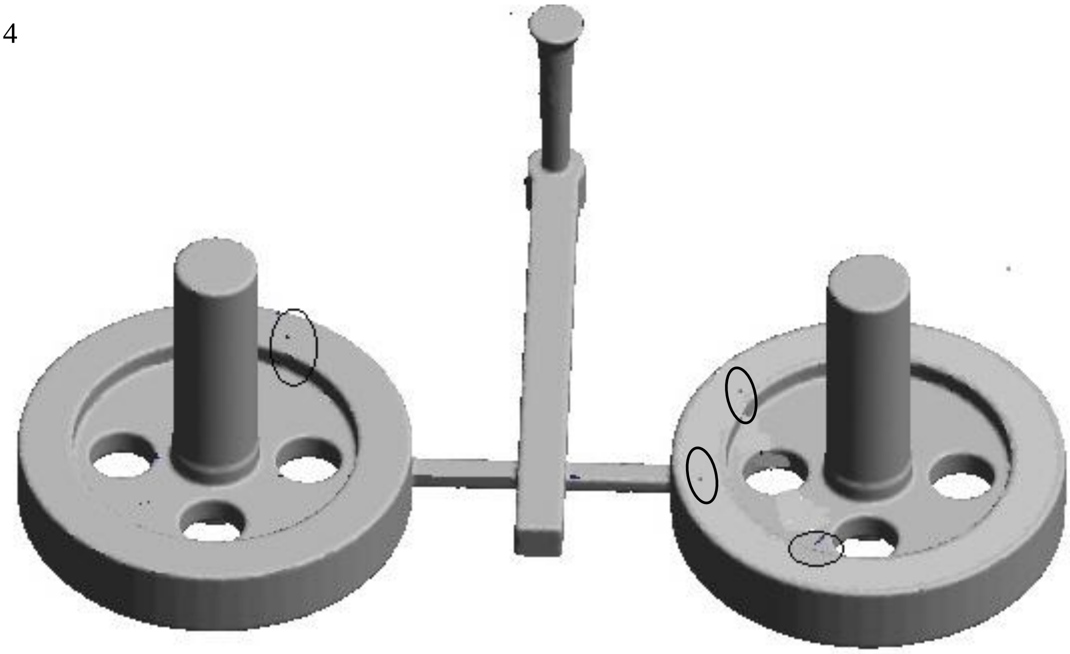
Figure D-1: Mold erosion of cast component in various gating and feeding systems of iteration no.2, 4 5, 6, 7 (according to the number declared in table A-1).

Air entrapment results: air entrapment in cast component with various gating and feeding systems are shown in figure D-2. Using black circles entrapped air is shown.

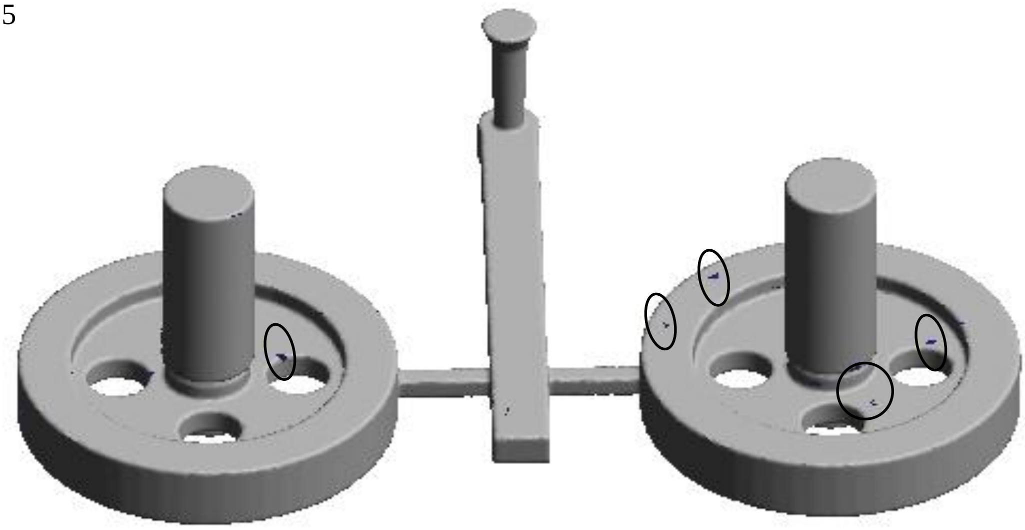
2



4



5



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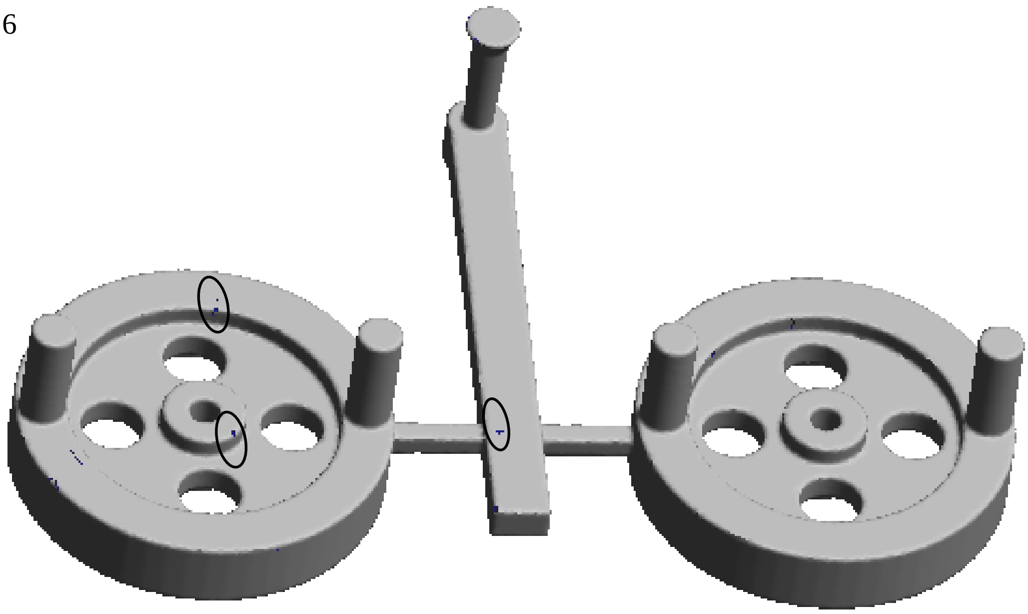

7

Figure D-2: Air entrapment of cast component in various gating and feeding systems of iteration no.2,4,5, 6, 7 (according to the number declared in table A-1).