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Experimental Investigation and Optimization of Hardness in Sand Casting Process by Using the Design of Experiments Approach

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Abstract: Casting is one of the most important process in manufacturing environment to develop a product for the customer needs and satisfaction. There is lot of casting process available in industrial world. Among various casting process, sand casting is one of the important process generally used for both ferrous and non ferrous materials. The solidification range of molten metal plays a vital role in sand casting process to decide the quality of the product. During solidification process, the results of casting defects such as shrinkage, porosity and hot tears are eliminated and a standard casting design system is essential which can be achieved by an experimental investigation. Recently, Aluminum (6063) plays a major role in automobile, manufacturing, nuclear and marine industries. In this experimental investigation, crucible furnace is used to melt the material and develop the product through sand casting methods. The important input process parameters such as vent hole angle and vent hole diameter are selected and studied at three different levels according to the recommendation of Design of Experiments Approach. The main objective of this experimental investigation is to find the optimum level of hardness in sand casting process by using Aluminum (6063) material. The hardness quality of test specimen is measured by using the Brinell hardness tester. This experimental results shows that, vent hole diameter plays a crucial role in hardness of sand casting process and the optimum level is recommended for further research.

Keywords: Sand Casting Process, Aluminum (6063) , Design of Experiments, Hardness.

1 Introduction

Most of the manufacturing industries are preferred to develop the products through manufacturing process like machining, casting, forging (or) welding. Sand casting is the one of the important casting methods used for both ferrous and non-ferrous materials. The major benefits of selecting the sand casting process are excellent dimensional geometry, easy to develop the patterns, increased production rate and less solidification time when compared to die casting. The most significant process parameters considered in sand casting process are vent hole, gating system, sprue & riser design, pattern allowances and tolerances. The factor affecting the bonding mechanisms are physical and mechanical properties, crystal structure and intermettalic compounds. The quality of the test specimen is depending upon the proper selection of input process parameters and materials. The literature review is essential to forecast the hardness of the test specimen during sand casting process.

Farzaneh Farhang Mehr et al. investigated the thermal behavior of the Casting/Chill material A319 alloy in sand casting process. The authors concluded that temperature plays major role in the sand casting process [1]. Priyank et al. studied the optimization of sand casting process parameters by Taguchi method and artificial neural network and reported that the vent hole is mainly used to exhaust the gases from the green sand and also facilitate to transfer the heat from mould cavity [2]. Seidu studied the consequence of carbon based materials as mould additives on the white cast iron. The effects of riser, gating, green sand, oxidation, casting heat treatment and machining allowance are analyzed. The authors reviewed the economical qualities of casting process [3]. Niranjan

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and Lakshminarayanan studied the optimization of process parameters for in situ casting of Al/TiB_2 composites through response surface methodology. The input process parameters selected for this experimental investigation are temperature, reaction time/min and mass fraction of TiB_2/% with 5 levels. The response surface methodology method is used to find the optimum level of input process parameters [4]. Yan Zhan et al. [5] analyzed experimental work for both lathe and lathe man. The results are analyzed by Genetic Algorithm with tabu (GA-TS) technique. The new network protocol developed for the manufacturing industries. Nukman et al. [6] investigated a new combination of Genetic Algorithm along with Artificial Neural Network (GA-ANN) applied for the cutting process of CO_2 laser. The simulation result showed the maximum error was below 10%. The Similar methods of Multidisciplinary Design Optimization (MDO) have been used for automobiles in Li Lei et al. [7].

Vasudev et al. proposed a methodology to optimize the mold box size and the number of cavities based on solidification time and mold temperatures are investigated. The authors studied the simulation by solid modeling and cavity-wall gap dimensions [8]. Surekha presented the Genetic algorithm (GA) and Particle Swarm Optimization (PSO) in the multi-objective optimization . It is found that hardness and bulk density of the cast material plays vital role in the optimum level of input process parameters [9]. Alonso-Santurde et al. investigated the green sand clay proportions 0–50% and heated up to 1050°C to produce brick for building construction. The clay based green sand is a better physical property. The optimum volume of sand is used for 35% of green sand and 25% of core sand for this brick work [10].

Singamneni et al. determined the mechanical properties of light metals such aluminum and magnesium alloy carried out by a 3D printing technology using the Taguchi Design of Experiments approach and rapid casting is done on the light metals in order to enhance the mechanical strength [11]. Paul studied the property of yola sand and effects of moisture content. The yola natural sand has been analyzed by the variation of moisture content range from 1 to 9 %. The author concluded that the optimum results of this experimental investigation are compression strength of 118.6 KN/m^2 and 5 % of moisture content [12]. Rao demonstrated the metal casting principle and practice in sand casting process. The composition of green sand like saw dust, coal and other additives are also investigated and the different percentage of additives included based on the standard procedure and analyzed the output responses like density, porosity, permeability etc [13]. Haq investigated the parameter optimization of CO_2 casting process by using the Taguchi's Method. The input parameters are evaluated and optimized to develop the high quality final product. The experimental result shows that the various CO_2 casting defects are investigated and the optimum results are recommended [14]. Aribo studied the permeability of green sand for Epe silica sand and also analyzed the sand properties of the recycled foundry sand to find green compression strength and permeability [15]. Tavakoli et al. studied the optimal riser design in sand casting process with evolutionary topology techniques and concluded that, solidification time is the major parameter for the optimum riser geometry in sand casting process [16]. Fu-Yuan Hsu demonstrated the multiple-gate runner system for gravity casting methods [17]. It is concluded that the runner design is important factor in the selection of effective casting methods [18].

Many of researchers carried out the trial and error based experimental analysis for conducting the investigation. Based on the literature review, it is found that sand casting process is one of the important methods for developing a product according to customer needs and this process provides an enhanced material strength and reduces the cost as well as production time. The significant objective of the present investigation is to develop the product by using Aluminum (6063) material with the help of design of experiments approach and found that process parameters plays a vital role in determining the strength and quality of the product by using sand casting process.

2 Experimental Work

Normally casting is the important process in making a specimen for the required shape and size with desired accuracy. Sand casting is one of the casting process in which Solidification of casting is based on the quantity of heat transferred by a substance during change of phase transition. During the solidification process, the casting result with defects like shrinkage, porosity and hot tears. The design of gating system, sprue, sprue basin and allowances are followed by the standard procedure in the sand casting process. The position of the vent hole angle (90° , 60° and 45°) with respect to the reference line is shown in Fig. 1.

The riser design is 55 mm, 50 mm and 50 mm for major diameter, minor diameter and height respectively [15]. The Aluminum (6063) melts in the crucible furnace is shown in Fig. 2.

In this research work, Aluminum (6063) material has been selected for this investigation. The chemical composition of the test specimen is presented in Table 1. Based on the customer requirements and industrial specifications, the most important input process parameters influencing the hardness are vent hole angle and vent hole diameter to develop the good quality of the test specimen as presented in the Table 2.

The total factors for level 1, level 2, level 3 are denoted by a, b, c respectively

$$(a\cdot a+a\cdot b+a\cdot c)+(b\cdot b+b\cdot c+b\cdot a)+(c\cdot b+c\cdot c+c\cdot a) \quad (1)$$

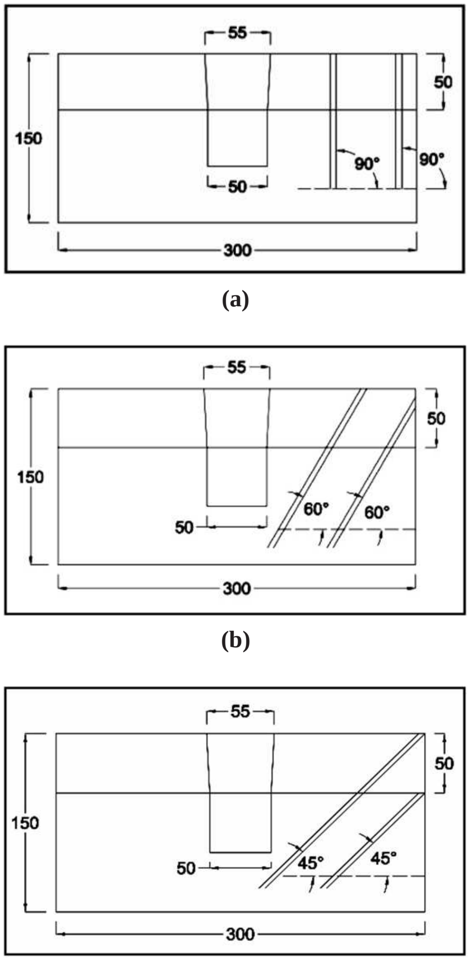

Fig. 1: Position of vent hole angle.

Fig. 2: Al (6063) melts in crucible furnace.

Table 1: Chemical composition of Aluminum (6063) material.

Element	Al	Cr	Cu	Fe	Mg	Mn
%	97.5	0.1	0.1	0.25	0.55	0.1

The Aluminum (6063) heated up to 780° C and poured the molten metal to the sand casting set up as

Table 2: Sand Casting-Process Parameters.

S.No	Input Parameters	Units	Levels		
			1	2	3
1.	Vent hole angle	°C	45	60	90
2.	Vent hole diameter	mm	3	5	7

Table 3: Design of Experiments for L_9 Orthogonal Array.

Exp. No.	Input Parameters	
	Vent hole angle (°)	Vent hole diameter (mm)
1	90	3
2	90	5
3	90	7
4	60	3
5	60	5
6	60	7
7	45	3
8	45	5
9	45	7

Fig. 3: Pouring of Al (6063) molten metal in Sand Casting setup.

shown in Fig. 3. The hardness of the test specimen is measured by using the Krystal Brinell hardness machine is shown in Fig. 4. The experiments were conducted based on the L_9 orthogonal array based on the Taguchi Design of Experiments approach and it is presented in Table 3.

2.1 BHN Equation

$$BHN = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]} \tag{2}$$

where
P = Applied Force (N)
D = Diameter of indenter (mm)
d = Diameter of indentation (mm).

$$BHN = \frac{2 \times 1000}{\pi 10[10 - \sqrt{10^2 - 3.8^2}]}$$
$$= 84.8 \sim 85 \quad \text{(presented in Table 4).}$$

Fig. 4: Brinell Hardness Machine.

Table 4: Experimental Results.

Exp. No	Input Parameters		Results	
	Vent hole angle	Vent hole diameter	Hardness	S/N Ratio
	deg.	mm	BHN	
1	90	3	85	38.5884
2	90	5	74	37.3846
3	90	7	60	35.5630
4	60	3	78	37.8419
5	60	5	65	36.2583
6	60	7	47	33.4420
7	45	3	71	37.0252
8	45	5	56	34.9638
9	45	7	39	31.8213

3 Results and Discussion

Sand casting process is used to develop the product for both ferrous and non ferrous materials. The important process parameters for this sand casting process are vent hole diameter and vent hole angle. The crucible furnace is used for this experimental investigation. Based on the Taguchi design of experiments, L_9 experiments are conducted to forecast the optimum level of input process parameters with the output response like hardness using the Minitab software is presented in Table 4.

From Table 4, the best possible level of input parameters are selected by using the response table, main effect plot, interaction plot, ANOVA table and validation. The effect of input process parameters in sand casting process to measure the hardness of aluminum (6063) material is shown in Fig. 5.

3.1 ANOVA

3.1.1 Sum of squares of vent hole Diameter

$$\frac{(\sum x_1)^2}{n_1}+\frac{(\sum x_2)^2}{n_2}+\frac{(\sum x_3)^2}{n_3}-\frac{T^2}{n} \quad (3)$$

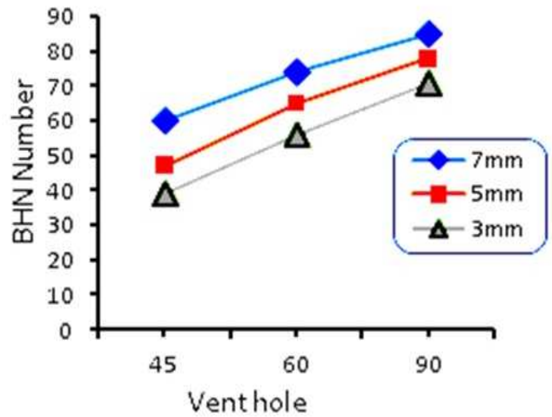

Fig. 5: Hardness variation of Aluminum (6063) material in sand casting process.

3.1.2 Sum of squares of vent hole Angle

$$\frac{(\sum y_1)^2}{n_1}+\frac{(\sum y_2)^2}{n_2}+\frac{(\sum y_3)^2}{n_3}-\frac{T^2}{n} \quad (4)$$

where
x_1 = BHN at 3 mm vent hole diameter
x_2 = BHN at 5 mm vent hole diameter
x_3 = BHN at 7 mm vent hole diameter
y_1 = BHN at 90° vent hole angle
y_2 = BHN at 60° vent hole angle
y_3 = BHN at 45° vent hole angle.

3.1.3 Sum of squares of vent hole diameter

$$\frac{(\sum x_1)^2}{n_1}+\frac{(\sum x_2)^2}{n_2}+\frac{(\sum x_3)^2}{n_3}-\frac{T^2}{n} = \frac{21^2}{3}+\frac{60^2}{3}+\frac{109^2}{3}-\frac{190^2}{9} = 1296.22 \quad \text{(presented in Table 6).}$$

Similarly

$$\frac{(\sum y_1)^2}{n_1}+\frac{(\sum y_2)^2}{n_2}+\frac{(\sum y_3)^2}{n_3}-\frac{T^2}{n} = 469.56 \quad \text{(presented in Table 6).}$$

3.1.4 Sum of squares of error

$$\text{Total sum of squares} = (\text{sum of vent hole diameter} + \text{sum of vent hole angle})$$

Table 5: Response Table for S/N Ratio.

Level	Vent hole angle	Vent hole diameter
1	34.60	37.82
2	35.85	36.20
3	37.18	33.61
Delta	2.58	4.21
Rank	2	1

Degree of freedom for vent hole diameter $= C - 1$
Degree of freedom for vent hole angle $= R - 1$
where
$C =$ Number of BHN in vent hole diameter
$R =$ Number of BHN in vent hole angle.

3.1.5 Mean sum of squares for vent hole diameter

$$\begin{aligned}&\text{Mean sum of square for vent hole diameter}\\&= \frac{\text{sum of vent hole diameter}}{\text{DOF}}\\&= 648.11 \quad \text{(presented in Table 6).}\end{aligned} \tag{5}$$

3.1.6 Mean sum of squares for vent hole angle

$$\begin{aligned}&\text{Mean sum of square for vent hole angle}\\&= \frac{\text{sum of vent hole angle}}{\text{DOF}}\\&= 234.78 \quad \text{(presented in Table 6).}\end{aligned} \tag{6}$$

3.1.7 Sum of squares of Error

$$\begin{aligned}&\text{Total sum of squares}\\&= (\text{sum of vent hole diameter} + \text{sum of vent hole angle})\\&= 1780.89 - (1296.22 + 469.56)\\&= 15.11 \quad \text{(presented in Table 6).}\end{aligned} \tag{7}$$

3.1.8 Mean square of Error

$$\begin{aligned}&\text{Mean square of Error}\\&= \frac{\text{Sum of squares of errors}}{\text{DOF}}\\&= 3.78 \quad \text{(presented in Table 6).}\end{aligned} \tag{8}$$

3.1.9 F value of vent hole diameter

$$\begin{aligned}&\frac{\text{Mean sum of square for vent hole diameter}}{\text{Mean sum of Error}}\\&= 171.56 \quad \text{(presented in Table 6).}\end{aligned} \tag{9}$$

3.1.10 F value of vent hole angle

$$\begin{aligned}&\frac{\text{Mean sum of square for vent hole angle}}{\text{Mean sum of Error}}\\&= 62.15 \quad \text{(presented in Table 6).}\end{aligned} \tag{10}$$

3.2 Response Table

The most important objective of this experimental investigation is to study the effect of input process parameters on the hardness and hence 'Larger is Better' condition is selected. Based on the research work, the response table for the S/N ratio is presented in Table 5

The highest average minus lowest average of each factor is calculated from the delta values in response table. This response table specifies the rank based on the delta values. Based on the response table shows that, vent hole diameter plays crucial role in the sand casting process followed by vent hole angle.

3.3 Main Effect Plot

The effect of input process parameters on the hardness of Aluminum (6063) material is shown in Fig. 5. The main effect plot is used to represent the optimum level of input process parameters for this experimental investigation. From this Fig. 6, it is represented that the effect of input process parameters increases with a increase in the level that is selected for this research work. The optimum level of sand casting process for this investigations are 90° vent hole angle and 3 mm vent hole diameter.

3.4 Interaction Plot

For effective optimization, interaction plot is used to demonstrate the interaction between the levels and input parameters. The hardness of aluminum (6063) for every experimental run is investigated by using the interaction plot as shown in Fig. 7. Based on the interaction plot, it is concluded that the maximum hardness of aluminum (6063) material in sand casting process can be achieved in 90° vent hole angle and 3 mm vent hole diameter.

Table 6: Analysis of Variance for Hardness.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%contribution
Vent hole angle	2	469.56	469.56	234.78	62.15	0.001	26. 37
Vent hole diameter	2	1296.22	1296.22	648.11	171.56	0.000	72.78
Error	4	15.11	15.11	3.78			0.85
Total	8	1780.89					100

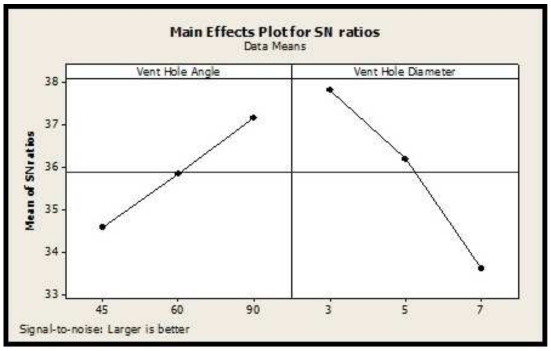

Fig. 6: Main Effect Plot for S/N ratio.

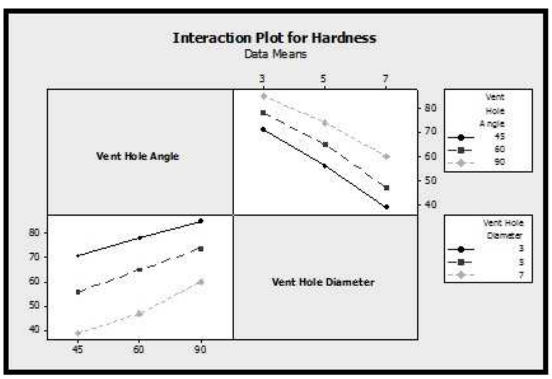

Fig. 7: Interaction Plot for Hardness.

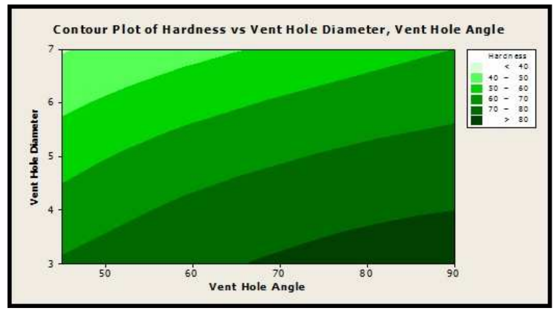

Fig. 8: Contour Plot for Hardness.

Table 7: Validated result for Hardness of Aluminum (6063) material.

Exp. No	Input Parameters		Hardness	
	Vent hole angle	Vent hole diameter	Expl. Results	Validated Results
	deg.	mm	BHN	BHN
1	90	3	85	87.48
2	90	5	74	72.82
3	90	7	60	58.16
4	60	3	78	75.99
5	60	5	65	61.33
6	60	7	47	46.67
7	45	3	71	70.245
8	45	5	56	55.585
9	45	7	39	40.925

3.5 Contour Plot

The contour plot is used to demonstrate the effect of input process parameters correlated with output responses. In this experimental investigation, the selected input process parameters are vent hole angle and vent hole diameter and the output response like hardness is represented in Fig. 8. From this contour plot it is observed that, hardness value decreases with increase in the vent hole diameter. The authors reported that, vent hole diameter plays vital role in affecting the hardness of aluminum (6063) material in sand casting process.

3.6 ANOVA Table

ANOVA table is a statistical tool used to compute the size of the difference between the data set. The influence of input process parameters on the output response is easily identified with the use of ANOVA table as presented in Table 6. Based on the ANOVA table, it is represented that vent hole diameter plays a crucial role for affecting the hardness of aluminum (6063) material in sand casting process with p-value of 0. The confidence level selected for this experimental investigation is 95%.

3.7 Validation

A regression analysis is used to predict the hardness of the aluminum (6063) material using the Minitab 16 software. The validation of experimental result is obtained by using the regression analysis. Regression analysis is a statistical tool and it is used to form the functional relationship among the various parameters. The relationship between the experimental result and validated result for this experimental investigation is

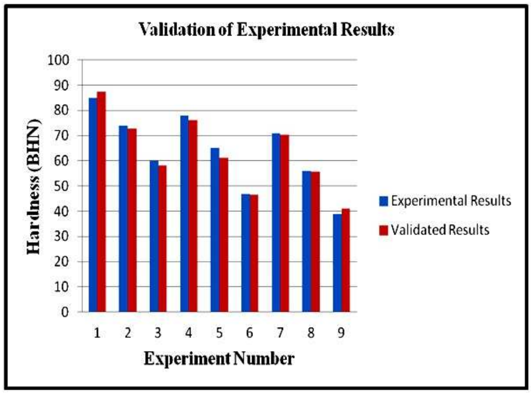

Fig. 9: Validation of Experimental results for Hardness of Aluminum (6063) material.

presented in Table 7. The experimental investigation of comparison graph as shown in Fig. 9.

The regression equation for the hardness of aluminum (6063) material in sand casting process is given below.

$$\text{Hardness} = 75.7 + 0.383\text{Vent Hole Angle} - 7.33\text{Vent Hole Diameter}.$$

4 Conclusion

This experimental investigation is to predict the hardness of the material in sand casting process by using the design of experimental approach. The Krystal Brinell hardness tester is used to evaluate the hardness of the test specimen. The authors reported the following significant conclusion based on the experimental results and analysis is listed below.

- Casting of Aluminum (6063) material presented enhanced mechanical properties.
- Solidification time varies with vent hole parameters to reduce the volume of material in the riser.
- Taguchi Design of Experiment is used efficiently in the optimization of hardness in sand casting process.
- The effective optimal parameters for this experimental investigations are vent hole diameter of 3 mm and vent hole angle of 90° .
- Vent hole parameters are more effectively influenced in sand casting.
- These parameters are mainly used for small scale industries and also it helps to improve the material hardness.

Based on the experimental investigation, it is found that the hardness is superior at ‘Larger is Better’ condition. This study is precious for the researchers to enhance the knowledge in sand casting process on Aluminum (6063) material.

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