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Porosity Analysis and Optimization of Casting Process Parameters using Simulation Software for Sand Casting

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Abstract: Casting is the oldest manufacturing processes used to manufacture metallic components. Sand casting is mostly used casting manufacturing process because of its process simplicity of producing complex geometry with ease. Various casting defects have adverse effect on casting quality and productivity. The defects in the component are identified to be solidification shrinkage, gas porosity, blow holes, pin holes, cold shuts, unfiled riser, misrun and incomplete mould cavity. The reasons of defects are analyzed as either improper selection of process parameter or improper design of gating and feeding system. Many researchers reported that 90% of the defects in casting are obtained only because of improper design of gating and feeding system. The main objectives were to study the existing design of gating and feeding system, to optimize the gating and feeding system using casting simulation is helpful to visualize mould filling, cooling, solidification and to predict the location of internal defect in casting such as sand inclusions, shrinkage porosity and cold shuts, it can be used for troubleshooting existing casting and to develop new casting without shop floor trials. The mould is modified accordingly with the simulation results and metal is poured into it. The casting produced are observed and found to have no defects. Taguchi technique is used for optimization of the parameters and orthogonal array is used for experimental purpose. Taguchi orthogonal array reduces these number of trials and cost and save time and give accurate results and this result to prepare the sand mold and cast the product.
Keywords: Casting, Defect, Simulation, Parameters, Filling analysis, optimization, method and design.

I. INTRODUCTION

Casting is the most economical processes in manufacturing industry to produce metallic components. Metal casting is the process of producing metal component parts of desired shapes by pouring molten metal into mould then allowing the metal to cool and solidify. The foundry engineer designs the gating and risering system for the casting. The time is spent in designing and redesigning the gating and riser system. It might take few days or up to several weeks, depending upon the complexity of the casting. Casting simulation process is developed from the methods which are useful to predict the defects and problems before the actual product of cast avoiding costly trail to prevent the defect. In the current scenario, the use of casting simulation software is increasing day by day in foundry industry and minimizing the shop floor trails to attain sound casting. The casting simulation technology has sufficiently matured and has become an essential tool for casting defect troubleshooting and method optimization.

A. *Classification of casting defects*

1) Filling related defects- sand inclusion, Blow holes, sand burning, misrun, cold shut.
2) Shape related defects- distortion or wrap, Mismatch defects, flash defects.
3) Thermal defects- Tears or Crack, sink mark, shrinkage.
4) Defects by appearance - cavities, discontinuities, Metallic projection, incomplete casting, defective surface and incorrect dimensions or shape.

B. *Inputs for the casting simulation process*

1) Geometry of the mold cavity (3D model of the casting, gating channels and feeders)
2) Thermo-physical properties (specific heat, density and thermal conductivity of the cast metal as well as the mould material, as a function of temperature).
3) Boundary conditions (i.e. the metal mould heat transfer coefficient, for normal mould as well as feed aids including insulation,

chills and exothermic materials).

4) Process parameters (such as pouring rate, temperature and time).

C. Need of casting simulation

Casting simulation should be used when it can be economically justified for quality enhancement by predicting and eliminating internal defects like yield improvement, porosity and rapid development.

1) Quality improvement: Improvement in quality improves the reliability of casting and reduces the excess cost of defective casting and other resources cost. The quality improvement can be obtained from simulation.
2) Yield improvement: With simulation technique, the casting process and method are optimized in short time and also, the casting process is optimized there will be very lesser wastage thus it results in reduces the effective melting cost per casting, yield improvement, and increases the net production capacity.
3) Rapid development: Simulation of casting is virtual process so there is no scrap material and other wastages. Casting through virtual trials eliminates the wastage of production resources and gives opportunity to foundry to take high order.

Table 1. Chemical Composition of LM-9 (EN 1706 AC-43100)

Material	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Others	Al
%	0.1	0.25-0.45	09.0-11.0	0.55	0.45	0.05	0.1	0.05	0.05	0.15	0.05	Remaining

II. LITERATURE REVIEW

The literature review is mainly focusing on design and optimization technique based on casting related defects and their research and outcomes. Marek Bruna et al done an advance calculation for the prediction of porosity formation for aluminum alloy by advance porosity module included in Pro-CAST software. In the experiment, he used thermal analysis to get accurate data about used alloy [Marek Bruna, 2017[1]. Sunil Umarane et al work on elimination of defects in aluminum alloy produced gravity die casting using simulation software. The defects observed are cracks, unfilled riser, solidification shrinkage and incomplete mould cavity and it occur due to improper selection of process parameter or improper design of gating and riser. The die is modified accordingly with the simulation results then casting is produced are observed no defects. [2] Sachin L. Nimbulkar et al gives that porosity is one of the defects in ductile iron casting and porosity amount is related to sand casting processes parameter. main objectives is to study the existing design of gating and feeding system and optimized the gating and feeding system using autocast X1 casting simulation software [3]. Rajulapati Ganesh et al in his work shows the velocity variations, pressure variations, solidification behavior and its effect on various defects like porosity, cold shuts etc in sand casting. Based on the results obtained in simulation respective changes can be made in order to avoid the defect [4] Kavad Mahesh et al performed simulation and experimental work on spheroidal graphite iron and observed defect occur at t junction in sand casting in his present work, he gives the effect of thermal as well as geometrical parameters on casting defects arises [5]. Ravi and Joshi (2007) et al worked on computer aided casting design and simulation of feeder and gating design of castings using AutoCAST software and they describe how it assists in designing, modeling, analyzing simulating and improving cast products. [6].

III. METHODOLOGY

Fig. 1 shows the overall process flowchart utilizes during the overall process of casting simulation

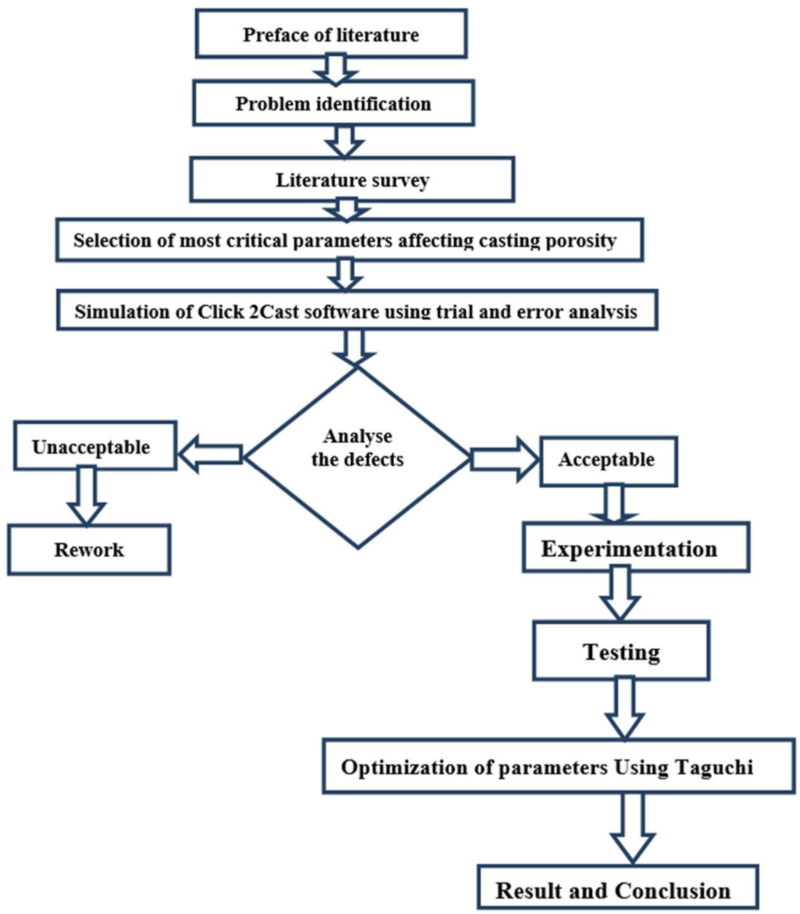

Fig. 1 Process flow Chart

Optimization method include simulation which helps in eliminating the cost of trial. the development stage as the gating can be easily modified using computer design software according to result obtained and then perform the simulation with modified gating that reduces the unnecessary iteration there by reducing lead time until the required quality is obtained.

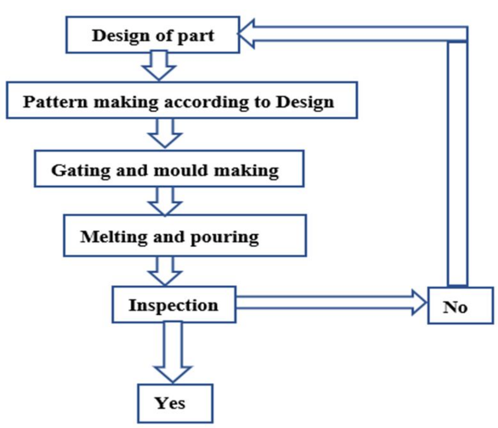

Fig.2 Steps involved in shop floor casting

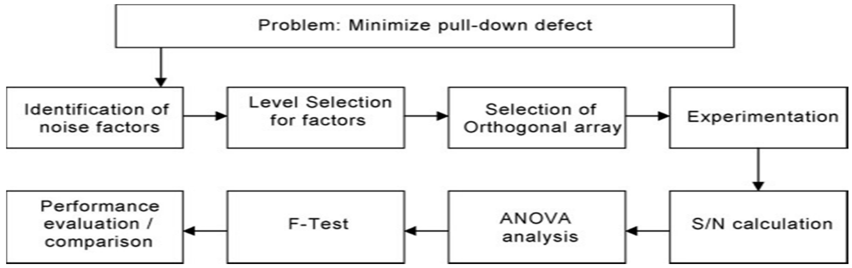

Fig.3. Factor optimization using Taguchi's DOE

IV. DESIGN OF CASTING PRODUCT

A. *Dimensional Details for Hexagonal Nut (Casting Part)*

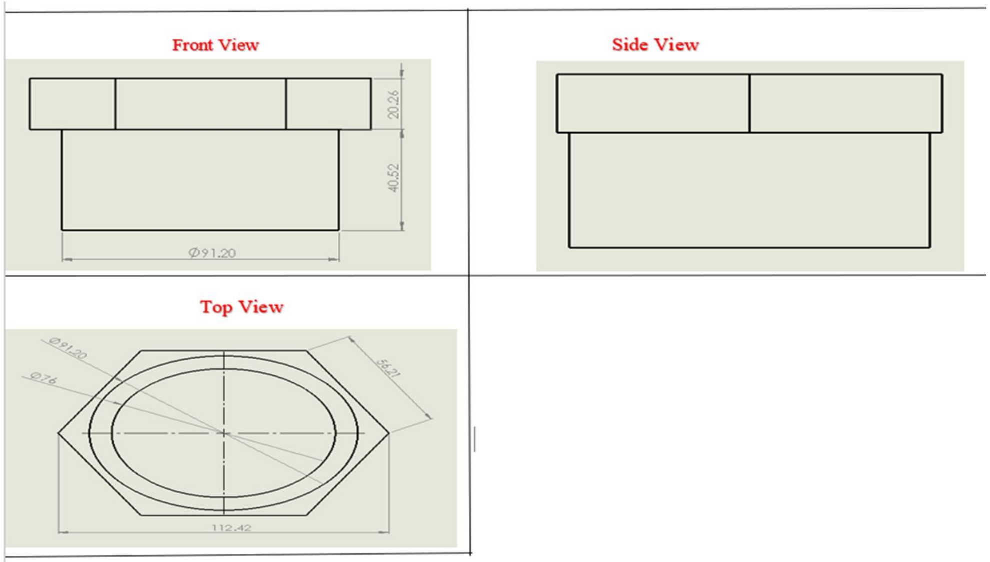

Fig. 4 Hexagonal Nut (Casting Product)

V. ANALYSIS OF CASTING SIMULATION

The casting simulation is done on the part from real life casting i.e., the lever arm which is made by using the graded gray cast iron and software used is click2cast which effectively shows the defects occurs in real casting process. The process parameters used in casting is listed as below.

Table 2. Input Parameter of Click2Cast Simulation

Size of molding box	260 x 250 x 150 mm
Volume of casting	247254.754mm^3
Modulus of casting	5.839054mm
No of cavity	1
Pouring temperature	680^0 C ,710^0 C ,740^0 C
Material	AC-43100 (LM-9)
Mesh size	3 mm
Mold material	Green sand
The initial temperature of the sand	20 ^{0}C

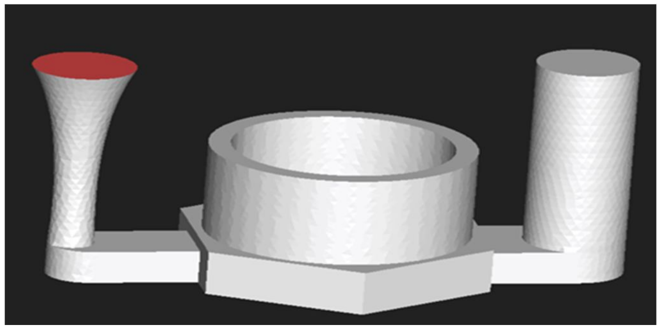

Fig. 5 Mesh model of part along with gating

A. Variation of Velocity During Filling

The optimal filling time depends on the speed of flow of the molten metal. This mostly varies within the mold openings and the gating channels. The metal will be hot and fast at these locations and thus it leads to huge damage if the molten flow is not maintained properly. The speed of the molten metal flow depends on two factors. The metallostatic head and the ratio of cross-sections of sprue exit, ingate and runner. Figures 6 and 7 showing the results of rate of flow of velocity in mold cavity at various filling rates using simulation software. Pouring velocity needs to be carefully controlled during the metal casting operation, since it has certain effects on the manufacture of the part. If it is too slow, the metal may begin to solidify before filling the mold, If the pouring velocity is too fast, then turbulence can result.

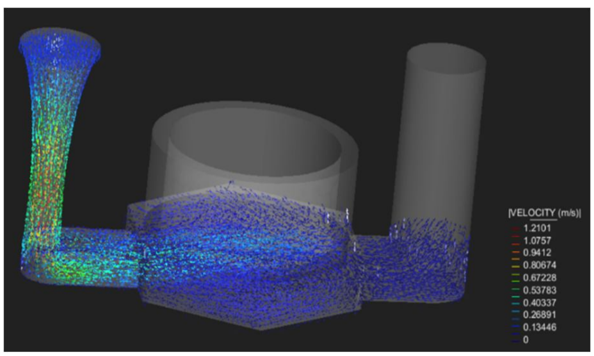

Fig. 6 Velocity variations after 50 % filling of Mould

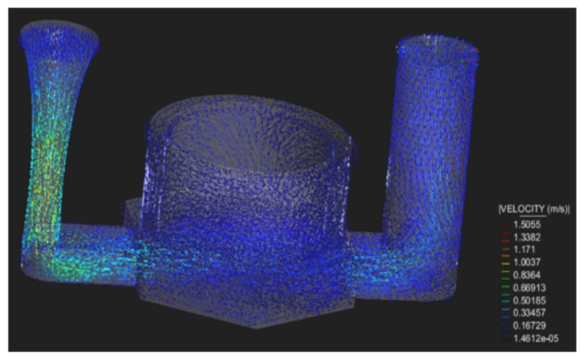

Fig. 7 Velocity variations after 100 % filling of Mould

From the results of velocity, it is clear that the filling velocity is being increased due to effect of gravity as well as the tapering of the sprue which avoids air aspiration effect and molten metal flows into the mold cavity and also there is no sudden changes observed in the velocity variations which shows there is no defect in gating system.

B. Variation of Temperature during Filling

Pouring temp. refers to the initial temp. of the molten metal used for the casting as it is poured into the mold. This temperature will obviously be higher than the solidification temperature of the metal. The difference between the solidification temperature and the pouring temperature of the metal is called the superheat. Fig. 8 shows the variation of temperature in mold during filling process.

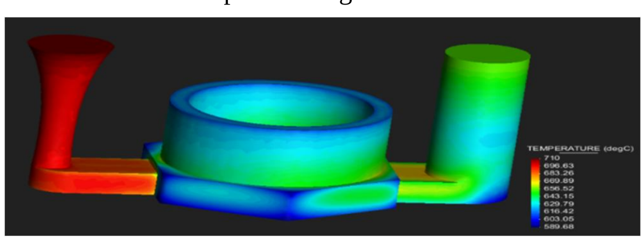

Fig. 8 Variation of Temperature during Filling

From the figure 8, it has been observed that the temperature at sprue area and at its base is more due to continuous travel of molten metal which is at high temperature.

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C. Variation of Pressure During Filling

A technological feature, fluidity, reflects the ability of liquid metal to flow continuously even as it solidifies via a given mold passage, filling it to reproduce the detailed design. When the molten metal rises in the mold, filling can be hindered due to the backpressure created by compressed air in the cavity thereby reducing the metallostatic pressure. Venting enables to regulate the back pressure.

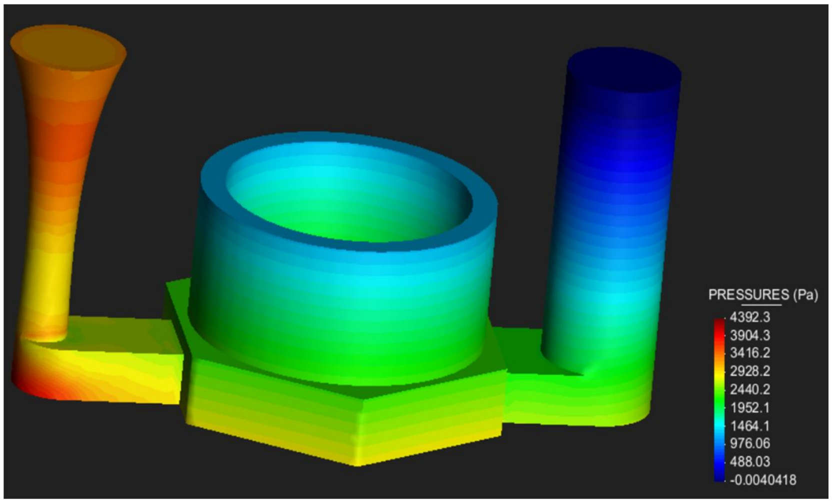

Fig. 9 Variation of Pressure in Mould During Filling Process

Figure 9 showing that the pressure concentration is high at sprue and sprue base due to continuous pouring of molten metal which is at higher temperature and remaining areas like riser will have less pressure as venting enables to regulate the pressure. If the pressure concentration is more at sprue, runner , pouring basin there may be no effect on the casted object as they are trimmed and scrapped later but if the pressure concentration is high at mould cavity necessary measures should be taken and design need to be modified.

D. Cold Shuts Formed During Filling

Poor fluidity of molten metal gives rise to misrun or cold shut. Cold shut occurs when streams of molten metal arising from opposite direction fail to fuse completely. Figure 10 shows results of cold shuts formed in casting during filling process.

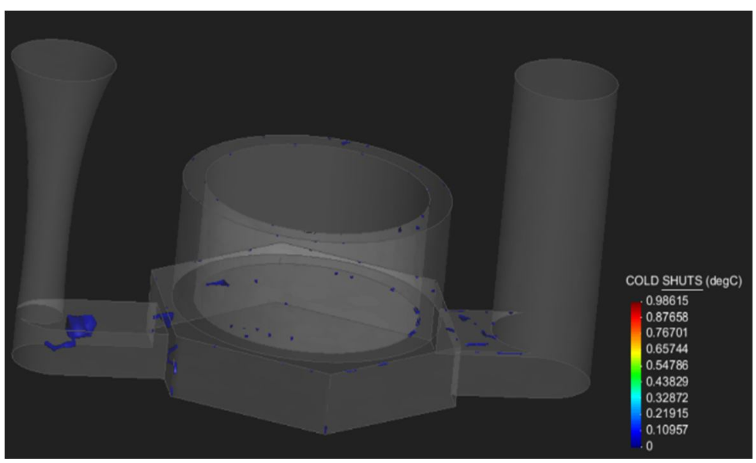

Fig. 10 Cold Shunts Formation during Filling Process

From the figure it is observed that cold shuts formed at mold cavity and riser areas which are minor but it is very common as the metal enters the runner path and there on into the mold cavity the streams of molten metal arise from opposite direction may not fuse properly.

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E. Porosity (%) Observed During Solidification

The casting voids most often referred to as porosity can be caused by solidification shrinkage, gas formation, or non-metallic compound formation, all while the metal is liquid. Large gas-related voids caused by trapped core or mold gases in the molten metal are called blowholes or blows.

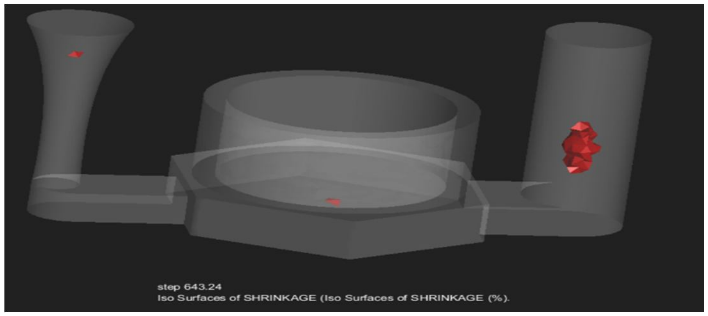


Fig. 11 Porosity (%) during Solidification Process

From the results of porosity observed that the porosity at inner part of mold cavity is high due to gas formation and during solidification it is very common that the mold cavity cools slowly and inner most part of the casting may not solidify properly as shown in figure 11 and there is also increase in porosity at centre due to continuous flow of molten metal.

F. Macro Porosity Observed

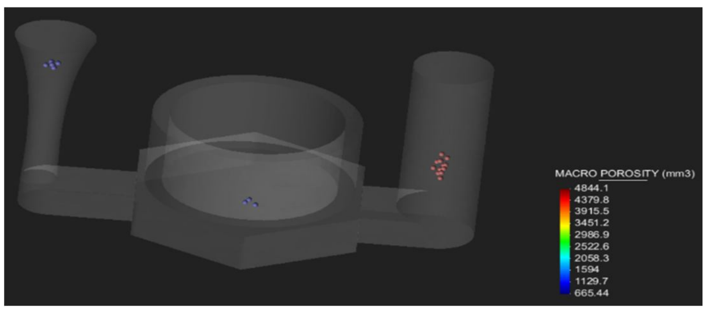


Fig. 12 Macro Porosity during Solidification Process

From the results of macro porosity it is clear that the solidification shrinkage at sprue and riser will have less effect as shown in figure 12 and as the gating system is scraped later it will not influence the properties of casted metal.

G. Solidification Temperature Analysis

The solidification of molten metal in the mold cavity takes place immediately after entering into the cavity. Solidification result of heat transfer from internal casting to external environments and the rate of solidification is not uniform throughout the casting. The solidification of liquid metal in the mold cavity starts from the edges of the casting and it progress towards the Centre of the casting. The solidification front directed from the thinnest section towards the thickest section and the thinner section solidifies quicker comparison to the thickest section.

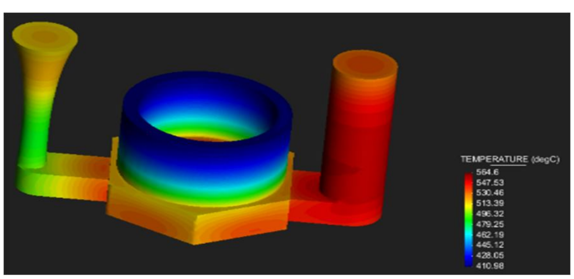


Fig.13 Temp Variation after 50% Filling

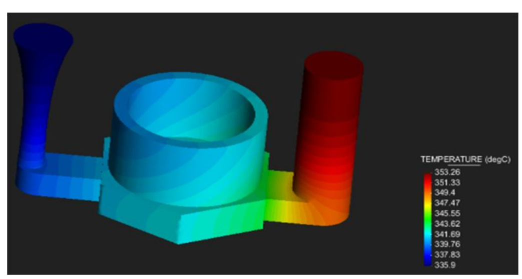


Fig.14 Temp. Variation after 100% Filling

From the figures 13 to 14, it is clear that solidification temperature will be more at the mold cavity due to no proper ventilation or absence of air and solidification time for mold cavity will be more when compared to remaining parts of gating system due to ventilation at sprue and riser and due to absence of air at mold cavity. Solidification time will be less at sprue and riser. Solidification temperature depends upon the surface area of the mold material, rate of heat transfer and temperature of liquid metal and properties of mold material

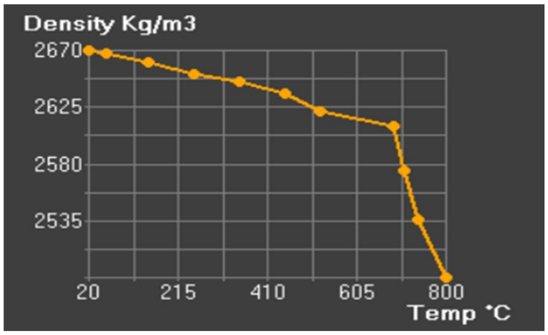


Fig.15 (a) Temp. vs. Density of LM9

Fig.15 (b) Temp. vs. Specific Heat of LM 9

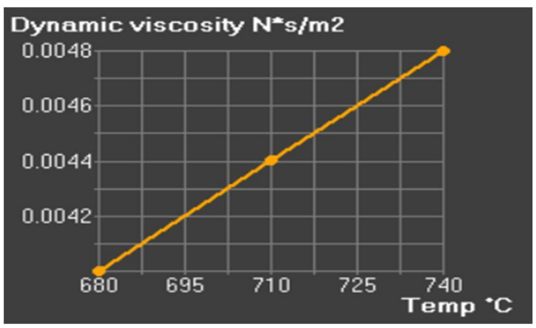


Fig.15 (c) Temperature vs. Dynamic Viscosity of LM 9

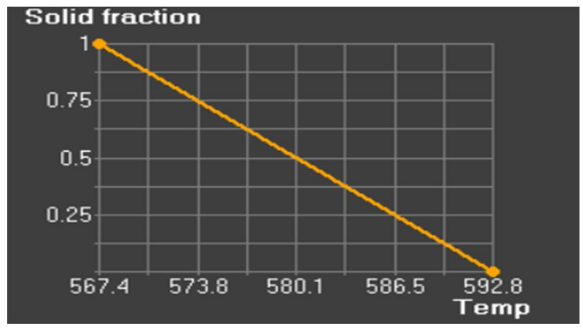


Fig.15 (d) Temperature vs Solid Fraction of LM 9

The temperature related properties are shown in Figure 15 (a) temperature vs. density, (b) temperature vs. specific heat, (c) temperature vs. Dynamic viscosity and (d) temperature vs. solid fraction.

VI. EXPERIMENTATION AND DISCUSSION

A. Product Mould Making and Cast

Fig. 16 Mould

Three mould of different dimensions have been designed. Three products for each case has been prepared using two box sand moulding. Total 9 product have been casted.

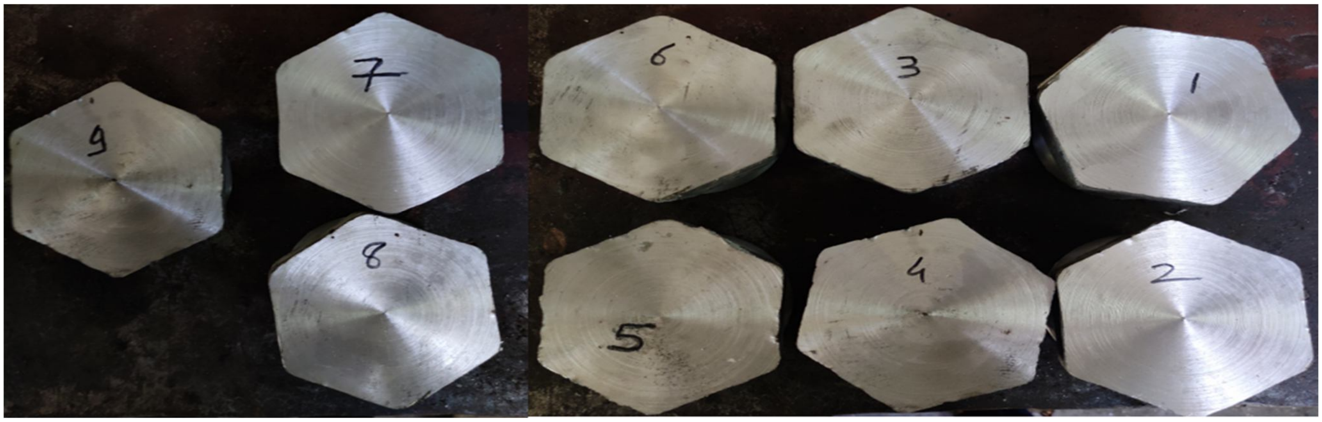
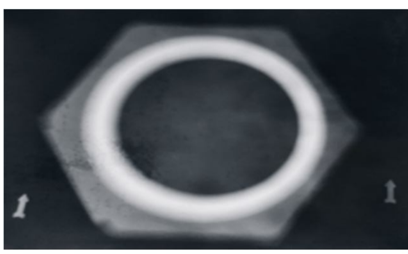


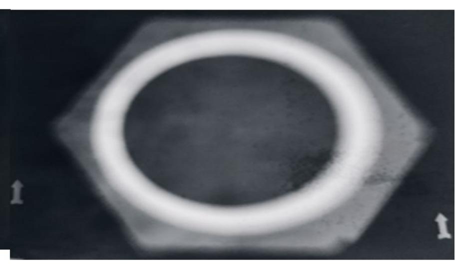
Fig.17 Experimental Specimen (Hexagonal Nut)

For each trial condition, three castings are made using randomization technique. The casting density was measured using simple experimental density device. Then porosity was calculated from the following relationship

$$\text{Porosity (\%)} = \left(\frac{\rho_o - \rho_s}{\rho_o}\right) \times 100$$

Where ρ0 is the density of a fully dense casting having no porosity (2.68 g/cm3) and ρs is the measured casting density.





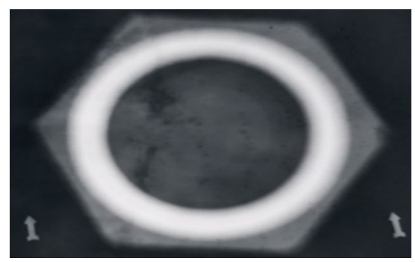


Figure 18 Case I Radiographic Film

Figure 19 Case II Radiographic Film

Figure 20 Case III Radiographic Film

B. Radiography Testing

Fig.21 Radiography Testing Set-up

It is noted from the literature that to detect the sub surface flaws in the casting sample, the radiographic test is the better. The radiographic tests of the casting sample are conducted for the purpose. The general principal of radiographic for inspecting the cast parts are similar to that the medical radiography. The method uses of X- ray for inspection, produced by gamma rays / X ray tube are produced radioactive isotope. Penetrating radiation is allowed to pass throughout solid parts in case of the casting that is under inspection rather that part of the human body, on to photographic image. As the result of an objective internal structure is the deposited on the film. The depending on the thickness and density of radiation that an object absorbs the energy and the energy is not absorbed by the object cause exposure to radiographic film. When the film is developed, the area will be dark and area of the film which is exposed to less amount energy remains lighter colour. Therefore, area of the thickness occurs due to discontinuities o, like crack / porosity area on the film denote of low density the inclusion such as slag. The inclusion is found high density will be obtaining the light areas such as of tungsten.

Table 3. Specification of Radiographic Testing Machine

Source	IR-192
Source size	2.7D×4.2H
S.F.D	12”
Specification	SWSI
Film type	Kodak AA400(D7)
Exposure time	40 min
Devolving time	6 min
Screen thickness	Front& Back both 0.1mm
Evolution as per	E-446
Acceptable standard	IS-2555

C. Levels of Input Parameters

Table 4. Process Parameters and Levels of Parameters

Sr No	Variable Factor	Symbol	Level 1	Level 2	Level 3
1	Pouring Temperature(°C)	A	680	710	740
2	Sprue Height (mm)	B	100	125	150
3	Pouring Time (sec)	C	4	5.5	7

Table 5. Response Table For Porosity % (Means)

Experiment no.	Pouring temperature (°C)	Sprue Height (mm)	Pouring time (sec)	Porosity (%)	Mean
1	680	100	4.0	4.6	4.6
2	680	125	5.50	9.4	9.4
3	680	150	7.0	14.8	14.8
4	710	100	5.50	1.2	1.2
5	710	125	7.0	6.6	6.6
6	710	150	4.0	8.3	8.3
7	740	100	7.0	13.7	13.7
8	740	125	4.0	19.4	19.4
9	740	150	5.50	16.8	16.8

D. Main Effects Plot for Porosity

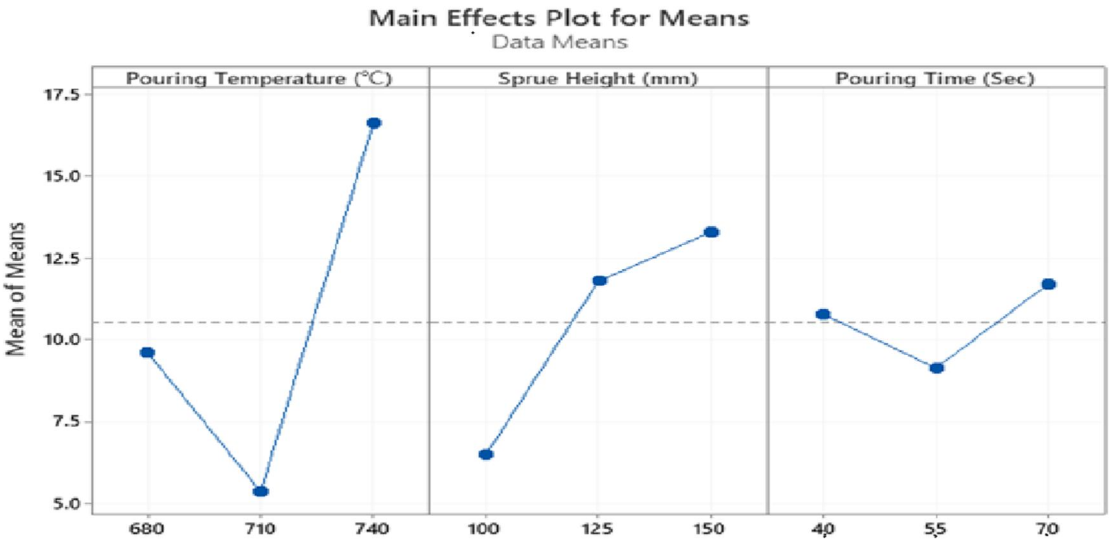


Fig.22 Mains Effects Plot for Porosity

Figure 26 show for main effect plot for means, parametric effect for response characteristics i.e. % porosity can be understood. parameters Pouring temp.710 (Level 2), Filling rate 281.22 gram/sec (level 1) and Pouring time 5.5 sec (level 2) gives the minimum % porosity.

Table 6. Optimum Level of Parameters

Sr. No.	Parameters	Optimum Level
1.	Pouring Temperature () [Level 2]	710
2.	Sprue Height (mm) [Level 1]	100
3.	Pouring Time (Sec) [Level 2]	5.50

E. ANOVA Result

Table 7. ANOVA calculations for Porosity (Means)

Sr no	Source	DOF	Seq. SS	Adj SS	Adj MS	F	P	Percentage of Contribution
1	Sprue Height	2	164.327	164.327	82.163	21.25	0.035	56.62
2	Pouring time	2	76.580	76.580	38.290	8.37	0.017	26.39
3	Pouring temperature	2	40.127	10.127	5.063	1.11	0.026	13.82
4	Error	2	9.147	9.147	4.573	-	-	3.17
5	Total	8	290.18	-	-	-	-	100.00

Table 8. show analysis of variance for porosity. Percentage of contribution of Sprue height, pouring temperature and Pouring time is 56.62%, 13.82% and 26.39% respectively. Sprue height is most dominant and Pouring temperature is least dominant.

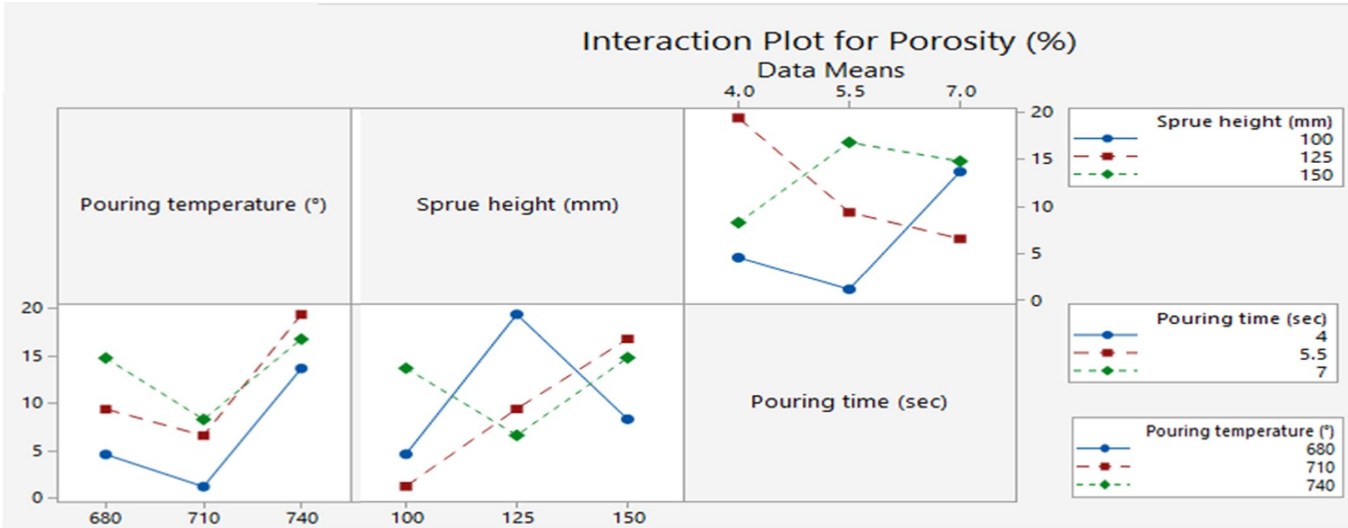


Fig. 23 Interactions Plot for Porosity (%)

VII. CONCLUSIONS

1) The casting simulation software Click2cast is based on finite element methods helps in easily visualizing the velocity, pressure, temperature change during the filling of mould Which is not possible in real life casting and it also helps in predicting the defects. like mould erosion, cold shut, porosity, air entrapment etc.
2) With the use of MINITAB software to minimize the porosity of the casting samples, for the given combination of the process parameters following optimal results were obtained:
a) Optimum Sprue Height=100 mm
b) Optimum Pouring time =5.50 sec
c) Optimum Pouring temperature=710°C
3) Sprue height play crucial role and contributed 56.62% to the overall contribution followed by pouring time and pouring temperature.
4) The results are consistent with the predicted feeding area of the riser after optimization design and process parameter adjustment. The performance of casting crossing is greatly improved by adjusting parameters and optimizing riser design.
5) The X-ray radiograph of the product taken shows that there were no internal defects in the castings.
6) From the above study it is concluded that the use of simulation method and taguchi in industry is economical, reliable, defect reduction, high accuracy parts with minimum losses due to rejections.

VIII. ACKNOWLEDGMENT

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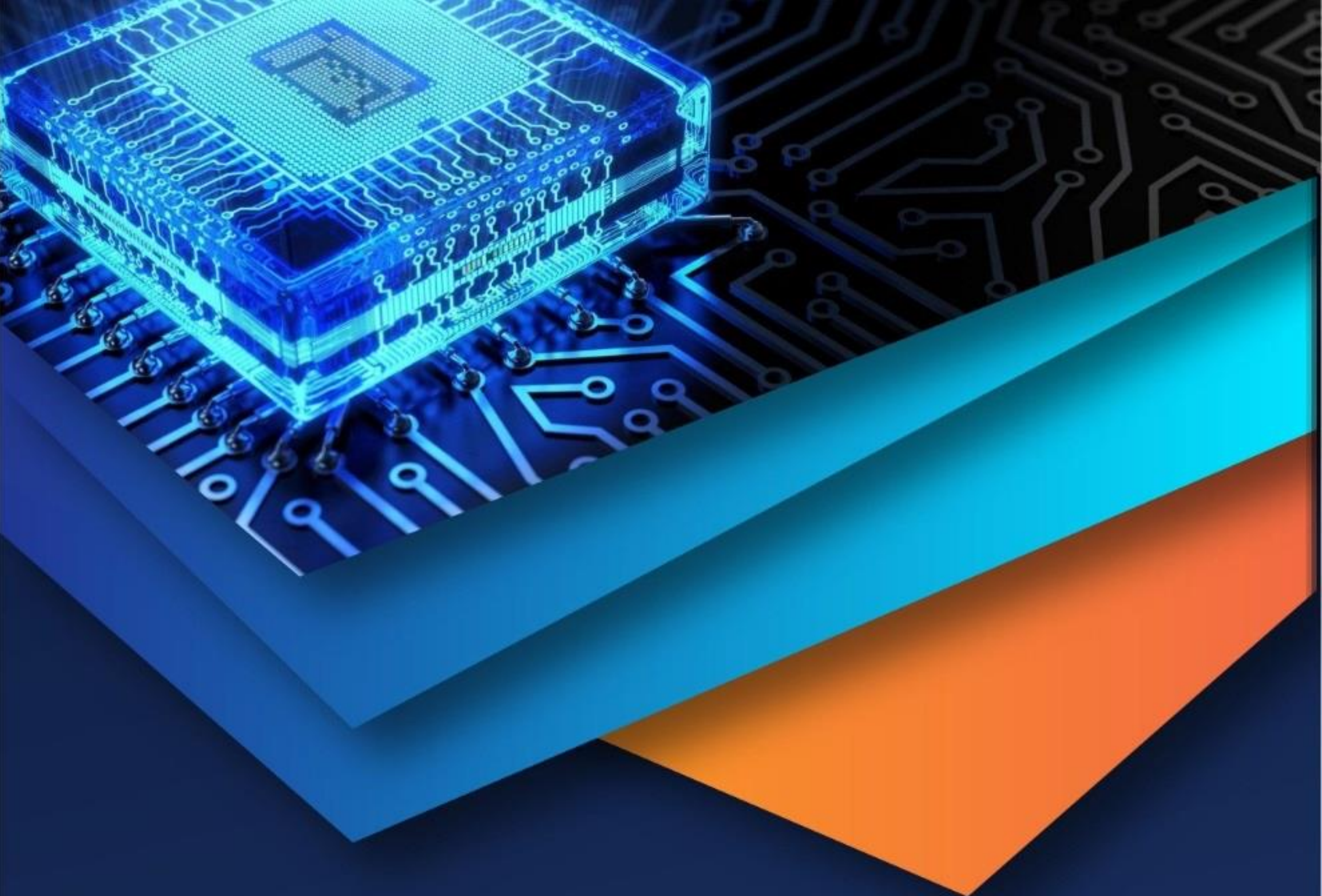

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